Mathematical modeling applied to integrated water resources management: the case of Mesta-Nestos basin

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T H E S E

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Modélisation appliquée à la gestion durable des projets de ressources en eau à l'échelle d'un bassin hydrographique. Le cas du Mesta-Nestos

Mathematical modeling applied to the sustainable management of water resources projects at a river basin scale The case of the Mesta-Nestos

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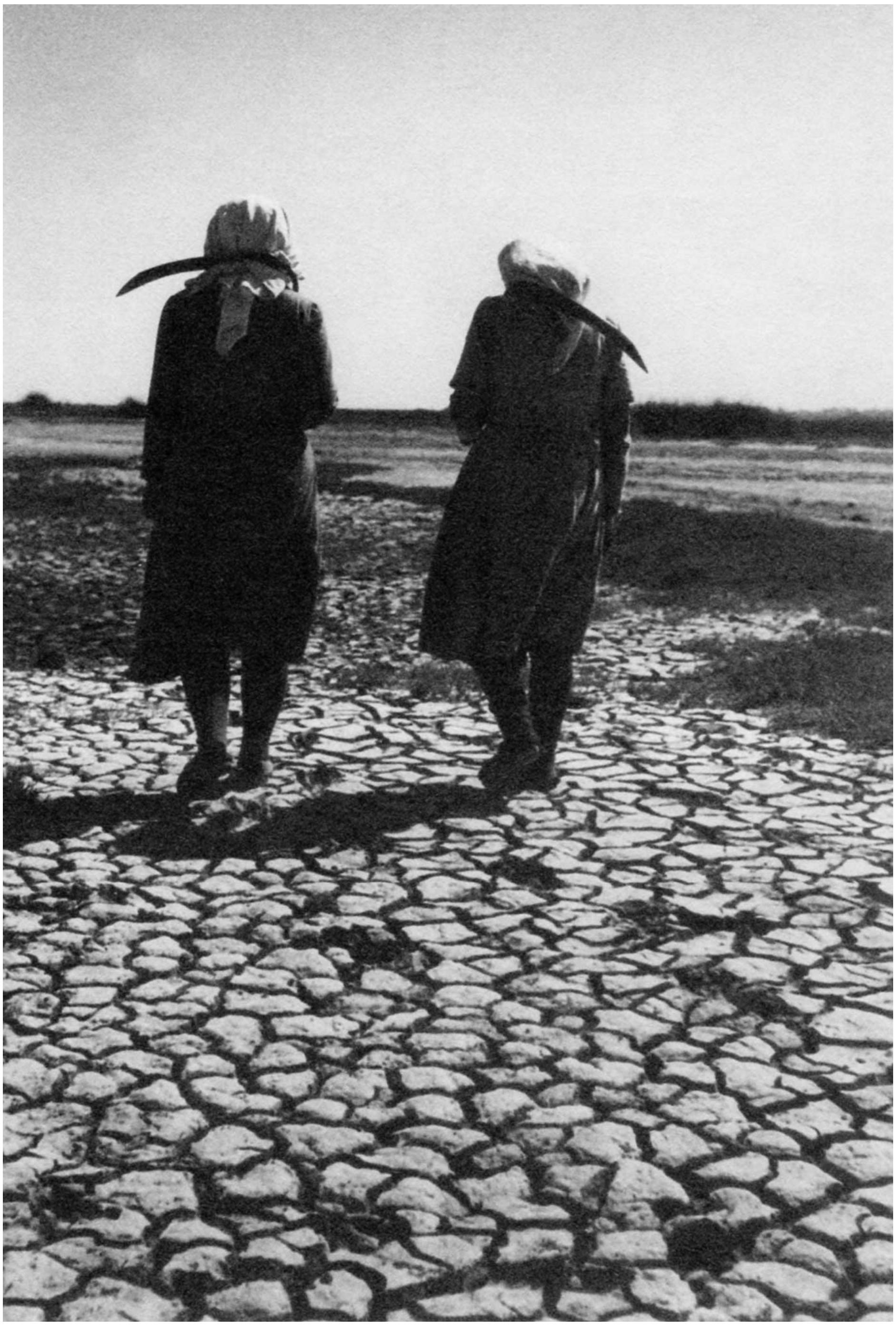
To my nephew

"Essentially, all models are wrong but some are useful"

Fondamentalement, tous les modèles sont faux mais certains sont utiles"

George E.P. Box & Norman R. Draper

Empirical Model-Building and Response Surfaces, Wiley, 1987



Nestos region, Xanthi, 1950

D.A. Harissiadis

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This doctoral thesis is the culmination of research efforts that began in 2001 and were successfully accomplished in 2008. I first became involved in studies on the Nestos/Mesta river basin as an undergraduate student, continued as a master degree student and finally, as a PhD candidate, made this area of study my specialisation.

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ABSTRACT

The construction of a large dam is a project of important economic and social consequences and this is the reason why it should be preceded by a careful socio-economic and operational study. On one hand, the operational investigation should take into account the dam's dimensions and purpose, the location of its watershed and its hydrology characteristics as well as environmental contraints due to international and national legislation. On the other hand, the socio-economic study should take into account all the variables which ensure the sustainability of the project.

Until a few years ago, the vast majority of dams were funded and consequently owned by the public sector, thus project profitability was not of highest priority in the decision of their construction. Nowadays, the liberalisation of the electricity market in the developed world has led to the privatisation of energy infrastructures and has set new economic standards in the funding and management of dam projects. The investment decision is based on an evaluation of viability and profitability over the full life cycle of the project, typically 50 years, on the basis of quantitative criteria such as the Net Present Value (NPV).

Since the fuel of a hydropower plant is water, its operation interferes with the water resources management of the river basin where it is situated. To this respect, new practices and regulations have recently developed such as the EU Water Framework Directive (WFD). They constrain any water resources project into following guidelines regarding its social and environmental impacts in accordance with long term issues such as its sustainability under climate change conditions.

The present work aims at exploring the coupling of mathematical models of hydrology, hydropower operation, climate change and economics in order to propose ways of making balanced decisions merging the demands of project investment criteria, public well being and river basin management best practices. It is illustrated by the investigation of the new hydropower and irrigation project of Temenos in the Mesta/Nestos river basin. This basin is shared between Bulgaria in its upstream northern part and Greece for its downstream part. The river ends in Aegean Sea after expanding into the Nestos delta which is occupied by a vast expanse of irrigated fields.

Currently, two hydroelectric power plants are located in the mountainous part of the Nestos basin: the Thissavros plant with a reservoir capacity of 565 million m^3 and further downstream, the Platanovryssi dam with a reservoir capacity of 11 million m^3. Both dams have been designed to operate in pump-storage mode for electricity generation. The future Temenos project is planned to be financed exclusively with private funds. Situated downstream from the previous dams, it is designed for electricity production, irrigation regulation, and should contribute to the improvement of the power produced by the existing complex.

The climate change scenarios developed by the Intergovernmental Panel of Climate Change (IPCC) with the publication of the Special Report on Emissions Scenarios (SRES) reveal possible future climate modifications at global scale. More specifically, according to the output of the several global circulation models (GCM), the global average surface temperature is predicted to increase by 1.4 to 5.8°C over the period 1990 to 2100. These temperature increases should drive evaporation rate increases and precipitation fluctuations. Consequently, a severe impact could result upon hydropower generation as it is sensitive to the amount, timing, and geographical pattern of precipitation as well as temperature.

Climate change studies over the Mesta-Nestos area have been based on the output of the CLM regional climate model from the Max Planck Institute for Meteorology, Germany. They concern the SRES scenarios A1B and B1. The CLM model uses a dynamically downscaling technique where boundaries conditions provided by global scale models such as ECHAM5/MPIOM are adapted to local conditions such as relief. The temperature, precipitation and evapotranspiration results obtained from CLM were used as input data to the spatially distributed hydrology model MODSUR-NEIGE for simulating the future water regime of the river basin. It was coupled with the HEC-ResSim reservoir simulation tool using a detailed technical representation of the dams and irrigation networks systems planned for the expansion of the existing irrigation in the Nestos delta and Xanthi plain areas. Finally, the appraisal of the Temenos project viability under future climatic conditions was carried out with the use of a special purpose economic tool which is based on the NPV rule.

The thesis proposes a holistic approach to project evaluation which goes beyond strict project financing pratices. The NPV based rule has been extended the merging of economic elements (energy and water selling prices) with social benefits (compensation to farmers in case of lack of water) and the value of the environment (costs for restoration of appropriate water status in case of failure to preserve a minimum environmental flow). It is argued that this combined approach offers a useful evaluation of the sustainability of water projects.

Furthermore, climate scenarios have been augmented by transboundary politics hypotheses based on the execution of the on-going flow treaty existing between Bulgaria and Greece about the Mesta-Nestos waters. Finally, in the context of compliance with the WFD basin management guidelines, the use of multicriteria decision analysis methods is explored in order to balance the conflicts of interests between all the actors which should be participating in the ultimate decision of financing and operating a multipurpose dam project such as Temenos.

RESUME

La construction d'un grand barrage est un projet aux conséquences économiques et sociales importantes voila pourquoi elle doit être précédée d'étude opérationnelle et socio-économique détaillée. En premier lieu, l'étude opérationnelle doit porter sur les dimensions et le régime d'utilisation du barrage, la configuration géographique de son bassin de drainage et ses caractéristiques hydrologiques aussi bien que sur les contraintes de type environnemental qui peuvent s'exercer dans un care législatif national ou international. En second lieu, l'étude socio-économique doit prendre en compte tous les paramètres susceptibles d'influencer sur la durabilité du projet.

Jusqu'à une époque récente, la large majorité des barrages était financée et gérée par le secteur public. Ainsi la profitabilité des projets n'était un élément prépondérant dans la décision de les construire. De nos jours, la libéralisation du marché de l'énergie dans les pays développés a conduit à la privatisation des infrastructures énergétiques et par voie de conséquence cela a conduit à l'application de nouveaux objectifs économiques dans le financement et la gestion des projets de barrage. Les décisions d'investissement sont conditionnées par l'évaluation de leur viabilité technique et de leur profitabilité tout au long de leur durée de vie qui est typiquement de 50 ans. Cette évaluation est basée sur l'usage d'un critère quantitatif appelé Valeur Actualisée Nette (VAN) aussi appelé en anglais Net Present Value (NPV).

Cependant, comme l'eau est le fluide nécessaire au fonctionnement des centrales hydroélectriques, leur exploitation interfère avec la gestion des ressources en eau du bassin hydrographique qui les accueille. De ce point de vue, de nouvelles pratiques et réglementations viennent d'être introduites dans l'Union Européenne par la Directive Cadre sur l'Eau (idem, WFD en anglais). Cette directive contraint chaque projet d'exploitation des ressources en eau à suivre des recommandations portant sur ses conséquences sociales et son impact sur l'environnement en respectant des contraintes à long terme portant sur sa durabilité en cas de changement climatique.

Le travail présenté porte sur l'exploration du couplage entre différents modèles mathématiques portant sur l'hydrologie, l'exploitation hydroélectrique, le changement climatique et l'évaluation économique dans le but de proposer les moyens d'effectuer des

décisions équilibrées satisfaisant aux exigences des critères de financement de projet , au bien être du public et aux pratiques qu'exigent la gestion de bassin hydrographique. Ce travail est illustré par l'étude du futur barrage de Temenos, projet mixte de production électrique et d'irrigation intéressant le bassin hydrographique du Mesta-Nestos. Ce bassin est partagé entre la Bulgarie pour sa partie amont et la Grèce pour sa partie aval. La rivière termine son cours dans la mer Egée après avoir formé le delta du Nestos dont la majorité de la surface est occupée par un système d'irrigation agricole.

Deux ouvrages hydroélectriques occupent actuellement la partie montagneuse du bassin du Nestos. Il s'agit du barrage Thissavros dont le réservoir a une capacité de 565 millions m3 et du barrage de Platanovryssi situé en aval du précédent et dont la capacité est de11 millions m3. Les deux barrages sont liés par un système de rétro-pompage STEP (Station de Transfert d'Énergie par Pompage). Le futur projet Temenos devrait être exclusivement financé sur fonds privés. Situé en aval des deux barrages précédents, il est configuré pour augmenter la production d'électricité du précédent complexe et pour la régulation du système d'irrigation de la basse vallée agricole du Nestos

Les scénarios de changement climatique (SRES) développés par le Groupe d'Experts Intergouvernemental sur l'Evolution du Climat (GIEC ou IPCC, en anglais) révèlent de possibles futurs changements climatiques décrits à l'échelle mondiale. Plus précisément, selon les résultats des modèles de circulation globale (GCM), la moyenne mondiale annuelle de la température de surface pourrait augmenter de 1.4 à 5.8°C sur une période allant de 1990 à 2100. Cette augmentation de température pourrait entrainer une augmentation de l'évaporation et influencer le régime des précipitations. Dans ce cas, un impact notable pourrait en résulter sur l'exploitation des installations hydroélectriques dont l'exploitation est particulièrement sensible à la quantité, au rythme et à la répartition géographique des précipitations et des températures.

L'étude du changement climatique sur la zone du Mesta-Nestos est base sur les résultats du modèle climatique régional CLM de l'Institut de Météorologie Max Planck, Allemagne. Elle s'intéresse plus particulièrement aux scénarios B1 et A1B produits par le SRES. Le modèle CLM effectue un transfert à échelle locale des résultats du modèle global atmosphère-océan ECHAM5/MPIOM utilisés comme forçage. CLM est en particulier conditionné par les conditions aux limites du relief local. Les séries mensuelles de température, précipitation et évapotranspiration produites par CLM ont été utilisées comme données d'entrée du modèle hydrologique distribué MODSUR-NEIGE de manière à simuler le régime hydrographique du bassin sous conditions de changement climatique. Ce modèle est couplé au modèle de barrage HEC-ResSim décrivant en détail tous les éléments techniques du complexe hydroélectrique du Nestos et des réseaux d'irrigation existant dans le delta du Nestos ainsi que leur future extension à la plaine de Xanthi. Enfin, l'évaluation de la viabilité du projet Temenos en conditions de changement climatique a été effectuée à l'aide d'un nouvel outil économique basé sur le calcul de la VAN et spécialement développé pour les besoins de l'étude.

La thèse propose une approche holistique de l'évaluation de projet qui dépasse le strict cadre économique. Le calcul de la VAN a été étendu de façon à réunir les éléments de strict rendement économique (recettes tirées de la vente de l'énergie électrique et l'eau d'irrigation, accroissement du revenu des agriculteurs) avec des éléments concernant les « externalités » du projet comme la valeur de l'environnement (coût de restauration du bon état des eaux de surface dans le cas où le débit environnemental minimal ne peut être maintenu) et les bénéfices sociaux (compensations aux agriculteurs dans le cas où les débits d'irrigation ne peuvent être délivrés). On argumente le fait que cette approche combinée offre un outil efficace d'évaluation du projet selon une approche de développement durable.

De plus, l'étude d'impact des scenarios de changement climatique a été augmentée d'une étude portant sur les conséquences que pourraient avoir différentes hypothèses d'évolution de la politique de gestion transfrontalière du bassin en relation avec l'exécution du traité de débit signé entre la Bulgarie et la Grèce à propos des eaux du Mesta-Nestos. Enfin, dans un contexte d'application des recommandations de la Directive Cadre de l'Eau (WFD), on propose d'explorer l'utilisation des méthodes de décision multicritère (MCDA, en anglais) pour gérer les conflits d'intérêt des différents acteurs du bassin dans la phase d'acceptation du projet Temenos et dans sa phase d'exploitation.

ΠΕΡΙΛΗΨΗ

Η κατασκευή έργων μεγάλου βεληνεκούς, όπως η κατασκευή ενός μεγάλου φράγματος, έχει σημαντικές οικονομικές και κοινωνικές συνέπειες. Αυτός είναι και ο λόγος για τον οποίο η λήψη τέτοιων αποφάσεων πρέπει να δικαιολογείται από αυστηρές και ταυτόχρονα λεπτομερείς κοινωνικοοικονομικές και επιχειρησιακές μελέτες. Όσον αφορά την επιχειρησιακή μελέτη ενός φράγματος, πρέπει να ερευνά το λόγο λειτουργίας του φράγματος, τις διαστάσεις του, τη γεωγραφική τοποθεσία της λεκάνης απορροής, τα υδρολογικά χαρακτηριστικά αυτής, καθώς επίσης και τους περιβαλλοντικούς περιορισμούς που περικλείονται στην εθνική και διεθνή νομοθεσία. Η δε κοινωνικοοικονομική μελέτη πρέπει να λαμβάνει υπόψη όλους εκείνους τους παράγοντες που εξασφαλίζουν τη βιωσιμότητα του έργου.

Μέχρι και μερικά χρόνια πριν, το γεγονός ότι η χρηματοδότηση κατασκευής των περισσοτέρων φραγμάτων εξασφαλιζόταν από το δημόσιο τομέα, ο οποίος είχε και την ευθύνη λειτουργίας τους, είχε ως αποτέλεσμα η κερδοφορία καθώς και η οικονομική απόσβεση της επένδυσης, αυτής καθ’ αυτής, να μην αποτελεί την ύψιστη προτεραιότητα στην απόφαση κατασκευής τους. Στις μέρες μας, η απελευθέρωση της αγοράς ενέργειας στον αναπτυγμένο κόσμο έχει και ως επακόλουθο την ιδιωτικοποίηση των ενεργειακών υποδομών καθώς και την θέσπιση νέων οικονομικών δεδομένων σχετικά με τη χρηματοδότηση και διαχείριση ενεργειακών έργων όπως τα φράγματα. Άρα, η απόφαση για επένδυση προϋποθέτει την αξιολόγηση της βιωσιμότητας και της κερδοφορίας του έργου καθ’ όλο τον κύκλο ζωής του, ο οποίος στην περίπτωση των φραγμάτων είναι 50 έτη, και βασίζεται σε συγκεκριμένα ποσοτικά κριτήρια αξιολόγησης, όπως η Καθαρή Παρούσα Αξία (Net Present Value – NPV).

Παρόλα αυτά, δεδομένου ότι η κινητήρια δύναμη ενός υδροηλεκτρικού εργοστασίου είναι το νερό, η λειτουργία του έρχεται σε αντίθεση με τη διαχείριση των υδατικών πόρων της λεκάνης απορροής στην οποία βρίσκεται. Για αυτό το σκοπό θεσπίστηκαν πρόσφατα από την Ευρωπαϊκή Ένωση νέες πρακτικές και κανονισμοί, όπως η Οδηγία Πλαίσιο για τα Ύδατα (Water Framework Directive – WFD), οι οποίοι ορίζουν συγκεκριμένες κατευθυντήριες γραμμές σχετικά με τις κοινωνικές και περιβαλλοντικές επιπτώσεις των έργων υδατικών πόρων, έτσι ώστε να επιτυγχάνεται η βιωσιμότητα σε συνθήκες κλιματικής αλλαγής.

Η παρούσα διατριβή έχει ως στόχο τη διερεύνηση της σύζευξης μαθηματικών μοντέλων υδρολογίας, υδροηλεκτρικής λειτουργίας, κλιματικής αλλαγής και οικονομικών μοντέλων, προκειμένου να προτείνει τρόπους λήψης ισορροπημένων αποφάσεων σε περιπτώσεις έργων υδατικών πόρων. Λαμβάνει δε υπόψη, τόσο τις απαιτήσεις των κριτηρίων που διέπουν ένα επενδυτικό σχέδιο, όσο και την κοινωνική ευημερία και τις ορθολογικότερες πρακτικές διαχείρισης μιας λεκάνης απορροής. Η προτεινόμενη μεθοδολογία εφαρμόζεται στο μελλοντικό υδροηλεκτρικό-αρδευτικό φράγμα του Τεμένους στη λεκάνη απορροής του ποταμού Μέστα/Νέστου. Η λεκάνη του ποταμού μοιράζεται μεταξύ της Βουλγαρίας, η οποία είναι η ανάντη χώρα, και της Ελλάδας η οποία είναι η κατάντη χώρα. Ο ποταμός λίγο πριν την εκροή του στο Αιγαίο Πέλαγος δημιουργεί το δέλτα του Νέστου το οποίο αποτελεί μια σημαντική για την Ελλάδα γεωργική περιοχή, αποτελούμενη από αρδευόμενες καλλιέργειες.

Την παρούσα χρονική στιγμή, στο ορεινό τμήμα της λεκάνης απορροής του Νέστου λειτουργούν δυο υδροηλεκτρικοί σταθμοί. Ο υδροηλεκτρικός σταθμός του Θησαυρού, ο οποίος βρίσκεται πλησίον των συνόρων των δυο χωρών με χωρητικότητα 565 εκατομμυρίων m^3 και ο σταθμός της Πλατανόβρυσης ο οποίος βρίσκεται στα κατάντη του πρώτου με χωρητικότητα 11 εκατομμυρίων m^3. Και τα δύο αυτά φράγματα έχουν σχεδιαστεί να λειτουργούν με ανάστροφη λειτουργία στα πλαίσια παραγωγής ενέργειας. Το μελλοντικό έργο του Τεμένους το οποίο θα χρηματοδοτηθεί αποκλειστικά από ιδιωτικά κεφάλαια σχεδιάζεται να κατασκευαστεί στα κατάντη των δύο προηγουμένων και θα έχει ως σκοπό τόσο την παραγωγή ενέργειας όσο και την αποθήκευση και διάθεση υδάτων για την κάλυψη των αρδευτικών αναγκών. Επιπρόσθετα, η κατασκευή του θα συνεισφέρει στη βελτιστοποίηση λειτουργίας των δυο προηγούμενων εν σειρά φραγμάτων.

Τα σενάρια κλιματικής αλλαγής τα οποία αναπτύχθηκαν από την Διακυβερνητική Επιτροπή για την Αλλαγή του Κλίματος (IPCC) με τη δημοσίευση της Ειδική Έκθεση μελλοντικών Σεναρίων Εκπομπών (SRES) αποκαλύπτουν πιθανές μελλοντικές μεταβολές του κλίματος σε παγκόσμια κλίμακα. Πιο συγκεκριμένα, σύμφωνα με τα αποτελέσματα των μοντέλων μεγάλης κυκλοφορίας (GCM) η μέση θερμοκρασία της επιφάνειας της γης προβλέπεται να αυξηθεί από 1,4 έως 5,8 °C κατά την περίοδο 1990 έως 2100. Επιπρόσθετα, οι θερμοκρασιακές αυξήσεις εκτιμάται ότι θα οδηγήσουν σε αύξηση του ρυθμού εξάτμισης των υδάτων και σε διακυμάνσεις των βροχοπτώσεων. Συνεπώς, μια πιθανή σημαντική επίπτωση των κλιματικών αλλαγών μπορεί να εντοπιστεί στην περίπτωση παραγωγής υδροηλεκτρικής ενέργειας, καθώς αυτή εξαρτάται από την ποσότητα, τον χρονισμό και τη γεωγραφική διάρθρωση των βροχοπτώσεων και της θερμοκρασίας.

Η μελέτη των επιπτώσεων της κλιματικής αλλαγής στη περιοχή της λεκάνης του Μέστα/Νέστου βασίστηκε στα αποτελέσματα του τοπικού κλιματικού μοντέλου CLM του Γερμανικού Ινστιτούτου Μετεωρολογίας Max Planck. Πιο συγκεκριμένα, χρησιμοποιήθηκαν τα αποτελέσματα των σεναρίων εκπομπών SRES που αφορούν τις περιπτώσεις των σεναρίων A1B και B1. Το μοντέλο CLM βασίζεται στην τεχνική δυναμικής αποκλιμάκωσης και οι οριακές συνθήκες λειτουργίας του οι οποίες προέρχονται από κλιματικά μοντέλα παγκόσμιας κλίμακας όπως το ECHAM5/MPIOM, προσαρμόζονται στις τοπικές συνθήκες όπως το ανάγλυφο του εδάφους. Τα δεδομένα θερμοκρασίας, βροχόπτωσης και εξατμισοδιαπνοής που ελήφθησαν από το μοντέλο CLM χρησιμοποιήθηκαν ως δεδομένα εισόδου στο χωρικά κατανεμημένο υδρολογικό μοντέλο MODSUR-NEIGE για την προσομοίωση του μελλοντικού υδρολογικού καθεστώτος της λεκάνης. Η σύζευξη του υδρολογικού μοντέλου με το μοντέλο προσομοίωσης ταμιευτήρων HEC-ResSim, το οποίο αναπαριστά λεπτομερώς τις τεχνικές παραμέτρους του φράγματος καθώς και των συστημάτων των αρδευτικών δικτύων, επέτρεψε την μελέτη της λειτουργίας του φράγματος καθώς και τη δυνατότητα επέκτασης των υφιστάμενων αρδευτικών συστημάτων στις περιοχές του δέλτα του Νέστου και της πεδιάδας της Ξάνθης. Τέλος, η αξιολόγηση της βιωσιμότητας του φράγματος του Τεμένους υπό συνθήκες κλιματικής αλλαγής πραγματοποιήθηκε με τη χρήση ενός ειδικού οικονομικού εργαλείου που βασίζει τη λειτουργία του στον κανόνα NPV.

Επιπλέον, η διατριβή προτείνει μια ολιστική και ευρύτερη προσέγγιση στην αξιολόγηση έργων σε σχέση με τις αυστηρές χρηματοδοτικές πρακτικές που εφαρμόζονται συνήθως σε επενδυτικά έργα. Ο κανόνας NPV διευρύνθηκε από αυστηρά οικονομικών παραμέτρων εργαλείο (τιμές πώλησης της ενέργειας και του νερού) με την ενσωμάτωση κοινωνικών ωφελειών (αποζημιώσεις στους αγρότες στην περίπτωση έλλειψης νερού) και την ενσωμάτωση της αξίας του περιβάλλοντος (κόστη για αποκατάσταση της καλής ποιότητας των υδάτων σε περίπτωση αποτυχίας διατήρησης της ελάχιστης οικολογικής παροχής). Εκτιμάτε ότι η συνδυαστική αυτή προσέγγιση προσφέρει μια χρήσιμη αξιολόγηση της βιωσιμότητας των έργων υδατικών πόρων.

Επίσης, η αξιολόγηση των επιπτώσεων της κλιματικής αλλαγής ενισχύθηκε από διασυνοριακές παραμέτρους πολιτικού επιπέδου που βασίζονται στην εφαρμογή της συνθήκης για το καθεστώς ροής του ποταμού Μέστα/Νέστου, που έχει υπογραφεί από τη

Βουλγαρία και την Ελλάδα. Τέλος, στο πλαίσιο συμμόρφωσης με τις διατάξεις της Οδηγίας-Πλαίσιο για τα ύδατα που αφορούν τη διαχείριση λεκανών απορροής, διερευνάται η χρήση μεθόδων πολυκριτηριακής ανάλυσης λήψης αποφάσεων. Στόχος είναι η εξισορρόπηση της σύγκρουσης συμφερόντων των φορέων που εμπλέκονται στη τελική απόφαση της χρηματοδότησης και λειτουργίας του έργου πολλαπλών χρήσεων του φράγματος του Τεμένους.

RESUME ETENDU

Introduction

Le développement du Nestos peut-il être prolongé de manière durable ?

1950, la Grèce du Nord émerge de 50 années de cataclysmes historiques. Avec le temps de la stabilité vient celui de la nécessité d'un développement économique susceptible de subvenir au surcroit de population déplacée lors de la « Grande Catastrophe » de 1922. Une priorité est donnée à l'accroissement de production agricole dans les plaines alluviales de l'Axios, du Strymon, du Delta du Nestos et de la région de Drama. A cet effet, ces espaces seront irrigués. De nos jours, le succès de ces efforts ne fait aucun doute et ces plaines agricoles irriguées sont parmi les plus productives du pays. En Europe, le revenu par hectare qu'elles procurent est au niveau des meilleures terres agricoles de France, par exemple. La seule différence réside dans le fait que la propriété y est encore morcelée et que donc le revenu par exploitant y reste modeste.

Pour ce qui concerne le Nestos, ce développement agricole s'est doublé de la mise en production hydroélectrique de la partie montagneuse du bassin, en aval de la frontière Bulgare. Conçu dans les années 1970, ce plan d'équipement sera réalisé en 1997 avec la mise en service des barrages de Thissavros et de Platanovryssi. Ce plan accompagnera les discussions bilatérales entre la Bulgarie et la Grèce qui s'achèveront en 1995 par la signature d'un traité de débit garantissant à la Grèce 29% du débit annuel moyen de la rivière Mesta formant la partie amont du cours du Nestos en Bulgarie. L'ensemble du bassin hydrographique drainé par ces deux branches en Bulgarie et en Grèce est donc appelé, bassin du Mesta-Nestos.

De nos jours, une question se pose dans la partie Grecque du bassin : peut-on prolonger le développement de ses capacités hydrauliques dans les domaines de la production électrique et de l'irrigation ? C'est l'objectif du projet Temenos. Ce projet porte sur la construction d'un barrage mixte en aval des deux précédents.

Le bassin du Mesta-Nestos

Le bassin du Mesta-Nestos est partagé entre la Bulgarie pour sa partie amont et la Grèce pour sa partie aval. En Bulgarie, la partie amont du bassin dit de la Mesta se situe au

Sud de la ville de Sofia, capitale de la Bulgarie. La rivière prend sa source dans les reliefs les plus hauts de l'Est de L'Europe, à savoir, le pic Mussala (2,925 m) dans les monts du Rila et le pic Vihren (2,915 m) dans les monts du Pirin. Cette partie amont draine en majorité des formations granitiques et métamorphiques. La rivière passe en Grèce dans la région Macédoine Est-Thrace où elle change de nom pour porter celui de Nestos. Elle longe alors la limite Ouest du massif des Rhodopes puis traverse en gorges escarpées les formations de marbre des monts Lekani pour se terminer en une plaine alluviale formant le delta du Nestos. Ce delta se termine dans la mer Egée en formant des lagunes côtières. La longueur totale du cours est de 255 km et le bassin de drainage couvre 6,218 km^2 dont 46% se situent en Grèce.

Le bassin du Mesta-Nestos s'étend en majorité sur une région montagneuse couverte de forêts ou de zones naturelles (75.41%). L'agriculture couvre pratiquement le reste de la surface. En Bulgarie, on trouve une agriculture traditionnelle de montagne sauf dans les plaines alluviales de Razlog et Blagoevgrad encore peu développées. Au contraire, la zone du delta du Nestos en Grèce abrite un réseau d'irrigation très développé servant une agriculture productive et dense. La partie Bulgare est occupée par une population d'environ 190000 habitants répartie en plusieurs agglomérations moyennes alors que la partie Grecque est quasiment déserte dans sa partie montagneuse, l'essentiel de la population (42 000 habitants) est concentrée dans le delta.

L'activité économique dans la zone de la Mesta bulgare porte essentiellement sur des industries de transformations de taille modeste et le développement d'un tourisme nival. Pour la partie Grecque, l'activité est essentiellement agricole. Ceci n'empêche pas l'existence d'ouvrages d'aménagements hydrauliques importants des deux cotés de la frontière. ^Ceux-ci se sont développés dans un contexte particulier de relations transfrontalières qui ont abouties à la signature d'un traité de débit en 1995.

Le traité transfrontalier et le contexte de gestion en Bulgarie et Grèce

Les négociations bilatérales sur la gestion des eaux du bassin Mesta-Nestos commencent dans les années 1960 (Accord de coopération, 1964), se prolongent dans les années 1970 (Nomination d'un comité de coordination, 1971) pour se terminer en 1995 par la signature du « traité de débit bulgaro-grec ». La Grèce obtient 29 pour cent du débit des eaux du fleuve pendant la durée de l'accord de 35 ans (1995-2030). Le pourcentage est calculé sur le débit « moyen annuel » de la Mesta sans mentionner son affluent le Dospat qui rejoint le cours principal après son entrée en Grèce. Depuis la signature, le comité bilatéral chargé du suivi n'a jamais fonctionné. D'autre part, la Bulgarie déclarant son adhésion à l'Union Européenne (UE) un peu plus tard, les deux pays s'engageront alors à améliorer la qualité des eaux conformément aux normes internationales et aux directives de l'Union Européenne. Aujourd'hui, comme membres de l'UE, les deux pays se conforment aux recommandations de la Directe Européenne sur l'Eau (WFD, en anglais). Dans ce cadre, la Mesta est gérée en Bulgarie par l'Agence de Bassin du District Ouest-Mer Égée et le Nestos est géré en Grèce par l'Agence Macédoine-Est et Thrace. En marge des relations bilatérales, les deux pays collaborent dans le cadre de diverses action européennes (INTERREG, PCRD) et internationales (UNESCO INWEB et HELP).

Lorsque les négociations bilatérales débutent dans les années 1960, la Bulgarie a conçu un vaste plan d'équipement du bassin de la Mesta comportant un réseau de six barrages interconnectés avec un réseau de stations de pompage destiné à détourner une partie importante des eaux hors du bassin en direction de la Maritza. Aujourd'hui, seul le barrage du Dospat a été construit et détourne les eaux de cet affluent vers la Maritza par le complexe hydroélectrique dit de la cascade de Vacha. En tête du bassin dans le Rila, divers ouvrages plus modestes ponctionnent l'eau en direction du barrage du Belmeken vers la Maritza. On estime que 10% à 20% des eux naturelles du bassin sont ainsi déjà détournées.

Du côté Grec, un barrage de régulation de l'irrigation du delta est conçu dans les années 1950 pour être implanté à Toxotes. Sa mise en exploitation complète accompagnée du réseau d'irrigation associé ne se terminera qu'au début des années 1970. C'est alors qu'un plan d'équipement hydroélectrique du Haut-Nestos est échafaudé. Deux grands barrages seront construits et mis en exploitation en 1997 (Thissavros) et 1999 (Platanovryssi).

Le cas d'école du projet Temenos

Le nouveau projet d'aménagement de Temenos

Le travail présenté dans cette thèse est illustré par l'étude du futur barrage de Temenos, projet mixte de production électrique et d'irrigation intéressant le bassin hydrographique du Mesta-Nestos. Deux ouvrages hydroélectriques occupent actuellement la partie montagneuse du bassin du Nestos. Il s'agit du barrage de Thissavros dont le réservoir a une capacité de 565 millions m3 et du barrage de Platanovryssi situé en aval du précédent et dont la capacité est de11 millions m3. Les deux barrages sont liés par un système de rétro-pompage STEP (Station de Transfert d'Énergie par Pompage). Le futur projet Temenos devrait être exclusivement financé sur fonds privés. Situé en aval des deux barrages précédents, il est configuré pour augmenter la production d'électricité du précédent complexe et pour réguler le système d'irrigation de la basse vallée agricole du Nestos.

L'évaluation économique du projet Temenos

La construction d'un grand barrage est un projet aux conséquences économiques et sociales importantes voila pourquoi elle doit être précédée d'une étude opérationnelle et socio-économique détaillée. En premier lieu, l'étude opérationnelle doit porter sur les dimensions et le régime d'utilisation du barrage, la configuration géographique de son bassin de drainage et ses caractéristiques hydrologiques aussi bien que sur les contraintes de type environnemental qui peuvent s'exercer dans un cadre législatif national ou international. En second lieu, l'étude socio-économique doit prendre en compte tous les paramètres susceptibles d'influencer sur la durabilité du projet.

Jusqu'à une époque récente, la large majorité des barrages était financée et gérée par le secteur public. Ainsi la profitabilité des projets n'était pas un élément prépondérant dans la décision de les construire. De nos jours, la libéralisation du marché de l'énergie dans les pays développés a conduit à la privatisation des infrastructures énergétiques et par voie de conséquence à l'application de nouveaux objectifs économiques dans le financement et la gestion des projets de barrage. Les décisions d'investissement sont conditionnées par l'évaluation de leur viabilité technique et de leur profitabilité tout au long de leur durée de vie qui est typiquement de 50 ans. Cette évaluation est basée sur l'usage d'un critère quantitatif nommé Valeur Actualisée Nette (VAN) aussi appelé Net Present Value en anglais (NPV). Ce critère est couramment utilisé dans la pratique du financement des projets.

Objectif de la thèse : La modélisation comme outil d'évaluation des risques

Cependant, comme l'eau est le fluide nécessaire au fonctionnement des centrales hydroélectriques, leur exploitation interfère avec la gestion des ressources en eau du bassin hydrographique qui les accueille. De ce point de vue, de nouvelles pratiques et réglementations ont été introduites dans l'Union Européenne par la Directive Cadre sur l'Eau (idem, WFD en anglais). Cette directive contraint chaque projet d'exploitation des ressources en eau à suivre des recommandations portant sur ses conséquences sociales et son impact sur l'environnement en respectant des contraintes à long terme relatives à sa durabilité en cas de changement climatique.

Le travail présenté porte sur l'exploration du couplage entre différents modèles mathématiques traitant de l'hydrologie, l'exploitation hydroélectrique, le changement climatique et l'évaluation économique dans le but de proposer les moyens d'effectuer des décisions équilibrées satisfaisant aux exigences des critères de financement de projet , au bien-être du public et aux pratiques qu'exigent la gestion de bassin hydrographique.

Modélisation physique du bassin du Nestos

Le système d'information géographique du bassin Mesta-Nestos

Les travaux de modélisation ont été précédés de la constitution d'un vaste système d'information géographique dédié au bassin. Récemment unifié dans le système ArcGIS, ce SIG a des contributions venant : des organismes grecs de statistique, de gestion de l'environnement et d'aménagement régional ; des partenaires universitaires grecs (Université Démocrite de Thrace-DUTH) de programmes bilatéraux gréco-bulgares (ex : TRANSCAT) et de partenaires étrangers en Europe (Ecole des Mines de Paris-ENSMP et Université Technique de Dresde-TUD) et aux Etats-Unis (West Virginia University-WVU), pour l'imagerie satellite en particulier. Les principaux thèmes cartographiques traités avec ArcGIS sont : le relief, le réseau hydrographique, la géologie et l'utilisation du sol.

Pour ce qui concerne le relief, on a retenu le modèle numérique de terrain (MNT) GTOPO30 de l'USGS à 1 km de résolution. Il a été traité par le système HydroDEM du CEMAGREF, France pour en extraire de manière automatique, un réseau hydrographique simplifié et les pentes de manière compatible avec le modèle hydrologique MODSUR-NEIGE. Le réseau hydrographique détaillé est venu du projet TRANSCAT. Une carte géologique unifiée sur l'ensemble des domaines grec et bulgare a été réalisée avec la coopération d'IGME, Grèce. La carte d'utilisation du sol a été obtenue à partir du projet Corine Land Cover à une résolution de 250m. Cette résolution a été retenue comme base pour la construction du modèle hydrologique. Tous les informations contenues dans le SIG on été géoréférencées et rectifiées en conformité avec le système projection national grec (Hellenic Geodetic Reference System-HGRS 87). On a construit pour le projet un serveur interactif des données sur Internet à base du système MapServer.

Les mesures climatiques disponibles sur le bassin

Les besoins liés à la calibration des modèles exigeaient que l'on réunisse un ensemble de séries chronologiques simultanées sur l'ensemble des territoires grec et bulgare. Cela n'a malheureusement été possible que pour des séries couvrant la période 1991-1995.

Les données de précipitations ont été obtenues à partir de diverses sources. En Grèce, auprès du service météorologique national (Hellenic National Meteorological Service_HNMS), de l'opérateur des barrages (PPC-DEH) et des partenaires universitaires (DUTH) et du programme de diffusion de l'OMM. En Bulgarie, les données ont été obtenues dans le cadre d'une coopération bilatérale (TRANSCAT et DUTH). On a réuni en tout 20 stations météorologiques pour l'ensemble du bassin. Cependant, en Bulgarie, les séries de la station de Mussala étaient trop lacunaires. On a donc procédé à leur « remplissage » par interpolation à partir de stations proches en utilisant le logiciel S-PLUS. Les précipitations du Pic Mussala ont été étendues à celles du pic Vihren pour lequel il n'existait pas de données.

Pour les températures, 2 stations de mesure journalière étaient disponibles sur la partie Bulgare (Mussala, Bansko communiquées par l'ENSMP) et plus de 10 stations sur la partie Grecque (HMNS). Enfin, des profils moyens mensuels d'évapotranspiration sont obtenus par la formule de Turc pour 2 stations périphériques au bassin : Sofia et Thessalonique. On a aussi utilisé les profils publiés par une thèse antérieure consacrée au bassin de Drama.

Les mesures hydrologiques et leur structuration

Les mesures de débits mensuelles dans les rivières ont été plus difficiles à réunir. Pour le domaine Bulgare, on s'est essentiellement basé sur les informations disponibles sur les serveurs liés à l'OMM (WMO) pour la station de Momina Kula sur la Mesta pour la période 1968-1997. Pour la Grèce, les données ont été obtenues auprès de l'opérateur des barrages (PPC-DEH) pour les stations de Papades, Thissavros, Platanovryssi et Temenos pour la période 1991-1995. D'autre part, le serveur de l'OMM a fourni les données de Temenos pour la période 1965-1996.

L'ensemble des données climatiques et hydrologiques a été structuré et géré à l'aide du système HEC-DSS de l'U.S. Army Corps of Engineers (USACE). Outre la gestion des séries chronologiques, ce système de mesure permet tout une série de manipulation de contrôle de la qualité des données, de changement de support temporel, de calculs d'indices statistiques et combinaisons mathématiques entre séries. Pour certains traitements spécifiques il a été augmenté par l'usage du logiciel S-PLUS

Evaluation d'un modèle hydrologique existant

Le projet EU PCRD-FP5 TRANSCAT (Integrated Water Management of TRANSboundary CATchments) avait pour but de créer un système d'aide à la décision pour la gestion des bassins transfrontaliers (2003-2006). Pour le bassin du Mesta-Nestos il a fait l'objet d'une collaboration entre l'Institute of Water Problems de Sofia et l'Aristotle University of Thessaloniki. Ce groupe a réalisé un modèle de simulation de débit sur la base du système HEC-HMS de l'USACE. C'est un modèle conceptuel à réseau hydrographique discret reliant des sous-bassins où ruissellement et infiltration sont agrégés. La calibration de ce modèle s'est effectuée pour la partie Bulgare à partir de données portant sur l'année 2000, la partie Grecque ne pouvant être calibrée postérieurement à la mise en fonctionnement des barrages sur le Nestos à partir de 1999. Les avantages de cette modélisation sont la prise en compte de l'infiltration et des détournements de débit pour la partie Bulgare. D'autre part, on a aussi tenu compte des sources karstiques bulgares dans le massif du Pirin et des pertes présumées dans le massif des marbres du Lekani. Cependant ce modèle présente deux inconvénients principaux : la fixation d'un « débit de base » rend difficile la prise en compte des effets du changement climatique et d'autre part, le modèle HEC-HMS étant fondé sur le principe de l'hydrogramme unitaire, il répond très mal à l'utilisation de données mensuelles seules disponibles sur l'ensemble du bassin. Voila pourquoi on a recherché une modélisation hydrographique plus adaptée.

Le choix d'une nouvelle modélisation hydrologique distribuée

Le modèle MODSUR-NEIGE est un modèle distribué créé à l'Ecole des Mines de Paris-ENSMP. Il comporte deux parties : un module dédié à la simulation du comportement de la neige couplé à un module dédié à la modélisation des transferts de surface. Pour chaque élément d'une grille couvrant le bassin (ici 250m), on définit une « fonction de production » traduisant les effets du couple végétation-sol. Pour le module nival, en fonction de la température journalière, on traite séparément le couvert forestier et les zones de sol nu. Pour le modèle transfert on définit les paramètres: Crt-Dcrt pour le bilan pluie-évaporation à l'interface; Cqr-Qrma pour le transit dans le non saturé et le ruissellement et Cqi-Qima, pour le transfert éventuel dans un aquifère de faible profondeur. Le programme peut être couplé à un modèle sous-terrain (MODCOU)

Mise en œuvre de la modélisation hydrologique MODSUR-NEIGE

La modélisation est basée sur la discrétisation spatiale du domaine de surface qui est découpé en mailles carrées de dimensions variables en adoptant une structure de données de type « Quadtree ». La grille est construite à partir du MNT GTOPO30 interpolé à 250m et traité avec HydroDEM

Les données de pluviométrie, températures et ETP sont étendues pour chaque station au sol aux éléments de la grille appartenant à sa zone d'influence. Les zones d'influence sont les polygones de Thiessen (idem, Voronoï) des points de station. L'ETP est répartie sur deux secteurs : nord Bulgare et sud Grec. La prise en compte effective des températures est limitée aux polygones de la haute montagne Bulgare au pic Mussala et au pic Vihren. Les paramètres définissant les conditions de fonctionnement nival, de ruissellement et d'infiltration sont déterminées pour chaque élément de la grille et définissent ce que l'on appelle des « fonctions de production ». Celles-ci sont extraites des types d'utilisation du sol fournis par la couche d'information de Corine Land Cover.

Calibration du modèle MODSUR-NEIGE

Compte tenu des conditions de disponibilité des données, la calibration de MODSUR-NEIGE n'a pu être construite que sur la période allant du 1 Août 1991 au 31 Décembre 1995. La difficulté principale rencontrée a porté sur le maintien des débits venant de la Mesta pendant l'été. Le bassin est divisé en quatre secteurs : le sous-bassin de Momina Kula avec infiltration dans une nappe souterraine de faible profondeur et prise en compte du phénomène nival; le sous-bassin allant de la frontière Bulgarie-Grèce à Temenos et le sous-bassin Temenos-Toxotes où seul le ruissellement est pris en compte ; le sous-bassin du Dospat pour lequel tout le produit du ruissellement est exclu du modèle pour reproduire les conditions réelles de dérivation des eaux du barrage du Dospat hors du bassin vers la Maritza.

La simulation du fonctionnement des barrages

L'objectif de la simulation des barrages est d'apprécier la faisabilité opérationnelle de l'ensemble des ouvrages existants et à venir dans la partie grecque, a savoir : Thissavros, Platanovryssi, Temenos et Toxotes. La modélisation des barrages du Nestos a été réalisée avec le programme HEC-ResSim (USACE). Cet outil fonctionne au pas horaire et optimise les flux en fonction de contraintes d'exploitation qui peuvent concerner la puissance électrique produite et les débits aux exutoires

Les paramètres du modèle hydro-électrique HEC-ResSim et ses résultats

Tous les paramètres utilisés dans HEC-ResSim ont été déterminés à partir des documents techniques de PPC-DEH. Les paramètres techniques des barrages portent sur les caractéristiques du réservoir, de l'évacuateur de crues, des équipements de la centrale (conduites d'entrée et de sortie, puissance installée et rendement) et la conduite de fuite. Les paramètres d'exploitation décrivent le cycle des opérations et les contraintes d'exploitation dans différents modes de fonctionnement (crue, mode normal et vidange). Pour ce qui concerne notre étude les contraintes d'exploitation imposées portent sur le maintien du: débit "environnemental" de 6m3/s et la priorité à la demande d'eau pour l'irrigation sur la production hydroélectrique aux niveaux de demande des agriculteurs. . Il est alimenté par les résultats de débits fournis par MODSUR-NEIGE après leur intégration dans le système de gestion HEC-DSS.

Les résultats de la simulation sont présentés sous forme des séries journalières intégrées dans le système HEC-DSS et concernent un très grand nombre de paramètres. Pour ce qui concerne la production électrique des trois barrages de Thissavros, Platanovryssi et Temenos on a retenu : le niveau du réservoir; les débits de sortie aux exutoires de la conduite de la centrale, la conduite de fuite et l'évacuateur de crue; la production d'électricité. Pour ce qui concerne le fonctionnement du réservoir de régulation de Toxotes on a retenu : les débits dans les deux canaux d'irrigation ouest-Kavala et est-Xanthi et le débit environnemental dans le lit naturel du Nestos.

Le changement climatique : une réalité locale ?

Le suivi des précipitations annuelles de 1934 à 1995 au pic Mussala (Monts du Rila), indique une tendance à la diminution. Celle-ci est-elle une manifestation du changement climatique ? Un certain nombre d'étude ont déjà porté sur ce sujet et notamment dans la partie haute du bassin de la Mesta. Les conclusions en sont encore imprécises mais il est incontestable que la région est soumise périodiquement à des périodes de sécheresse relative. D'autres travaux ont aussi portés sur l'impact possible des changements climatiques prévus par le GIEC (IPCC) mais que ce soit en Bulgarie ou en Grèce, ils n'ont pas concerné le territoire précis du Mesta-Nestos et ils ont fait l'usage de résultats de modèles climatiques assez anciens peu adaptés aux conditions locales du climat. Voici pourquoi on s'est attaché dans notre travail à prendre mieux en compte cette composante locale.

Les scénarios de changement climatique

Les scénarios de changement climatique (SRES) développés par le Groupe d'Experts Intergouvernemental sur l'Evolution du Climat (GIEC ou IPCC, en anglais) prévoient de possibles changements climatiques décrits à l'échelle mondiale. Plus précisément, selon les résultats des modèles de circulation globale (GCM), la moyenne mondiale annuelle de la température de surface pourrait augmenter de 1.4 à 5.8°C sur une période allant de 1990 à 2100. Cette augmentation de température pourrait entrainer une augmentation de l'évaporation et influencer le régime des précipitations. Dans ce cas, un impact notable pourrait en résulter sur l'exploitation des installations hydroélectriques dont l'exploitation est particulièrement sensible à la quantité, au rythme et à la répartition géographique des précipitations et des températures. Le « Special Report on Emission Scenarios » (SRES) préparé par le GIEC (IPCC) décrit les scénarios possibles de changement climatique suivants : « stabilisation 2000 », B1, B2, A1, A2 et leurs variantes. Les scénarios pris en compte pour le cas du projet Temenos sont : « stabilisation 2000 » pour lequel on envisage une stabilisation du climat aux conditions actuelles ; le scénario B1 qui est un cas d'émissions faibles en gaz à effet de serre où on envisage une coopération mondiale autour des solutions aux problèmes sociaux, économiques et environnementaux et le scénario A1B qui cas d'émissions plus fortes qui envisage une croissance très rapide s'appuyant sur des sources d'énergie équilibrées entre fossiles et autres (nucléaire, renouvelables).

Le modèle climatique régional CLM

L'étude du changement climatique sur la zone du Mesta-Nestos est basée sur les résultats du modèle climatique régional CLM de l'Institut de Météorologie Max Planck, Allemagne dont sont disponibles en ligne au World Data Center for Climate, Hamburg (CERA). Elle s'intéresse plus particulièrement aux scénarios B1 et A1B produits par le SRES. Le modèle CLM effectue un transfert à l'échelle locale des résultats du modèle global atmosphère-océan ECHAM5/MPIOM utilisés comme forçage. CLM est en particulier conditionné par les conditions aux limites du relief local. Les séries mensuelles de température, précipitation et évapotranspiration produites par CLM ont été utilisées comme données d'entrée du modèle hydrologique distribué MODSUR-NEIGE de manière à simuler le régime hydrographique du bassin en cas de changement climatique. Ce modèle est couplé au modèle de barrage HEC-ResSim décrivant en détail tous les éléments techniques du complexe hydroélectrique du Nestos et des réseaux d'irrigation existant dans le delta du Nestos ainsi que leur future extension à la plaine de Xanthi.

Evaluation de la durabilité du projet Temenos

Un outil d'évaluation de la durabilité du projet Temenos

L'évaluation de la viabilité du projet Temenos en conditions de changement climatique a été effectuée à l'aide d'un nouvel outil économique basé sur le calcul de la VAN et spécialement développé pour les besoins de l'étude. La thèse propose une approche holistique de l'évaluation de projet qui dépasse le strict cadre économique et s'inspire des démarches récentes dites « d'Investissement Socialement Responsable ou ISR ». Celles-ci prônent d'associer à la stricte évaluation financière des projets, une évaluation de leurs bienfaits ou impacts dans les domaines sociaux et environnementaux.

Le calcul de la VAN du bilan du projet a ainsi été étendu de façon à réunir les éléments de strict rendement économique (recettes tirées de la vente de l'énergie électrique et de l'eau d'irrigation ainsi que l'accroissement du revenu des agriculteurs) avec des éléments concernant les « externalités » du projet que sont la valeur de l'environnement (coût de restauration du bon état des eaux de surface dans le cas où le débit environnemental minimal ne peut être maintenu) et les bénéfices sociaux (compensations aux agriculteurs dans le cas où les débits d'irrigation ne peuvent être délivrés). On argumente le fait que cette approche combinée offre un outil efficace d'évaluation du projet selon une approche de développement durable.

Les termes financiers du projet Temenos

Ils sont basés sur le dossier de la société MECHANIKI. Les paramètres sont : le taux actuariel, les recettes tirées de la vente de l'électricité et celles venant de la vente de l'eau d'irrigation. On fait l'hypothèse que ces deux termes évoluent de manière parallèle à l'inflation annuelle. Les éléments de coût d'investissement et d'opération (fonctionnement) sont inspirés du dossier initial d'investissement constitué par PCC-DEH avant la construction des deux barrages hydroélectriques existants

Les termes liés à l'activité agricole

Le delta du Nestos est actuellement une région agricole importante pour l'économie régionale et nationale qui couvre une surface de 37.700 ha, desquels 18.900 ha sont irrigués par voie gravitaire. Ce réseau d'irrigation a été développé sur la période 1950-1965 et donne actuellement de nombreux signes de dysfonctionnement. La demande en eau est actuellement de 225 millions m3 par an (Année 2000). Elle couvre les besoins de l'ensemble Ouest du delta administré par la Préfecture de Kavala et une partie minoritaire à l'Est sur le territoire de la Préfecture de Xanthi. Un des objectifs du projet Temenos est de développer l'irrigation de cette partie Est pour servir l'ensemble de la plaine de Xanthi soit un besoin supplémentaire d'environ 100 millions de m3 par an.

Des données agricoles détaillées sur les exploitations ont été obtenues auprès du Service National de Statistiques de la Grèce. Elles ont permis de définir un profil moyen de production des exploitations pour caractériser les deux types d'agriculture existant dans la région : l'agriculture irriguée dans la partie Ouest du Nestos (Kavala) où le maïs domine en associant avec des cultures techniques comme l'asperge et l'agriculture non irriguée dans la partie Est (Xanthi) avec un profil plus diversifié (blé dur, en particulier) mais moins rémunérateur.

La modélisation du revenu agricole est conduite en utilisant le modèle CAPRI (Common Agricultural Policy Regional Impact). C'est un modèle agro-économique des revenus agricoles à l'échelle des régions européennes. Il permet l'analyse des impacts de la PAC au niveau régional et l'évaluation des objectifs de l'Agenda 2000 et de l'accord de Luxembourg 2003. Le revenu par hectare calculé par CAPRI a été utilisé pour quantifier l'accroissement de revenu espéré lors du passage à une agriculture irriguée dans la plaine de Xanthi grâce à la mise en œuvre du projet Temenos. Il donne aussi une valeur intrinsèque de production utilisée pour l'évaluation des compensations offertes aux agriculteurs en cas de non respect des débits d'irrigation.

La valeur économique de l'environnement

On évalue la valeur que l'homme attribue à l'environnement du Nestos de façon à quantifier les destructions ou impacts éventuels causés par le non respect des conditions de débit environnemental minimum. Chacun des termes de valeur économique totale (VET) de l'environnement est passé en revue : l'usage direct : pèche, tourisme, rafting ... ; les bienfaits indirects : espèces sauvages, littoral, forêts ... ; la valeur d'option ou de legs futurs : éducation, parcs ... ; et enfin, la valeur d'existence ou de non usage. Cette évaluation est comparée aux démarches du même type adoptée pour la même zone géographiques à propos d'autres enjeux environnementaux.

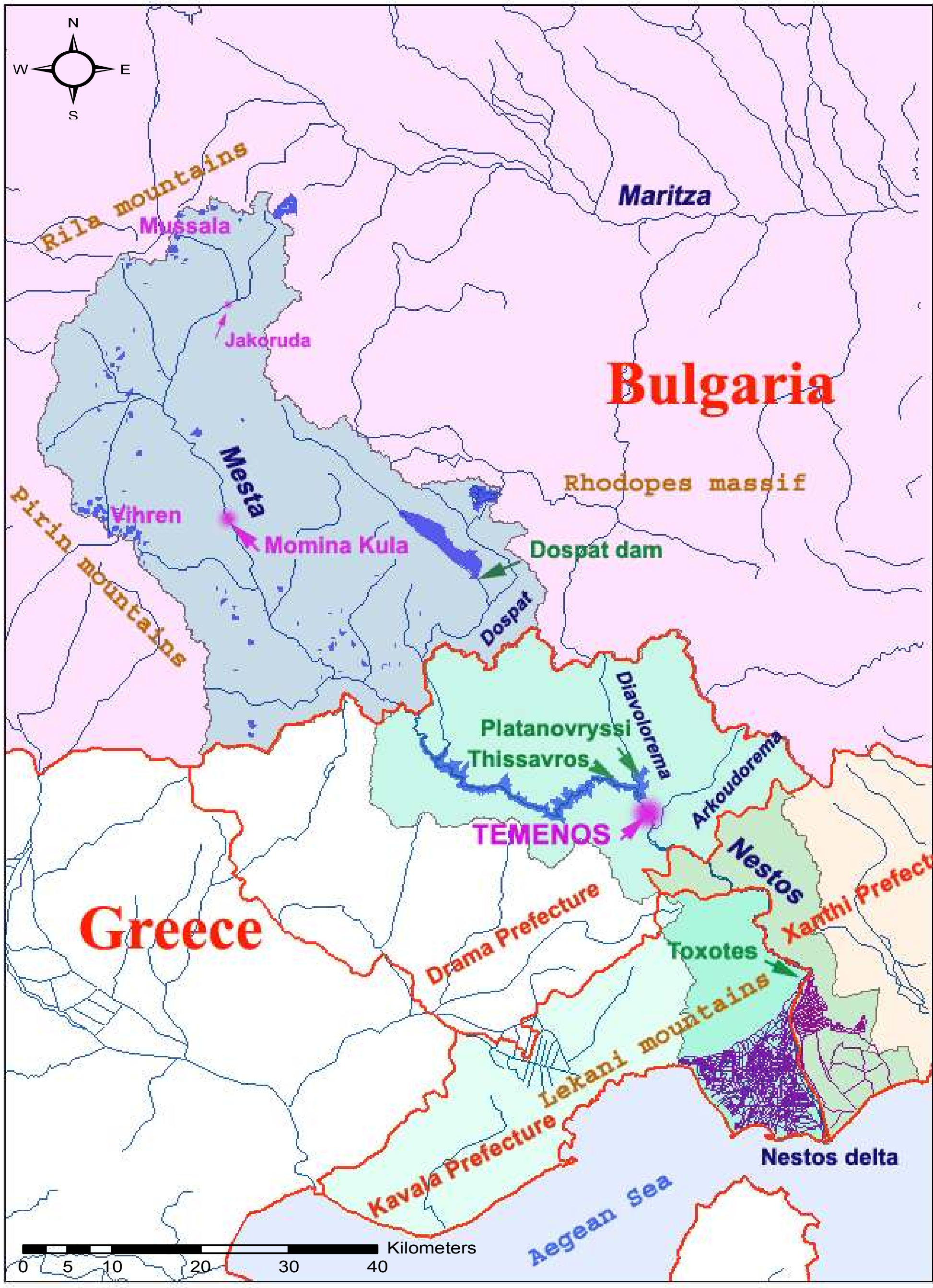
Evaluation de la durabilité du projet Temenos sous hypothèses climatiques et transfrontalières

L'étude d'impact des scenarios de changement climatique a été augmentée d'une étude portant sur les conséquences que pourraient avoir différentes hypothèses d'évolution de la politique de gestion transfrontalière du bassin en relation avec l'exécution du traité de débit signé entre la Bulgarie et la Grèce à propos des eaux du Mesta-Nestos. Les résultats montrent qu'en cas d'évaluation du climat de type GIEC-B1 ou GIEC-A1B la rentabilisé du projet ne peut être assurée. L'application stricte du traité à 29% des eaux de la Mesta est bien entendu un facteur aggravant qui, même dans les conditions de stabilisation du climat actuel, rend la rentabilité très faible.

Conclusion - Les conflits d'exploitation et leur possible médiation

Différentes hypothèses de gestion ont été testées en dehors de celles relatives à l'accord bilatéral. Elles démontrent les capacités de l'outil de simulation intégrée réalisé dans cette thèse à révéler les conflits potentiels entre les différents acteurs du bassin Meta-Nestos. Dans un contexte d'application des recommandations de la Directive Cadre de l'Eau (WFD), on propose en conclusion d'explorer l'utilisation des méthodes de décision multicritère (MCDA, en anglais) pour gérer les conflits d'intérêt des différents acteurs du bassin dans la phase d'acceptation du projet Temenos et dans sa phase d'exploitation.

SITUATION MAP



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I - INTRODUCTION

Situated in South-Eastern Europe (SEE), the Mesta/Nestos river basin is a transboundary river basin shared between Bulgaria and Greece. Historical descriptions of the Mesta/Nestos River date back to the 5th century BC, where according to the ancient Greek historians Thucydides and Herodotus, the Nestos River was a significant river for the inhabitants of the region and a source of growth for their cities. The Romans called this river "Mestus", a name which was adopted by the Bulgarians. Thus, the upper part of the river, which belongs to Bulgaria, is named Mesta and the part of the river which crosses Greek territory is named Nestos.

I-1 – The physiographic features of the Mesta-Nestos basin

The basin extends from the North, where the headwaters are located in the Rila and Pirin mountains of Bulgaria, to the South East where river ends in a delta situated on the Aegean sea coast of Northern Greece. In total, the Mesta/Nestos river flows some 255 km and its catchment area covers 6,218 km^2, of which 2,863 km^2 (46%) belongs to Greece. The morphology of the area is mostly mountainous with the exception of the delta region, which covers an area of 550 km^2 (Fig. 1)

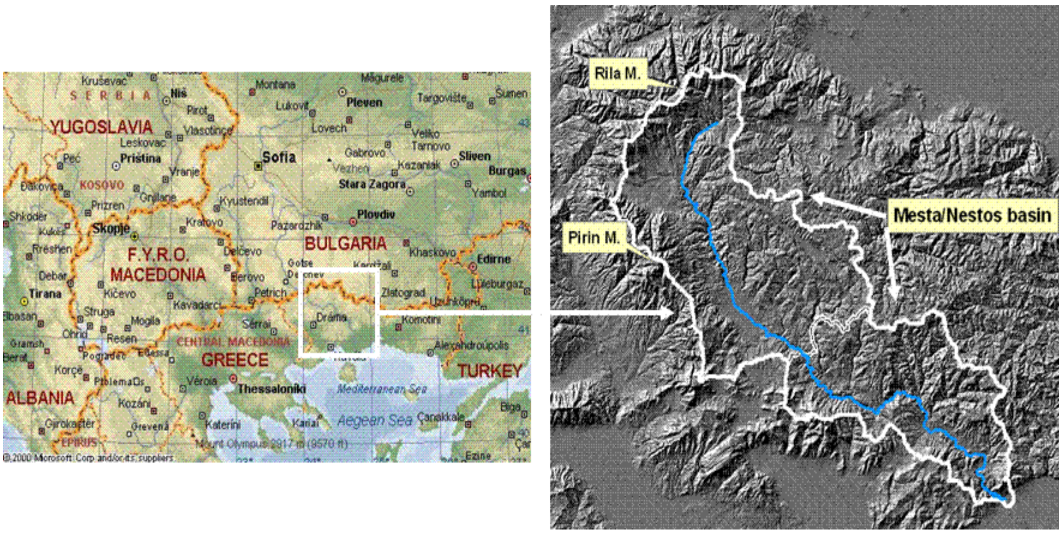


Figure 1 - Geographical location of Mesta/Nestos river basin

The upper part of the Mesta basin is situated near Sofia, the capital city of Bulgaria. The waters originate from the highest reliefs of Eastern Europe, namely, peak Mussala (2,925 m) in the Rila and peak Vihren (2,915 m) in the Pirin. In Bulgaria much of the course cuts through granite and igneous rocks. The Mesta River enters Greece in the region of East Macedonia and Thrace where it changes its name to Nestos. Flowing along the Western border of the metamorphic Rhodopes massif in its upper part, the Nestos river cuts towering canyons through the marble formations of the Lekani mountains. At its end, the main stream spreads over the coastal plain of Chryssoupoli and expands as a deltaic system with freshwater lakes and ponds forming the Nestos delta.

Due to its natural environment (Fig. 2) the Mesta-Nestos basin in mainly covered by forested or natural grassland areas (75.41%). Agriculture occupies most of the remaining space (20.30%). In Bulgaria, this includes non-irrigated crops in the mountainous regions of the Mesta basin as well as permanently irrigated land located in Bulgaria in the upper plains of Razlog and Blagoevgrad. In Greece, the agriculture in concentrated in the Nestos delta area. Natural water bodies (1.3 %) such as salt marshes and coastal lagoons are concentrated along the Aegean sea. Finally, urban areas occupy a modest 1.0% of the catchment. This class includes discontinuous urban areas, industrial or commercial units, road and rail networks and associated land, port areas, airports, mineral extraction sites, dump sites, construction sites, green urban areas and sport and leisure facilities.

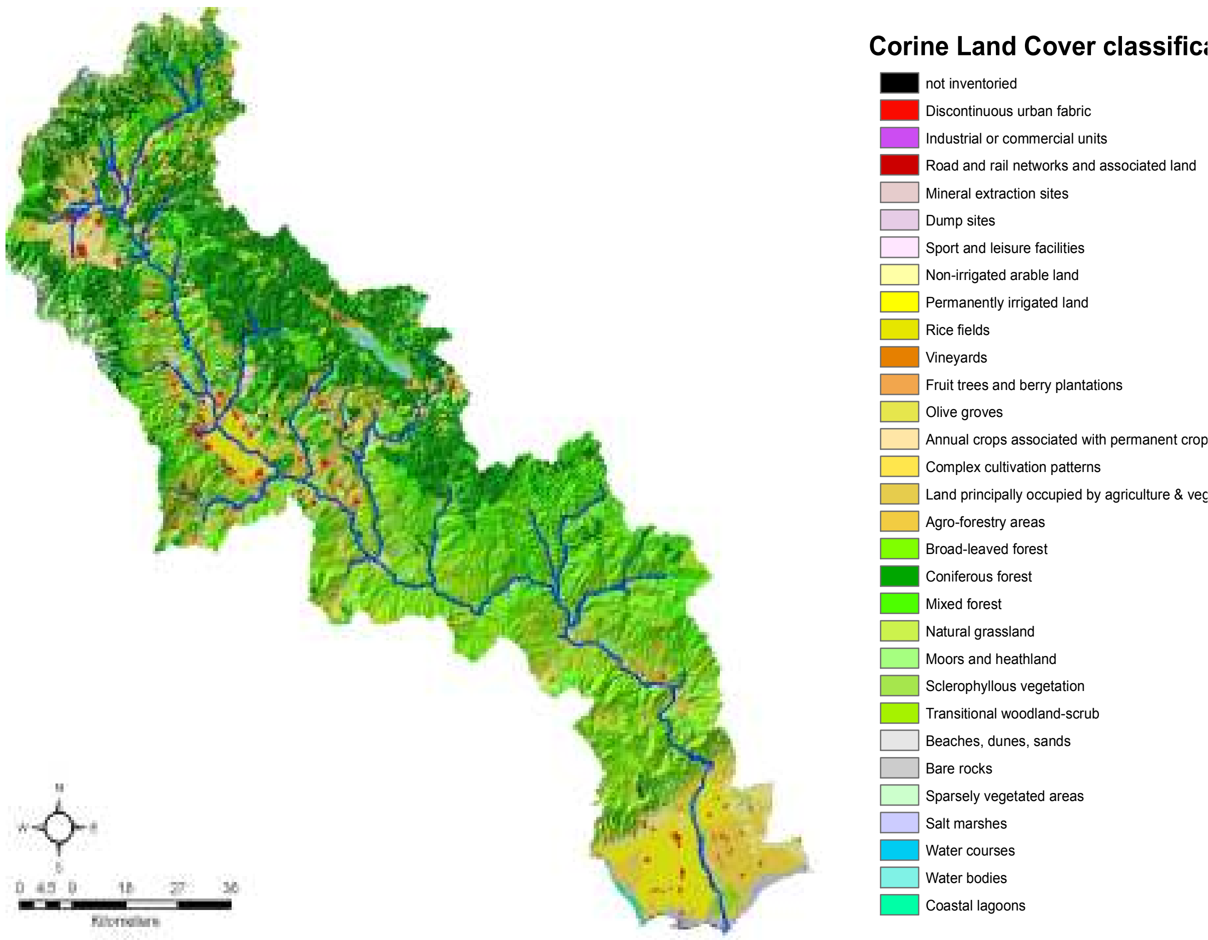


Figure 2 - Land use and land cover of the Mesta/Nestos river basin based on CORINE Land Cover classification[1]

[1] CORINE (Coordination of Information on the Environment) Land Cover is a European Commission programme intended to provide consistent geographical information on the land cover of the 27 Member States of the European Community.

I-2 – **Economic activities and water usage in the area**

A - Administrative structure and demography

On the Bulgarian side, the Mesta/Nestos river basin covers eleven municipalities. Most of them are part of Blagoevgrad District. The two municipalities of Batak and Velingrad also belong to the Papardzhic District and the municipality of Dospat belongs to Smolyan District (Table 1). The total population of the Mesta basin is approximately 190,000 inhabitants, which represents 2.5% of the population of Bulgaria (Ruszczyk H. et al., 2001). The largest towns are: Gotse Delchev (33,000 inhabitants), Razlog (22,100 inhabitants) and Bansko (13,000 inhabitants).

Municipality	District/Prefecture	Country	Population (Census 2001)	Area in Km2
Gurmen	Blagoevgrad	Bulgaria	14,709	388
Batak	Pazardzhik	Bulgaria	7,068	60
Gotse Delchev	Blagoevgrad	Bulgaria	32,309	330
Bansko	Blagoevgrad	Bulgaria	13,542	475
Razlog	Blagoevgrad	Bulgaria	21,783	440
Yakoruda	Blagoevgrad	Bulgaria	10,909	339
Belitza	Blagoevgrad	Bulgaria	9,558	293
Velingrad	Pazardzhik	Bulgaria	42,416	92
Hadzhidimovo	Blagoevgrad	Bulgaria	10,609	327
Satovcha	Blagoevgrad	Bulgaria	17,635	332
Dospat	Smolyan	Bulgaria	10,288	275
Sidironero	Drama	Greece	430	351
Paranesti	Drama	Greece	1,646	786
Topeiros	Xanthi	Greece	11,347	287
Chryssoupoli	Kavala	Greece	15,678	244
Oreinou	Kavala	Greece	1,610	257
Nikiforos	Drama	Greece	376	25
Kato Nevrokopi	Drama	Greece	2,123	351
Stavroupoli	Xanthi	Greece	2,709	284
Keramoti	Kavala	Greece	6,039	114

Table 1 - Population and surface of the municipalities belonging to the Mesta/Nestos basin

The Greek part of the basin covers the prefectures of Drama, Kavala and Xanthi which belong to the departments of Eastern Macedonia and Thrace. For the main part of its course, the Nestos river defines the boundary between these two departments.

The population of the area is approximately of 42,000 inhabitants settled in 115 villages and some small towns. The most densely populated part is the Nestos delta where Chryssoupoli is the largest town with 8,000 inhabitants (Figure 3).

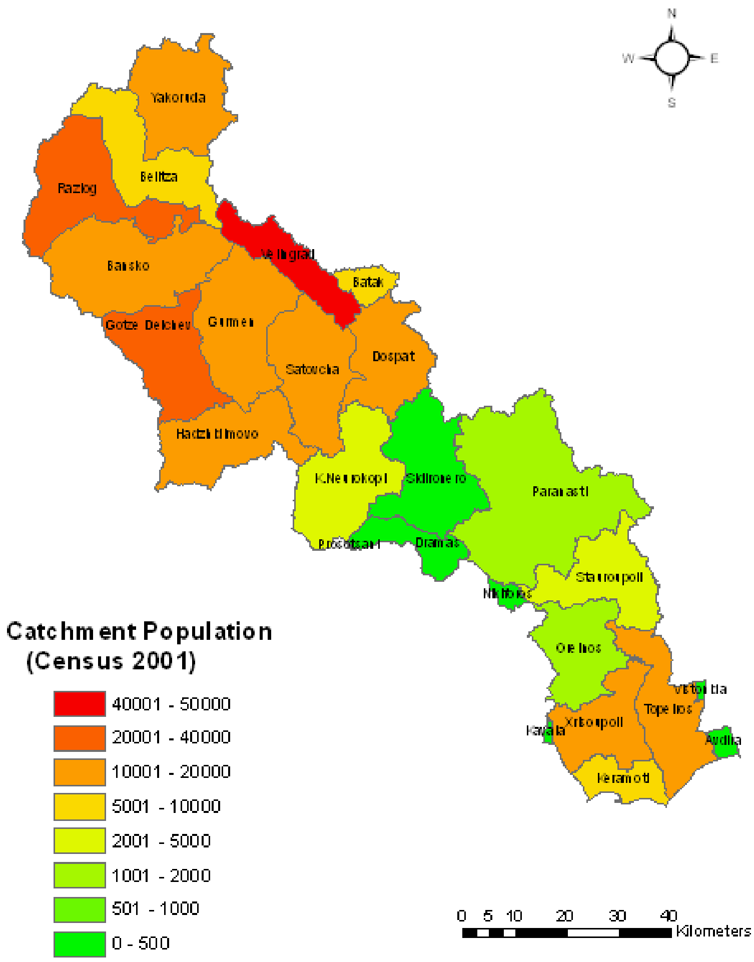


Figure 3 - Distribution of population in Mesta/Nestos basin

B – The situation in Bulgaria

In Bulgaria prior to 1990, the regional economy was dominated by a few large state-owned enterprises in electronics, machine building, and chemical industry. These companies were the main employers in the region. These large companies exported their products to the former USSR markets. Once the market situation changed and the former USSR could not afford to purchase the Bulgarian-made products, these companies faced extremely difficult times and could not find other markets to accept their low quality products.

Currently, the number of employed in the region is estimated to be approximately 60,000 persons. The employment pattern has changed substantially in the past few years, primarily since Bulgaria decided to join the European Union, which it did in 2007. During the pre-accession period, the prime foreign investors came from Greece due to the geographical proximity, incentives from the EU INTERREG program and former business and cultural ties.

Agriculture and forestry is first economic sector of the Bulgarian region with 33.8 % of the employment. The trend noted in the 90's towards considerable reduction of the production output has begun to be reversed. However the problem of finding markets for the agricultural yields and organization of the sector continues to act as an important limiting factor for further growth. The main crops are vegetables, vineyards, potatoes, cotton, fruit as well as cereals. Industry is still a significant sector with 28.7% of the labor force. The main industrial branches are the extraction industry, the ore enrichment plants, the food and beverages production, tobacco processing, machine tools engineering and metallurgy as well as clothing and textile. But the highest economic development is found in the tourism activities essentially developed around the ski resort of Bansko and the leisure activities offered by the Pirin National Park area.

According to data from 1998, the mean water consumption for water supply on the Bulgarian side is 5.2 million m^3 per year, of which 56% come from surface waters and the rest from groundwater sources. For industrial use, 3.8 million m^3 per year are consumed mainly in the municipalities of Razlog and Belitsa. For agriculture, the irrigated area covers 18600 ha with a modest annual water consumption of 50 million m^3 per year (Mihailov 1996). The river Mesta watershed is equipped with the three small hydroelectric power plants (HEPP), Yakoruda, Razlog and Toplika with total power of 1.542 MW. A large reservoir cuts through the Dospat river (Fig. 4) in the Eastern part of the basin and diverts an estimated 378 million m^3 per year to the Maritza basin.

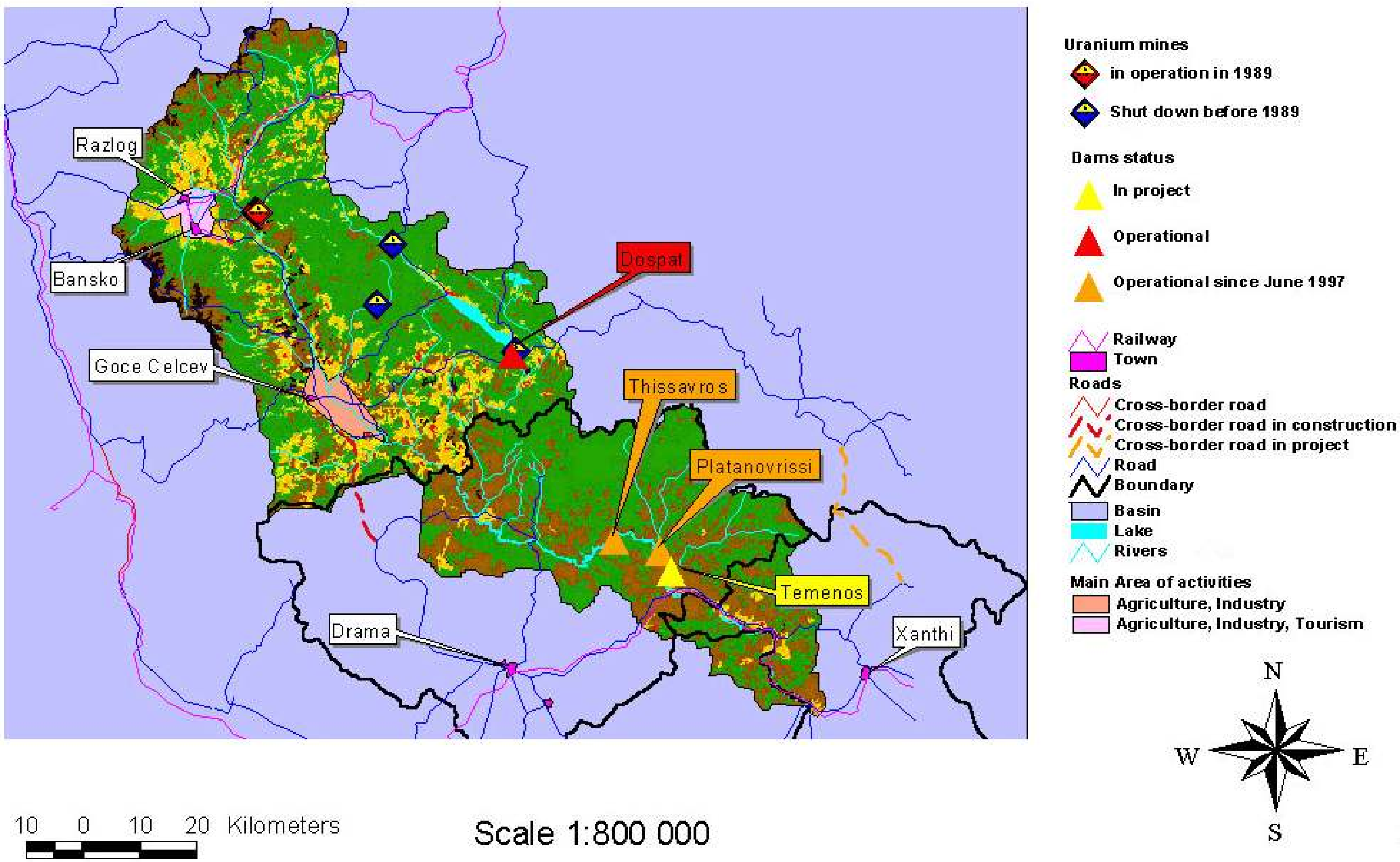


Figure 4 - Human activities in the inland part of the Mesta-Nestos river basin

C – The situation in Greece

On the Greek side, most of the economic activity is concentrated in the agriculture of the Delta although a few industries have developed in relation with the urban areas of the port of Kavala and the town of Xanthi.

The Nestos delta is considered to be one of the most productive agriculture areas in Greece. It is served by extensive irrigation network which covers an area of 15,390 hectares. In the western side of the river stream 8 irrigation networks cover an area of 12,290 hectares situated in the Kavala prefecture, while in the eastern side a more modest network covers an area of 3,100 hectares in the prefecture of Xanthi (Table 2). The main crops produced in the delta are cereals, rice, tobacco, sugar beets as well as asparagus and kiwi fruit. Most of these products are completely allocated to foreign markets, i.e. the asparagus production is entirely exported other European Union states. Agriculture provides employment to 50% of the labor force of the area. Industrial activities employ 24% of the labor force while 26% of the labor force is engaged in tertiary activities, a percentage that is relatively low compared to the national average. Tourism is still to be developed in order to exploit the natural beauty of the region, especially the upper part of the Nestos basin.

Name	Municipality	Area (hectares)
Irrigation network of Chryssoupoli:	Kavala	2,045
Irrigation network of Eratino - Piges:	Kavala	2,515
Irrigation network of Geronta – N. Karvali:	Kavala	2,160
Irrigation network of western head race channel:	Kavala	370
Renovated irrigation network of Chryssoupoli	Kavala	990
Irrigation network of Erimonisio - Karies:	Kavala	2,710
Irrigation network of Chaidefto:	Kavala	1,500
Irrigation Network of Thalassia-Kremasti	Xanthi	3,100
Total area:		**15,390**

Table 2 - The existing irrigation networks in the Nestos delta area
(Source: PPC-Environmental Report, 2004)

The water supply of the local municipalities comes from the use of groundwater karst springs originating from the southern rim of the Lekani marble massif. The springs of Paradissos and Stratonon supply a total of five million m^3 per year. In other parts of the basin, the water supply is more problematic in a number of mountainous communities, mainly during summer.

The main sector of water consumption is the irrigation system of the delta which consumes a total of 345 million m^3 per year of which 255 million m^3 per year are required by the Kavala prefecture side (western part of the delta) and 90 million m^3 per year are used by the Xanthi prefecture on the opposite side (Prefecture of Eastern Macedonia and Thrace, 2000). The two channels are served by the Toxotes irrigation dam which is situated at the delta's neck.

Further upstream from the delta, the Nestos river is interrupted by the two large hydroelectric dams of Thissavros which started operation in 1996 and of Platanovryssi which started operation in 1999. This complex is operated by the Public Power Corporation of Greece (PPC). The reservoir of Thissavros dam has a surface area of 18 Km^2 and stores 565 million m^3 of water and the reservoir of Platanovryssi has a surface area of 3.25 Km^2 and stores 63 million m^3 of water. It is of note that none of these installations diverts water outside the watershed.

I-3 - **The water quality status**

The Mesta/Nestos river basin is presently equipped with water quality stations situated in Bulgaria (2 stations) and in Greece (4 stations). While most of the streams are considered of high environmental quality, some problems are persistent and should be addressed. Water quality analyses (Argiropoulos D. et al., 1996; Papachristou et al., 2000; Darakas, 2002), using standards set by the EU and Greece for various water uses, show that in general the water of the Mesta/Nestos River meets standards for class A3 drinking water. However, the main causes of concern are:

- Domestic wastewater from cities and villages discharging into the river and its tributaries, mostly on the Bulgaria side.
- Wastewater from the few industries and handicrafts factories located in the catchment's area in Bulgaria.
- Drainage ditches particularly developed in the Nestos delta in Greece which receives residues of pesticides and fertilizers.
- Alteration of stream flow, water quality and temperature due to the Dospat dam in Bulgaria as well as the Thissavros and Platanovryssi dams in Greece.

A - Urban wastewater management

In the Mesta basin, the towns of Razlog (22,100 inhabitants) and Bansko (13,000 inhabitants) are the only ones equipped with sewerage networks and should shortly be equipped with proper waste water treatment plant (WWTP) (Darakas E., 2002). This equipment is still not planned for the town of Gotse Delchev (33,000 inhabitants).

In the Nestos delta, the town of Chryssoupoli (8,000 inhabitants) is the only one served by a central sewerage system combined with a treatment plant. Upstream, only the town of Stavroupoli and five other villages are equipped with sewer networks but their raw waters are directly discharged in the Nestos stream. The rest of the mountain villages are served by private cesspools which are mainly drain tanks, polluting the groundwater and consequently causing indirect pollution to the Nestos River (Papachristou E., 1994).

B - The pollution from agriculture

Despite the fact that the cultivated area of the Mesta covers an area 18,600 ha, diffuse agricultural pollution has not been regularly monitored in this area. In the Greek part, the agricultural activities of the northern mountainous section of the basin are very limited. In this region there are only 2,500 hectares of cultivated land and therefore the pollution load is not significant. In the delta part, starting from Toxotes, the cultivated area extends approximately 37,700 ha from which 15,390 ha are intensively irrigated using a gravity network and 3,400 ha are irrigated using groundwater pumping. However, pesticides and fertilizers are mostly conveyed by drainage ditches directly to the coastal interface. Thus most of the pollution is concentrated in the lagoons and in the sea shore.

C - The impact of industrial activities

Even though the number of industrial units in the Mesta basin region of Bulgaria has recently decreased, the remaining industrial wastes are still discharged untreated in the river tributaries. Of particular concern has been the uranium mine of Eleshnitza near Bansko. Although the mining activities had ceased for a relativelylong time, leaching from the mining pit remained a problem. In 2005 the European Union sponsored remediation efforts (Ref.: EuropeAid/112196/D/W/BG) and a monitoring network as been put in operation (Ref.: EuropeAid/112194/D/S/BG). In the Greek part of the basin, no significant industrial or handicraft activities that could pollute the Nestos river stream exist.

I-4 - The politics of transboundary water

According to reports submitted to the UN, about 50% of the land on Earth (excluding Antarctica) is located in internationally shared water catchments and about 40% of the world's population lives in these areas. As far as river basins are concerned, it is estimated that there are more than 200 transboundary river basins world wide (Ganoulis et al., 2003).

As for the South Eastern Europe region (Fig. 5), prior to 1992 there were only six international river basins, whereas after the collapse of the Yugoslav Federation, the number of internationally shared river basins in the area more than doubled. In fact nowadays there are fourteen (14) internationally shared river basins as well as four transboundary lake basins (Ganoulis et al., 2006).

Figure 5 - Transboundary rivers and lake basins in South Eastern Europe.

In Greece the issue of the internationally shared waters is of great importance since the majority of the river basins which are located in the northern part of the country have transboundary nature. More particularly, Greece is the downstream country in 4 river basins: the Vardar/Axios river basin shared with F.Y.R. of Macedonia, the Struma/Strymon and the Mesta/Nestos river basins shared with Bulgaria and the Maritza/Evros/Ergene river basin shared among Bulgaria, Turkey and Greece.

Thus, for Greece the contracting of bilateral agreements on the management of the water resources with the upstream countries is a highly priority issue in order to ensure adequate river flow regimes on its territory.

Currently, although Greece has tried to set official legislative frameworks with the neighboring countries for the management of the transboundary waters, the only ratified bilateral treaty being the one signed by Greece and Bulgaria which concerns the Mesta/Nestos River basin.

A - Water legislation and international supporting programs

Both Bulgaria and Greece are managing theirs river basins under a series of supranational standards either international or European in scope. The most important legislations which both countries have ratified are: the Convention of the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) and the European Union Water Framework Directive 2000/60/EC.

The Water Convention is intended to strengthen national measures for the protection and ecologically sound management of transboundary surface water and groundwater. The so-called Helsinki Convention establishes the cooperation between the country members of the United Nations Economic Commission for Europe (UNECE) for an integrated approach in the scope of sustainable development. It was signed on behalf of the European Community in Helsinki in March 1992 and approved by the Council Decision 95/308/EC. The text obligates the parties to prevent, control and reduce water pollution from point and non-point sources and includes provisions for monitoring, research and development, consultations, warning and alarm systems, mutual assistance, institutional arrangements, and the exchange and protection of information, as well as public access to information. Moreover, the text strengthens the cooperation on bilateral or multilateral levels for the conservation of water resources and environmental protection. The Helsinki rules introduced the concept of "equitable utilization" of the transboundary waters taking into account activities which are likely to cause "transboundary impact". Greece signed the agreement in 1996 after Bulgaria which signed it back in 1992.

The EU Water Framework Directive (WFD) sets standards that EU member states must follow in terms of water quality protection and sustainable management of water resources. It puts the emphasis on the management at river basin level and recommends an equitable water pricing based on a comprehensive cost-benefits analysis including a full valuation of environmental impacts. In addition, the WFD promotes the participation of the public in the decision making procedures. It was adopted as Greek legislation in 2003 (Law 3199/9-12-2003) and as Bulgarian legislation in 2000. Since then, the management of the Mesta River basin in Bulgaria is under the authority of the West Aegean Sea Basin District and in Greece, the Nestos river basin in managed by the Region of Eastern Macedonia and Thrace.

Various international and European programs are also supporting efforts by both countries to cooperate in research and development projects aimed at a better joint understanding of their shared waters.

For example, the International Network of Water-Environment Centres for the Balkans (INWEB) is a UNESCO chair which has been created in order to promote the cooperation among the Balkans countries in the fields of water resources and environmental protection. For some Balkan basins such as the Mesta-Nestos basin it is also augmented by specific programs such as the joint UNESCO-WMO HELP initiative in order to create a new approach to integrated catchment management through the creation of a framework for water law and policy experts, water resource managers and water scientists to work together on water-related problems. Additionally, both nations have enlisted extensive areas of the mountainous part of the basin as well as the natural wetlands of the delta part into International environmental programs such as RAMSAR or European environmental programs such as NATURA 2000.

At the European level various joint initiatives are funded by the PHARE and INTERREG programs. The aim of these programs is to improve the economic and social cooperation at the regional level. For example, since 1997 the Euroregion Nestos-Mesta has been formed with the help of an INTERREG II program. It is an initiative which coordinates cross border activities between the town of Drama in Greece and eight Bulgarian municipalities under the umbrella of Blagoevgrad. On the other hand, Energy, Environment and Sustainable Development (EESD) Programs funded by the EU such as TRANSCAT (Integrated Water Management of TRANSboundary CATchments) project (2003-2006) aim at promoting an operative and integrated comprehensive Decision Support System (DSS) for the Mesta/Nestos river basin.

B - The Mesta-Nestos river basin bilateral treaty

Cooperation efforts between Greece and Bulgaria in the field of shared water resources have a long history. The initial agreement concerning the Mesta/Nestos River basin was signed in 1964 and only after trial and effort and political negotiations which lasted more than thirty years did the two parties conclude in the bilateral treaty of 1995. The historical timeline of the agreements and protocols which have been signed are the following:

- the "Agreement on Cooperation between the People's Republic of Bulgaria and the Kingdom of Greece concerning the utilization of the waters of the rivers crossing the two countries" signed in Athens on July 9th, 1964 (Legislative Decree 4393/1964, Official Gazette 193/A/4-11-64);

- the "Agreement for the Establishment of the Greek Bulgarian Committee for cooperation in the fields of electric energy and the utilization of the waters of the rivers crossing the two countries" signed in Sofia on July 12th, 1971 (Legislative Decree 366/1976, OG 160/A/25-6-1976);

- an "Aide-Memoire" signed by the Deputy Ministers of the Environment of Bulgaria and Greece in 1991 concerning a project for "Monitoring of water quantity and quality of the rivers Maritza/Evros, Mesta/Nestos and Strouma/Strymonas (OG 161/A/30-10-1991);

- the "Agreement between the Government of the Hellenic Republic and the Government of the Republic of Bulgaria for the Waters of River Nestos" signed in Sofia on December 22nd, 1995 (Law 2402/1996, OG 98/A/4-6-1996);

- the "Memorandum of Understanding in the field of Environment and Sustainable Development" signed by the Greek and Bulgarian Ministers of Environment on November 1st, 2002 (Law 3367/4-7-2005). This text refers to the European Union Water Directive 2000/60/EC as a common framework for the management of the transboundary waters.

The original text of bilateral agreement between Bulgaria and Greece for the waters of River Nestos published in the Official Gazette of the Hellenic Republic is presented in Annex I. It consists of eight articles taking into consideration both quantitative and qualitative issues as follows:

- The amount water flowing into the Greek part of the basin is determined as a percentage of the mean annual runoff in the Bulgarian part of the watershed. This mean annual runoff is estimated at 1.5 billions m^3 per year on the basis of historical data gathered from 1935 until 1970. The percentage of the water inflow is fixed at 29% of the Bulgarian side runoff. The mean annual runoff should be re-estimated every seven years by a common Hydro-Economy committee.

- In case of an increase of inflow into the Greek part of the basin above the 29% level, Bulgaria is not entitled to receive compensation.

- The two parties are obligated to exchange data about the quality and the quantity of the water from both sides of the border. Furthermore, information and data should be exchanged in case of hydraulic works which may affect the watercourses as well as the quality of the water.

- The two parties are obligated to implement all necessary measures which should improve the waters' quality status and sustain the balance of the river's ecosystem. The criteria used for monitoring the water quality, the placement of the monitoring stations, the frequency of measurements and the method of analysis of the samples should coincide with the water quality standards of the European legislation.

- A joint Hydro-Economy committee should be responsible for monitoring the implementation of the agreement.

- The duration of the agreement is for 35 years and it should be enforced following the date of its ratification by the two countries' parliaments.

- One year before the expiration of the agreement, the two parties are committed to re-negotiate a new cooperation agreement.

- The Hydro-Economy committee is responsible for solving any potential disagreements or misinterpretations related to the implementation of the agreement. If the committee is not able to resolve a potential disagreement, the matter should be forwarded to a governmental level in both countries.

It is worth noting the reactions of the public opinion about the bilateral agreement as it was reported in the press. The agreement was ratified by the Greek parliament on May 29, 1996 and was considered a signficant diplomatic success which would set the stage for further amelioration of the relationships between the two neighboring countries. However, because the River Nestos agreement was signed at the same time as an agreement related to the opening of three new cross-border passages, the majority of the Greek press focused on the latter subject. The ratification of the agreement by the Bulgarian parliament took place on March 28, 1996. It was coupled with the reaction of the opposition party which refused its endorsement and accused the government of betraying national interest by agreeing to deprive the local Bulgarian communities of their needed water. Thus, the attitude of the Bulgarian national press was divided on the subject.

C - The deficiencies of the bilateral treaty

Unfortunately the ratification of the bilateral treaty by Bulgaria and Greece was not a panacea to the problems related to the management of the Mesta/Nestos River.

In particular, as the agreement did not properly delineate the limits of the Mesta/Nestos river watershed, it left unclear whether the 29 % of the water assigned to Greece would correspond to the flow of the main river course (i.e., the Mesta) or if it should apply to the whole runoff gathered in the watershed upstream from the border with Greece. In particular, the agreement does not explicitly include the Dospat River one of the main tributaries of the Nestos River which joins the main course after it has entered Greek territory. The Dospat course is dammed and most of its waters are diverted toward the Maritza river basin.

It is also worth noting that although the agreement refers to measures aimed at the sustainability of the ecosystems, no precaution has since been taken in order to define alternative scenarios in case of extreme phenomena such as floods and droughts (Mylopoulos Y. et al.,. 2004)

Furthermore, since the ratification of the agreement in 1996, the Hydro-Economy committee has never been active. Although it should have been responsible for the updating of the original mean annual water runoff estimation at 1.5 billions m^3 per year, the committee ignored a reported decrease of the river runoff of 600 million m^3 per year (Ganoulis J. et al., 2007) In addition, the exchange of data between the two countries relative to the waters' quality and quantity is left problematic although it could improve in the future as both countries as EU members are committed to the requirements of the EU Water Framework Directive (WFD).

D - The water abstraction scheme in Bulgaria side of the basin

According to the bilateral agreement, Bulgaria may abstract up to 71 % from the Mesta waters which amounts to about one billion m^3 per year following the annual quantity of basin water mentioned in the text. This is a huge amount compared with the relatively modest needs of the local irrigation and water supply systems (ref., Section I.2 above). It raises the question of understanding on what technical grounds this amount of abstraction can be justified.

The answer to the previous question may probably be found in a document titled: "Development plan of the Mesta/Nestos River, November 1975" which is part of the technical archives of the feasibility studies which followed in Greece the signature of the 1971 bilateral agreement. The document reproduces the Bulgarian management plan at that period which should have been applied to the Mesta basin (Fig. 6). It displays a cascade of dam complexes and diversion tunnels to the Maritza basin, for irrigation, water supply and hydropower purposes. In effect, the initial diversion of the Mesta waters to the Maritza basin had started in the 1950s, in particular in the Dospat, and the 1975 basin management plan calls for the construction of a series of new dams (Baroutin, Mesta, Gostoun, Ilindene) along with their diversion network to the existing Maritza basin dams (Batak, Vacha and Belmekene-Sestrimo).

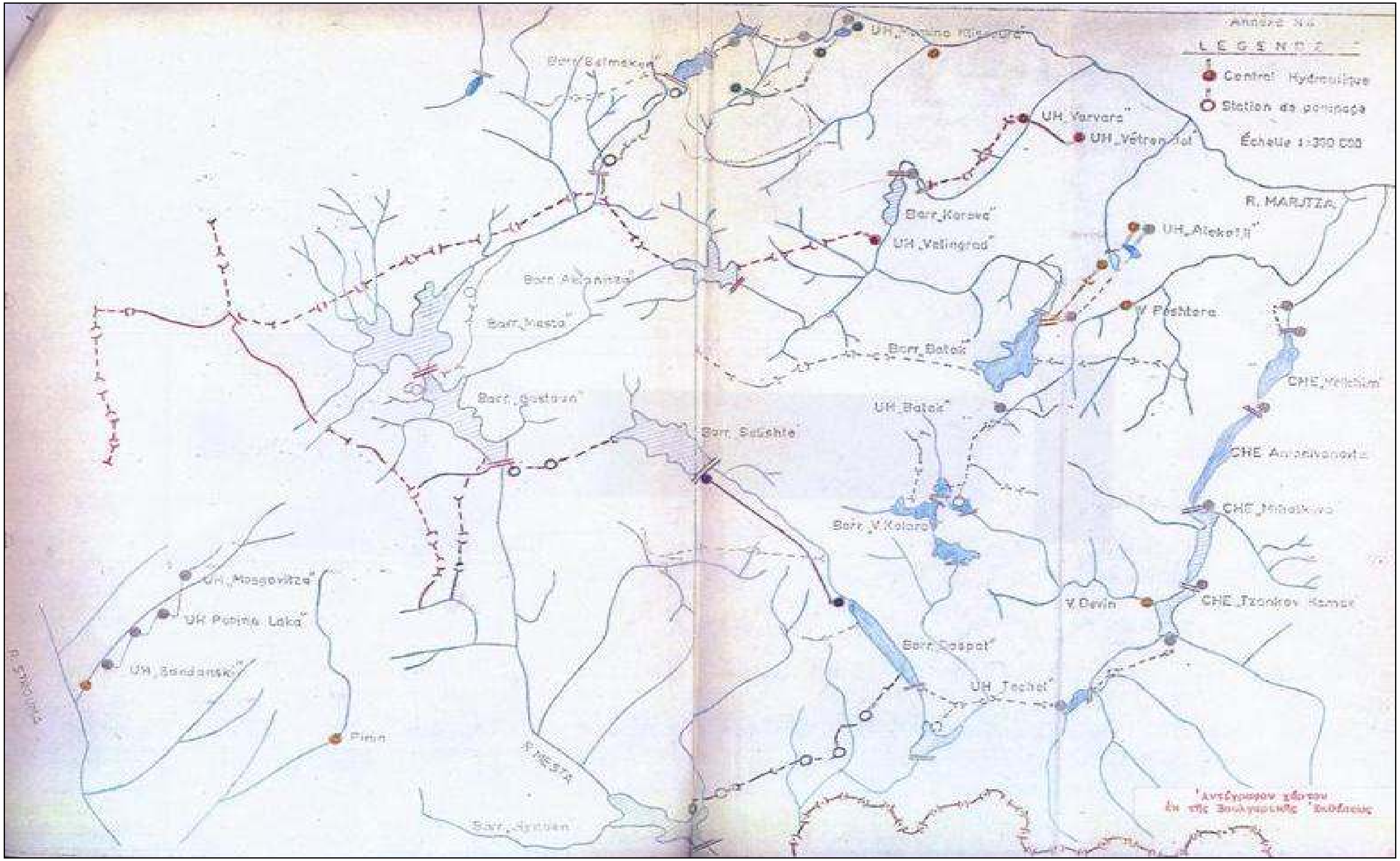


Figure 6 - Diversion of water from the Mesta basin to the Maritza basin through a cascade of dam complexes according to the development plan of Mesta River basin of 1975

As it is illustrated in Table 3, the annual diverted water volumes in 1975 were equal to 378 million m^3 per year while after the completion of the supplementary works they were estimated to be 1.273 billion m^3 per year.

Construction Period	Dam Complex	Reservoirs in the complex	Water Use	Diverted water (million m^3)
1953 - 1974	BATAK	VASSIL KOLAROV, BATAK, CHIROKA POLIANA	Irrigation of 60.000 ha in the Maritza basin Water supply	40
	VATCHA	DOSPAT	Irrigation of 86.000 ha in the Maritza basin Power production Water supply	250
	BELMEKENE - SESTRIMO	BELMEKENE - SESTRIMO	Irrigation of 50.000 ha in the Maritza basin Power production Water supply	88
Total				**378**
1975 - 1990	VATCHA	BAROUTIN	Irrigation of the Maritza basin	38
		MESTA, GOSTOUN	Irrigation of the Maritza basin	558
Total				**596**
1990 -		ILINDENE	Irrigation of the Maritza basin	299
Total				**299**
GENERAL TOTAL				**1273**

Table 3 - Diverted water volumes from the Mesta basin to Maritza basin according to the Bulgarian development plant of 1975.

It is obvious that at this period Bulgaria clearly intended to abstract 71 % of the Mesta water volumes in order to facilitate the development of the Maritza basin agriculture as well as the production of hydropower. However, after the collapse of the Socialist Eastern block, this ambitious project was abandoned. Although it is still part of the bilateral agreement, such an ambitious diversion project could be argued to be contrary to the Helsinki Convention and the EU Water Framework Directive (2000/60/EC). Nevertheless, such a hypothesis cannot be fully ruled out when planning any development project on the Greek side (i.e., Nestos river) of the basin. Besides, the scheme on the Bulgaria side is still alive as it can be found in a patent claim registered in 2004 and which defines a series of dams on the upper Mseta river which would divert water though the Belmeken-Sestrimo hydropower cascade toward the Maritza river (Kukov and Stanilov, 2004)

I-5 - **Planning for the Temenos dam project**

The idea of the construction of a complex of hydropower and irrigation dams on the Nestos river was conceived soon after the end of the Second World War. The initial study was carried out by the Greek Ministry of Public Works. However, the project is still not yet fully complete.

A – The complex of dams on the Nestos river

The development works started with the elevation of levees (1952-1958) on each side of the Nestos river in the delta region. It was meant for the protection of the local inhabitants and the agricultural land from flood events. This was followed by the construction of the Toxotes dam (1960-1966). Located at the delta's neck, it is a regulation dam of 280 m in length (Fig. 7) meant for the diversion of the water to the left (Xanthi side) and right (Kavala side) banks of the river watercourse into an irrigation network. The feasibility study of the Temenos dam was carried out by the Knappen-Tippetts-Abbett-McCarthy Engineering, an American construction company (YDE, 1954).

Figure 7 - The Toxotes dam (in the background)

and one of its diversion channels (in the foreground)

The feasibility study of the construction of the upstream dams was carried out in 1971-1972 by a foreign engineering consulting firm on behalf of PPC. However, the actual development started in the mid 1990s, following the signature the agreement with Bulgaria for the regulation of the Nestos river waters in 1995-1996. The initial project (Fig. 8) included the construction of three "en cascade" Hydroelectric Plants (HEP): the pump storage Thissavros HEP (381 MW), the pump storage Platanovryssi HEP (162 MW) and the mixed hydropower-regulation Temenos HEP (19 MW).

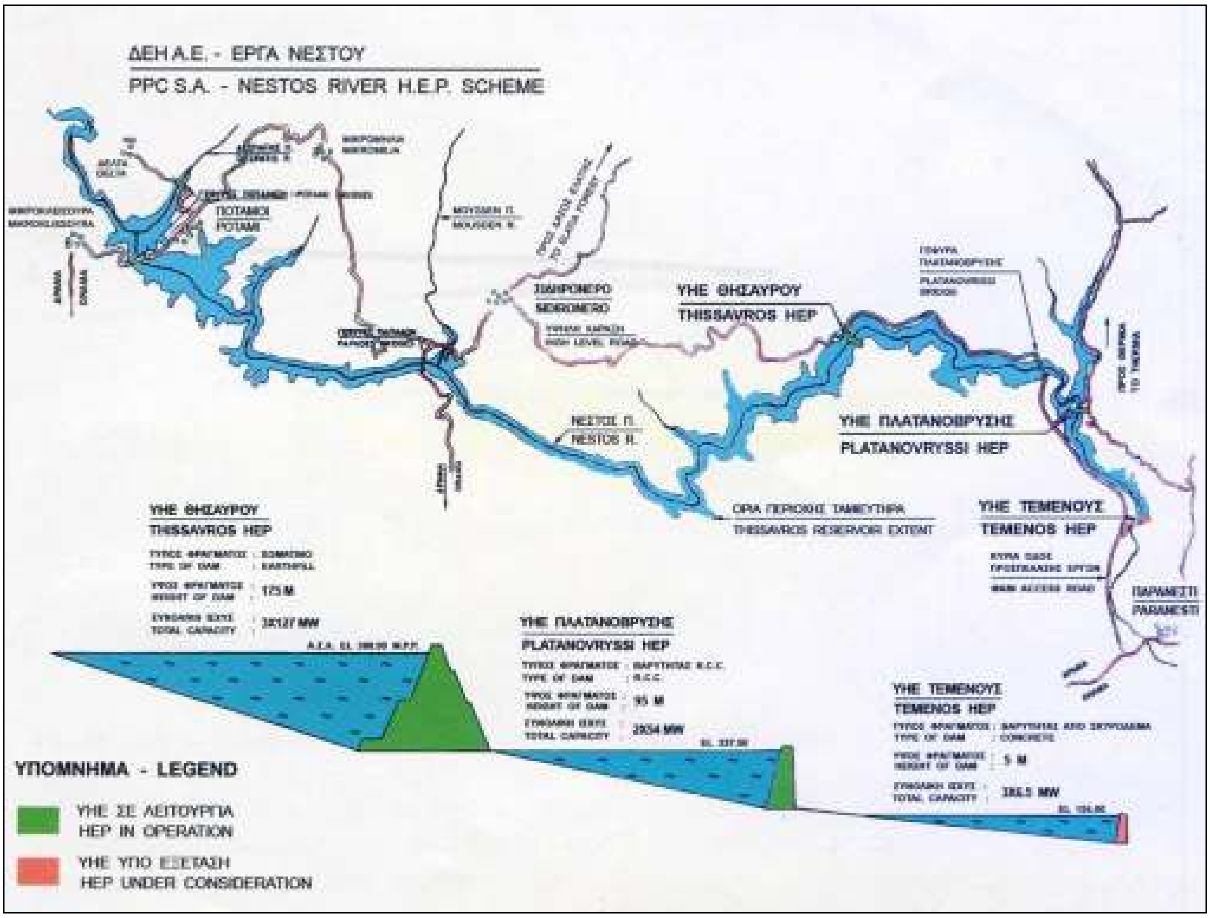


Figure 8 - Representation of the three dams "en cascade" on the Nestos River and its main characteristics (source: PPC).

Both Thissavros and Platanovryssi dams have been conceived in order to meet the peak demand of the Greece national power grid by operating a few hours per day. On the other hand, the Temenos dam was designed to store the released water volumes of the upstream dams during the power production operation and to meet the area's daily irrigation needs and environmental requirements. However, due to the lack of capital, the construction of the whole project could not be completed and only two dams (Fig. 9) have been built so far: Thissavros (1996-1997) and Platanovryssi (1998-1999).

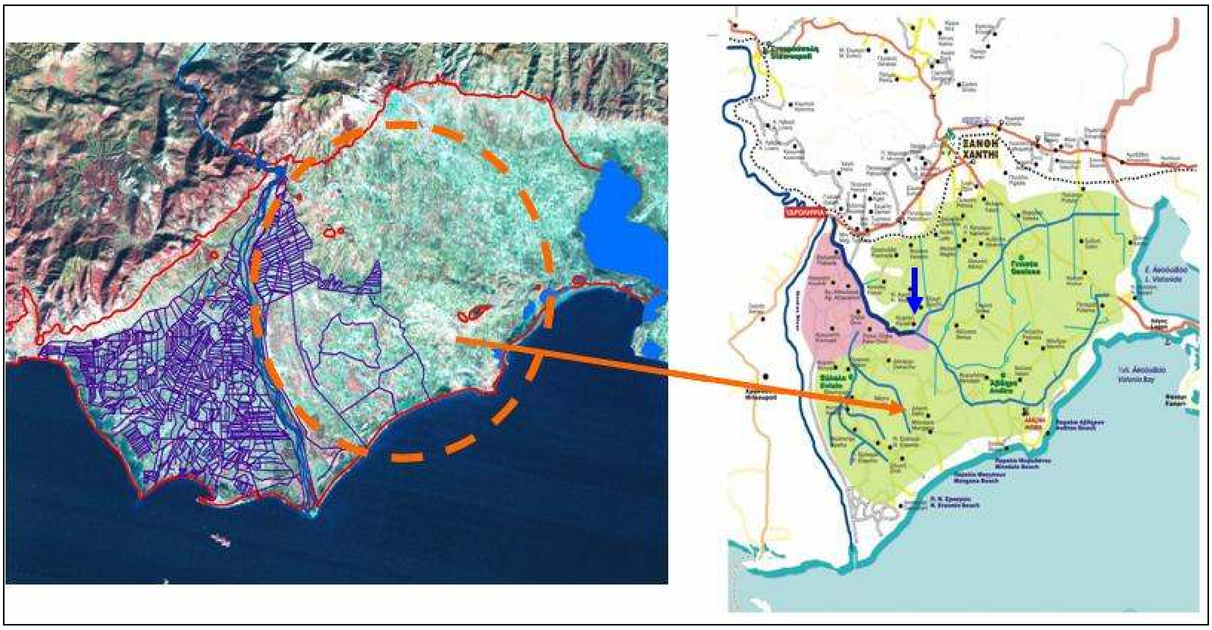
Figure 9 – Location of the Nestos dams' complex with the two existing hydropower dams of Thissavros and Platanovryssi (in yellow) and the would be Temenos project (in red) (Source: GoogleEarth)

B – The future benefits of the Temenos project

The construction of the Temenos dam is still on the Northern Greece development agenda due to the significant benefits it would bring both for economic and environmental reasons. In terms of electric power production, it should enable a better operation of the pump-storage dams of Thissavros and Platanovryssi. At present, although the two plants were exclusively constructed for hydropower purposes, they need to respond to the needs of the irrigation network in the delta area during the summer and consequently are releasing water which could be better saved for serving the peak demand in electric power needed by Southern Greece in the area of Athens.

But the most striking needs are found in the recent development of agriculture in the area. The western part of the delta which belongs to the Prefecture of Kavala is totally irrigated by the Nestos waters through extensive irrigation networks (Fig. 10a). In contrast, the irrigation network on the eastern part of the delta (i.e., the Xanthi plain) covers only a small proportion of the total agricultural land. For this reason, groundwater pumping increased in that portion of the delta up to the point where recent intrusions of salted water near the coastal zone (Petalas C., et al., 2002) have put an end to this development.

One of the main objectives of the Temenos dam project is thus to serve the extension of the irrigation system in the Xanthi plain in order to prevent the negative impact on the groundwater and further develop agriculture. The Prefecture of Xanthi with the cooperation of the Democritus University of Thrace (DUTH) has conducted a project study in order to build a system of underground pipelines (Figure 10b) of 2.5 m in diameter which would both serve the irrigation demand and recharge the aquifers in order to push back the interface of fresh and saltwater in the subsurface.



a) Current irrigation network in the Nestos delta *b) Future water diversion for irrigating the plain of Xanthi*

Figure 10 - Agriculture development in the Nestos delta-Xanthi plain area.

The building of the Temenos project could also have other significant fringe environmental benefits such as an increase in the temperature of the water released downstream of the Nestos dams complex. Currently the temperature of the released water from the Thissavros and Platanovryssi dams is much lower in the summer than it should be and this impacts negatively the fish population and the irrigation practices. This is mainly due to the pool depth of the existing dams. The downstream presence of a more modestly elevated dam such as Temenos would create a helpful buffer effect and reduce the impact on the ecosystem.

C – Where project economics meets uncertain change

During the reconstruction phase which took place in Europe after WWII under the umbrella of the Marshall Plan, priority was set on the development of large projects which were meant to meet the expanding demand of basic necessities such as energy and transportation. In many ways this approach was mimicking the success of the Tennessee Valley Authority during the USA “New Deal” of the late 1930s. Profitability was put in a lower priority than the social rewards coming with the development of the national economies. It is under these circumstances that the Nestos dams were designed in the 1970s under the auspices of PPC, the national Hellenic energy company. The proposed development of the Mesta dams during the same period in Bulgaria follows similar goals even though it was conceived under a strikingly different political regime.

Nowadays, conditions are very different. The globalization of the economy and the liberalization of the energy markets in the European Union (Energy Directive 2003/54/EC) and the merging of all members’ agriculture economic sector under the same umbrella are completely redefining the rules by which investment projects are undertaken. In Greece, PPC no longer holds a monopoly position in the Greek electricity market. Furthermore, by moving from national responsibility into the private sector, energy projects must follow the rule of competition and private project financing. This why, as of today, at least two Greek private construction companies: MICHANIKI and TERNA ENERGY have tendered for the construction of the Temenos dam project.

However, in order to attract private investor funding, technical projects must nowadays demonstrate their profitability and sustainability using a standard set on economic concepts, among which the most important is the Net Present Value (NPV). The NPV is measure of profitability which takes into account the full life cycle of the project from construction to closure. It needs also to include in a convincing way an evaluation of all the risks which could degrade the “nominal” production goal put forward in the project proposal.

In traditional project dimensioning, such as the ones which had been built originally by PPC or even in the new proposals put forward by the two Greek construction companies, the flow regimes and the irrigation demands which are used for the evaluation are in general average annual values which are meant to be stable throughout a project life cycle of typically 50 years. This stability hypothesis does not obviously picture the reality of the evolution of factors such as climate change or the evolution of economy. In the case of Temenos, the added factor of the evolution of the Bulgaria water demand and its potential influence on the profitability on the project needs obviously to be considered.

It is the purpose of this thesis to demonstrate how the latest developments in the science of mathematical modeling in climate, hydrology and hydropower simulation may contribute to a better evaluation of the risks which should be taken into account in hydropower and irrigation project economics. This approach will be demonstrated on the case of the Temenos dam. Furthermore, more general concepts related to environmental impact, sustainability of agriculture economy and decision making will be explored while putting the emphasis on the influence of the various climate change scenarios which have been recently defined by the IPCC.

II – MODELS AND METHODS

Water resources planning and management involve the development, control, protection and beneficial use of surface and ground water resources. Consequently, it addresses a broad spectrum of applications including agricultural, industrial and municipal use with regards to pollution prevention, hydroelectric power generation, erosion and sedimentation control and the proper design of storm water drainage and flood waters control to reduce damages due to extreme precipitation events.

Mathematical modeling plays an important role in these fields of application. From the scientist's and the researcher's perspective, the role of mathematical models is to provide a better understanding of real world processes. From the water manager perspective, mathematical modeling is a way to generate quantitative information in support of decision making activities.

During the last three decades, much progress has been made in the field of mathematical modeling applied to water resources planning and management. A diversity of software packages have been developed and play nowadays an effective role in all aspects of water management. In addition, the progress in computer technology facilitates the use of even the most complex mathematical models. Powerful computers are no longer the privilege of well endowed organizations, but can be easily obtained by individuals.

However, even if the computer models provide more accurate results and additional information, but they do not solve decision and implementation problems by themselves. In particular, the user is responsible for choosing among the large number of software packages. Moreover, the model selection must be made carefully because the water resources models results are often limited by the accuracy of data which is used as input for their calibration. This is an important factor which conditions the ultimate quality of the results. Consequently, a researcher's expertise is often welcomed in reviewing these results and interpreting correctly their significance and limitations.

II-1 - **Hydrology models**

II-1-1 - Mathematical modeling of river basin hydrology

Rain water and snow melt are transported through natural hydrologic processes such as infiltration, evaporation, and evapotranspiration. Mathematical models simulate the physical processes by which precipitation is converted to surface runoff and ground water flow. Simulation results are presented in the form of stream flow hydrographs computed at given points along the river network. These are required by different types of applications such as dam construction, irrigation network planning, flood control improvements and bridge dimensioning. Other mathematical models are addressing transport phenomena as well as chemical or biological processes. Their results take the form of time series of the concentration in chemical or organic components in the water. These outputs are needed for water quality management activities from which the control of the drinking water supply is most essential.

In so called "basin models" all the hydrologic processes modules are integrated at watershed scale in order to facilitate river basin management.

A - Historical references and models classification

Despite the fact that hydrological modeling exists since the beginning of the previous century, the simulation of the whole hydrologic cycle at a watershed scale really started in the 1960s with the digital revolution. Today the results from hydrological models are fairly accurate and extend to environmental and ecosystem management. They are also frequently coupled with other models, such as those dealing with climate change or water economics. This coupling provides more realistic prediction of water demands and their future effects.

Such a large number of hydrology related computer models have been developed that it is now difficult to provide a comprehensive survey of such models. In 1991, the US Bureau of Reclamation compared 64 watershed hydrology models which were classified into four categories and this inventory was later updated (Burton J. S., 1993) in the *Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 1990's*.

Singh V. P. (1995) summarized 26 popular models from around the globe and the Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data (USGS, 1998) published the *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, which summarized many popular watershed hydrology models developed by federal agencies in the United States.

Later, Wurbs R. A. (1998) listed a number of generalized water resources simulation models and classified them in seven broad types:

- watershed
- river hydraulics
- river and reservoir water quality
- reservoir/river system operation
- ground water
- water distribution system hydraulics
- demand forecasting

The classification of hydrological models is a matter of great interest because it facilitates the selection of the appropriate model to be applied to specific circumstances. Nevertheless, as each model is often devoted to a particular application, another classification may be organized on the basis of model use and may lead to more refined categories. For example, the American Society of Civil Engineers - ASCE (1996) reviewed and categorized flood analysis models into (1) event-based precipitation-runoff, (2) continuous precipitation-runoff (3) steady flow routing, (4) unsteady-flow flood routing, (5) reservoir regulation, and (6) flood frequency analysis. A rather extensive classification based on the same principle has been recently published by Singh and Woolhiser (2002).

An additional factor in the classification of hydrology models is related to the amount of refinement conducted in the treatment of spatial phenomena. If a numerical solution of partial differential equations in two or three space dimensions is explicitly used, it is considered to be a "distributed" model. Otherwise, if the explicit spatial derivatives are replaced by some form of averaging over geographic zones it is labeled as a "lumped" model.

In the case of a lumped model, precipitation data is averaged over the whole basin or some sub-basin areas over which simplified hydrology equations are solved. Final flow results are usually computed at a limited number of points along the river network. Such a model may produce reasonable results but because of the spatial variability of hydrological parameters such as soil type, relief slope and land-use cannot be accurately represented, the model cannot be expected to realistically represent the flow conditions at any point in the watershed.

On the other hand, a distributed model is based on a densely spaced grid. For each cell of this grid, the water balance is calculated using meteorological data and appropriate spatial parameters. The spatial density of the grid is adapted to the desired level of accuracy in the representation of the physical phenomena. Compared to the lumped type, a distributed hydrological model describes with more details the physical mechanisms which depend upon the spatial non-uniformity of the river basin hydrological parameters. The recent development of techniques such as remote sensing imagery and geographic information systems (GIS) has helped in the representation of watershed spatial characteristics and the further development of spatially distributed models.

One of the major advantages of spatially distributed hydrological modeling lies also in the derivation of runoff values at any point of interest inside the watershed. The use of a spatial grid enables this "multipoint" computation since water balance terms are explicitly computed for each grid cell. Nevertheless calibration for this category of hydrologic models is more challenging due to the large number of parameters which need to be adjusted. These different approaches will be later illustrared through the description of two models which have been used in order to simulate the hydrology behavior of the Mesta-Nestos basin.

II-1-2 - HEC-HMS, an example of lumped river basin flow model

The *Hydrologic Modeling System* (HEC-HMS) from the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) is designed to simulate the precipitation-runoff processes of multibranch river systems.

HEC-HMS is a spatially lumped model (also known as conceptual model) which evaluates the hydrologic cycle of specified sub-watersheds and interconnects their respective outflows. The HEC-HMS software is organized in a cascade of specialized modules, including:

- Estimation the volume of runoff, given the precipitation and the properties of a particular sub-watershed;
- Direct-runoff module that can accounts for surface flow, storage and energy losses as water runs down the stream channels;
- Base flow specification based on annual flow statistics;
- Hydrologic routing that accounts for storage and energy flux as water moves through the connected stream channels with a realistic representation of natural confluences and bifurcations;
- Modeling of water-control equipments, including diversions and storage facilities.

The program features a completely integrated work environment including data base, data entry utilities, computational engine and result reporting tools. A graphical user interface allows the users easy movement between the different components of the program.

HEC-HMS has a wide range of applications including large river basin water supply and flood hydrology, and small urban or natural watershed runoff. One of the advantages of the program is that it can be coupled with a group of different programs provided by HEC in order to study water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

HEC-HMS model used in the TRANSCAT project

The TRANSCAT project, which was supported by the EU FP6 program and was terminated in 2006, addressed the objectives of the "Energy, Environment and Sustainable Development (EESD) Program" in "Sustainable management and quality water". The TRANSCAT Consortium gathered 12 research institutions from 9 European countries, and aimed at contributing to the process of implementing the Water Framework Directive (WFD) in transboundary basins. The main objective of the project has been to build an operational and integrated Decision Support System (DSS) for optimal water management of the transboundary river catchments.

The transboundary river basin of Mesta/Nestos was one of the test cases selected in TRANSCAT. It was modeled using HEC-HMS Version 3.0.0, issued at the end of 2005. Figure 11 displays some of the elements of the model.

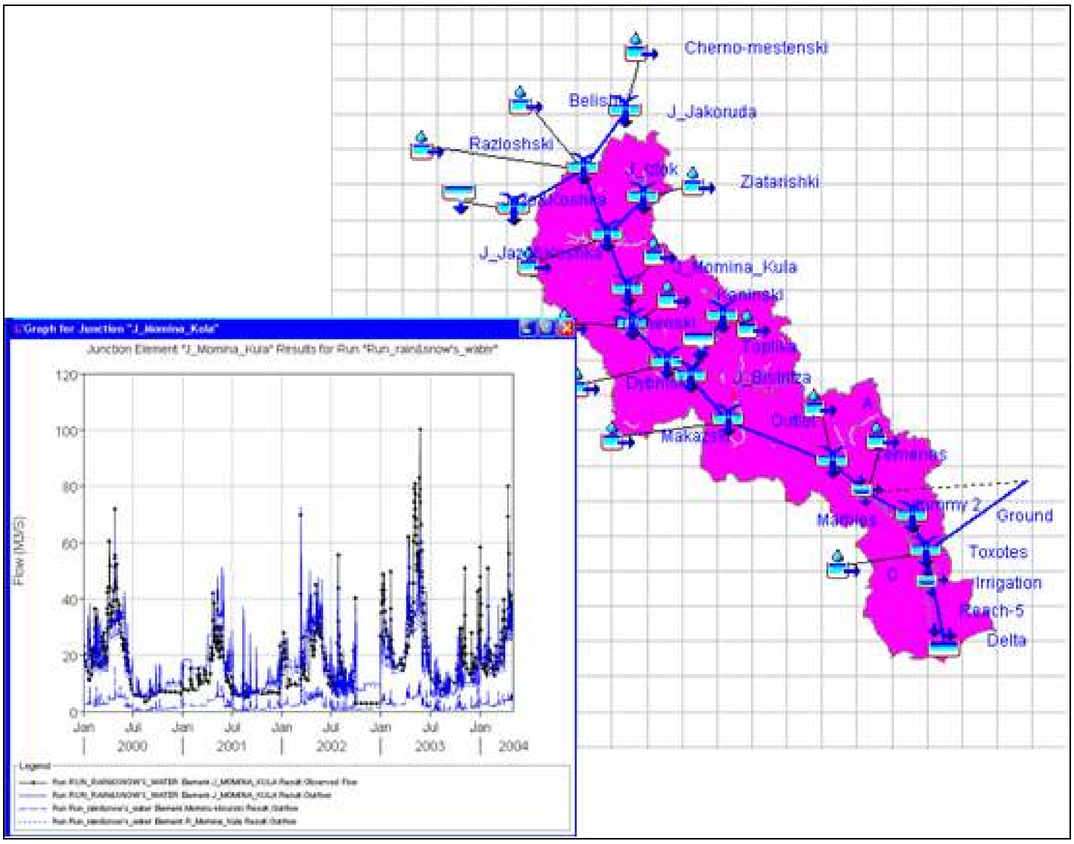


Figure 11 - Mesta/Nestos basin under the TRANSCAT project and the simulation result at Momina Kula station (Bournaski et al., 2006)

Unfortunately, the test simulation TRANSCAT project using a combined set of hydrologic data from Bulgaria and Greece is restricted to the year 2000. Thus any use of the model for different meteorological conditions would need a complete recalibration. The main drawback of the HEC-HMS model is that it was essentially conceived in order to compute transient flood hydrographs. It is not able to adapt by itself the river annual base flow values under the influence of climate change. This is why a more flexible tool such as the MODCOU distributed model was preferred.

More recently, the Soil and Water Assessment Tool (SWAT) from the United States Department of Agriculture (USDA) has been recently applied to model the hydrology and river load transport of the lower Nestos basin downstream from the Temenos project (Boskidis I. et al, 2008). It is a lumped sub-watershed model similar to TRANSCAT with added capacity for modeling the transport of pesticides and the interaction with agriculture practices. Its mains applications are targeted toward the study of pollution transport. The validation of the lower Nestos SWAT model was conducted for the period from May 2007 to December 2007.

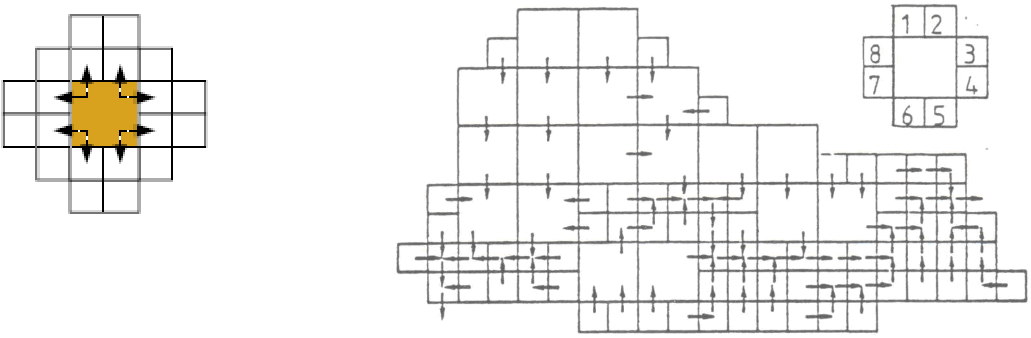
II-1-3 - The MODSUR distributed hydrology model

The MODSUR simulation model or "*modélisation des transferts de surface*" is part of a wider MODCOU simulation model or "*modélisation couplée des transferts de surface et des transferts souterrains"* which has been developed at Ecole Nationale Supéreure des Mines de Paris (Ledoux E. et al., 1989) in order to simulate the spatial and temporal evolution of the water table and river flows. It was originally tested on a small French Mediterranean coastal river and later applied operationally to the Adour river stream flow in the Pyrenees (Girard and Boukerma, 1985). It has since been routinely applied at different spatial scales from small watersheds of a few square kilometers to large scale areas of the order of a hundred thousand square kilometers (Ledoux E. et al., 1989). The latest applications are now aimed at climatology studies over large basins, particularly in France. This includes the Seine river basin (Ledoux E. et al., 2007), the Aquitaine basin (Habets F. et al., 1999) and the Rhone river simulations (Golaz et al., 2001, Ottlé et al., 2001).

A specific version of the program called MODSUR-NEIGE has been developed on the principle of "degree days," originally developed by USACE (U.S. Army Corps of Engineers, 1956).

This principle was later adapted to the distributed model principle (Charbonneau R. et al., 1971) using an approach which seperates the process between forested and aforested areas.

The model is based on a dense spatial grid made of variable size square cells. Characteristics of the surface domain (runoff directions, altitude, soil and land-use) are attached to each cell. The grid topology is based on the so-called 4 neighbors rule (idem, 4-connectivity). Each cell may only be connected to cells of the same dimension, or cells which four times larger, or cells that are one quarter of the size (Fig. 12). The surface water is transferred through the runoff network or networks to the catchment outlet. The ensemble of connected cells builds a runoff network which gathers the flow down to the catchment outlet.



a) 4-connectivity algorithm for the definition of runoff direction

b) Typical surface runoff network

Figure 12 – Topology of a MODSUR mode grid

In MODSUR (Fig. 13) the water budget is computed for each grid cell, using a system of four reservoirs dividing the rainfall in storage, infiltration, surface runoff and evaporation. In MODSUR-NEIGE a snowmelt module is added. In the MODCOU model, infiltration is transferred via the NEWSAM diffusivity equation based ground water module (Ledoux E. et al., 1989). But the infiltration reservoir of MODSUR has also some capacity of modeling the behavior of near surface aquifers and this is the option which was used for modeling the Mesta-Nestos basin. As the main subject of my work relates to the part of the watershed upstream from Toxotes and as this area is mainly mountainous, it was decided that the capacities of MODSUR were sufficient for modeling the effect of the few groundwater tables found essentially on the Bulgarian side.

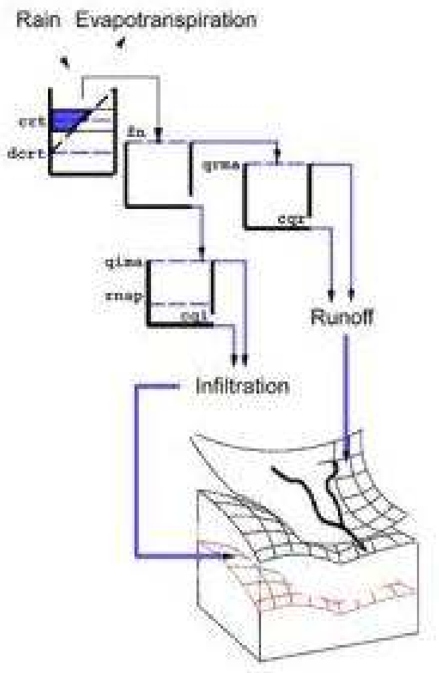
	**The parameters used in MODSUR**
	dcrt = minimum amount of moisture in top soil reservoir content below which evapotranspiration and gravity flow are impossible
	crt = midlevel in top soil reservoir (for a given value of **dcrt**, ETR is a function of crt)
	rir = maximum value of infiltration for a given time-step (in mm)
	qrmax = maximum level in the rainfall reservoir(in mm)
	cqr = drying up coefficient of the rainfall reservoir
	qimax = level of overflow of the groundwater reservoir (in mm)
	cqi = drying up coefficient of the groundwater reservoir
	rnap = delay coefficient of infiltration
	rrui = delay coefficient of runoff

Figure 13 - Schematic description of a production function of the MODCOU model

The detailed processes taken into account by MODSUR for each grid cell are based on the following equations (reservoir parameters are in bold):

Upper surface reservoir

The repartition of rainfall water into runoff, infiltration and evapotranspiration is defined by parameters ***crt*** and ***dcrt***. The rain water routing is given by the following equations if R is the incoming run-off from neighbouring cells and P is the amount of rain:

$Rmax = 2*\mathbf{crt} + \mathbf{dcrt}$

$Rba = max\ (\mathbf{dcrt}\ , R) - \mathbf{dcrt}$

$Rha = min\ (R + P\ , Rmax) - \mathbf{dcrt}$

$dR = max\ (0\ , Rha - Rba)$

$Eau= max\ (R + P – Rmax\ , 0) + dR(2Rba + dR)/(4(\mathbf{crt} - \mathbf{dcrt}))$

$ETR = min\ (ETP\ , R + P - Eau)$

$R = R + P - Eau - ETR$

Partition reservoir between runoff and infiltration

Parameter ***rir*** corresponds to the maximum value of infiltration expressed in millimeters (mm). It controls the partitioning between water which will infiltrate into the soil (*Qitot*) and water which will runoff at the surface (*Qrtot*) according to the following rule:

If water level in cell reservoir < rir then Qitot = water and Qrtot = 0

If level ≥ rir then Qitot = rir and Qrtot = water - rir

Infiltration transfer reservoir

The coefficient ***rnap*** defines a time delay between infiltration (*Qitot*) and drainage (*Qi*). The calculation is the done as follows:

$$Rnap = Rnap + Qitot$$

$$\text{If } Rnap < Qima;\ Qi = cqi*Rnap$$

$$\text{If } Rnap \geq Qima;\ Qi = (Qitot - Rnap) + cqi*Rnap$$

Runoff transfer reservoir

Finally, runoff is defined in almost the same way as infiltration. In this case, the delay coefficient is ***rrui*** and the amount of water which runs off is *Qr*. The calculation is similar:

$$Rrui = Rrui + Qrtot$$

$$\text{if } Rrui < Qrma;\ Qr = cqrRrui$$

$$\text{if } Rrui \geq Qrma; Qr = (Qrtot - Rrui) + cqrRrui$$

All the reservoir parameters such as: ***crt, dcrt***…etc, are defined by the user on the basis of a typical association between geology, pedology, land cover and land use. Each association is called a "production function" in MODSUR. It is spatially distributed over the model grid. The set of "production functions" used in a particular MODSUR run builds the equivalent of a thematic map of the basin classified by broad behaviors in terms of infiltration, runoff and evapotranspiration properties. Each grid cell may contain a certain proportion of each of these "production functions", the sum of proportions being equal to one. This enables a more realistic representation of terrain properties when the grid cells are large (for example: 8 by 8 kilometers).

A particular class of "production function" called "river cells" is also preset in order to account for the routing of water through river streams. All parameters defining each "production function" except "river cells" need to be calibrated against the available flow measurements. The calibration is performed in an iterative fashion.

A - Input data

The set of input data needed for running MODSUR consists of the topography of the basin, daily rainfall, daily temperature, evapotranspiration as well as the spatial distribution of the "production functions".

Topography of the basin

The topography characteristics (runoff directions, drainage network, altitudes and slopes) are integrated in the model spatial grid. The construction of the grid is accomplished by the manipulation of a digital elevation model or DEM. In the case of the Mesta-Nestos, two DEMs were used. The first DEM is the United Geological Survey (USGS) EROS GTOPO30 30 arc second (approximately 1 kilometer) DTM, interpolated to 250m. The second DEM was obtained from the Shuttle Radar Topography Mission (SRTM) with 100 m postings. DEM manipulation has been conducted using HydroDem (Leblois E., 1993) and HEC-GeoHMS, an extension of the ArcView GIS software program (see, Section III.3.1). The model grid was constructed using the SIGMOD program (Golaz-Cavazzi C., 1995).

Daily rainfall

Every cell of the grid is associated with rainfall data. The Thiessen polygon (idem, Voronoï polygon) method is used to estimate areal daily rainfall from existing stations. The Thiessen polygon mesh is then disaggregated to the more refined model grid. This function has been implemented as a built-in option of the ArcGIS software.

Evapotranspiration

MODSUR input Potential Evapotranspiration (PET) values are usually determined using the Penman formula. It requires: temperature, precipitation, wind speed, humidity, and solar radiation. Alternatively, in case of lack of detailed data the more simplified Turc formula can also be used.

Production functions

In the case of the Mesta-Nestos basin, the information needed to build the "production functions" in MODSUR is essentially based on the infiltration properties of soils and underlying rocks and the evapotranspiration of natural or agricultural lands. Available in form of polygonal shaped maps in a GIS, this data needs to be disaggregated to the more refined model grid using a technique similar to the one used for areal rainfall.

B - Output

MODSUR produces daily results of the runoff and river stream flow for any element of the model grid. These results are subsequently processed to produce monthly averaged flows. One advantage of the MODSUR module is that it enables the computation of the flow for any "river" cell rather than only at the river basin outlet. This is very useful when planning water diversion or dam construction projects.

C – Examples of connection of MODSUR-MODCOU with other models

The MODCOU-ISBA scheme (Habets F. et al., 1999)

The coupling of the Interface Soil Biosphere Atmosphere (ISBA) surface model with MODCOU enables the integration of atmospheric and hydrological simulations at the regional scale (Ledoux E. et al., 2002). It is part of the operational tools used by the Météorologie Nationale in France and its partners in Europe. It is in particular the case of the Bulgarian Meteorological office which has been using ISBA-MODCOU to model the Maritza river basin.

The MODCOU-STICS scheme (Ledoux E. et al., 2007)

The MODCOU-STICS model predicts the fate of nitrogen fertilizers and the transport of nitrate from the rooting zone of agricultural areas to surface water and groundwater in the Seine basin, taking into account the long residence times of water and nitrate in the unsaturated and aquifer systems. Information on pedology characteristics, land use and farming practices is used to determine the spatial units to be considered. These data are converted into input data for the crop model STICS, which simulates the water and nitrogen balances in the soil-plant system with a daily time-step.

A spatial application of STICS has been derived at the catchment scale, which computes the water and nitrate fluxes at the bottom of the rooting zone. These fluxes are integrated into surface and groundwater path using MODCOU, which calculates the daily water balance in the hydrological system, the flow in the rivers and the piezometric variations in the aquifers, using standard climatic data (rainfall, PET). The transport of nitrate and the evolution of nitrate contamination in groundwater and to rivers are computed by the NEWSAM code. This modeling chain is a valuable tool to predict the evolution of crop productivity and nitrate contamination according to various scenarios modifying farming practices and/or climatic changes.

II-2 - **Dam simulation**

A dam is an artificial barrier that restrains the natural flow of water and builds a reservoir. Originally many dams were constructed to prevent flooding events, but they can also provide water for irrigation purposes, storage and delivery of municipal and potable water, generation of hydroelectric power, improvement navigation and creation recreation areas. Most dams nowadays serve more than one purpose.

In the case of the Mesta/Nestos River basin, the existing Thissavros and Platanovryssi dam complex is mainly used for generating hydroelectric power, whereas the downstream dam of Toxotes is used for regulating the water for irrigation. The future Temenos dam is conceived to provide both hydropower and irrigation. In this section I will illustrate mathematical modeling techniques used in order to simulate the functioning of dams and provide procedures for the optimization of their operation. The focus will be placed on the HEC-ResSim modeling tool.

II-2-1 - Hydroelectric production and hydropower plants

A hydropower plant converts water potential energy into electricity. The dam reservoir water is driven through a large, narrow pipe called tailrace or penstock, and in this process is boosted. Thus, initially the potential energy is converted to kinetic energy. The boosted flow of water turns a turbine, which turns a generator and produces electric energy. In large reservoirs, the available power is generally only a function of the hydraulic head and rate of fluid flow. In a reservoir, the head is the height of water in the reservoir relative to its height after discharge.

In general, the amount of energy ***E*** released by lowering an object of mass ***m*** by a height ***h*** in a gravitational field is:

$E = mgh$ where ***g*** is the acceleration due to gravity

By dividing both parts of the previous equation with time ***t***, the power is related to the mass flow rate $\frac{m}{t}$:

$$\frac{E}{t} = \frac{m}{t} gh$$

Substituting $\boldsymbol{P}$ for $\frac{E}{t}$ and expressing $\frac{m}{t}$ in terms of the volume of liquid moved per unit time, the rate of fluid flow $\boldsymbol{\Phi}$, and the density of water $\boldsymbol{\rho}$, we arrive at the expression:

$$P = \rho \phi g h$$

where the produced power $\boldsymbol{P}$ is in watts, the rate of flow $\boldsymbol{\Phi}$ is measured in m^3/s and the head $\boldsymbol{h}$ is measured in meters.

For a particular project two terms are physical constants: the density of water $\boldsymbol{\rho}$ is expressed in kg/m^3 and the acceleration of gravity $\boldsymbol{g}$ is expressed in m/s^2. For instance, for 1000 kilograms of water (1 cubic meter) falling from 100 meter, the produced potential energy is of about 0.272 kW.

Based on the amount of energy produced, hydropower plants are classified by the US Department of Energy (DOE) as: large hydropower plants (LHP) for a capacity of 30 megawatts, small hydropower plants (SHP) for a capacity ranging between 100 kilowatts and 30 megawatts, and micro hydropower plants, for less than 100 kilowatt capacity.

The basic components of a hydropower plant (Fig. 14) are the following:

- **Dam**

Most hydropower plants rely on a dam that holds back water, creating a large reservoir. Usually, reservoirs are located at a height which is different from that of the dam's outlet. However, there exist hydroelectric plants with no reservoir capacity and which are called run-off-the-river plants. Dams are characterized according to their size (height), intended purpose or structure. Their engineering will be different depending on their purpose: flood control, irrigation, municipal and industrial water supply and hydroelectricity generation. Based on their structure and the type of material used for their construction, dams are classified as timber dams, arch-gravity dams, embankment dams or masonry dams (ICOLD[2]).

[2] International Commission of Large Dams (ICOLD), http://www.icold-cigb.net/

- **Intake**

This is the water passageway through the dam's structure towards the turbine. The intake gates regulate the volume of water that enters the penstock, which is a pipeline ending up at the turbine.

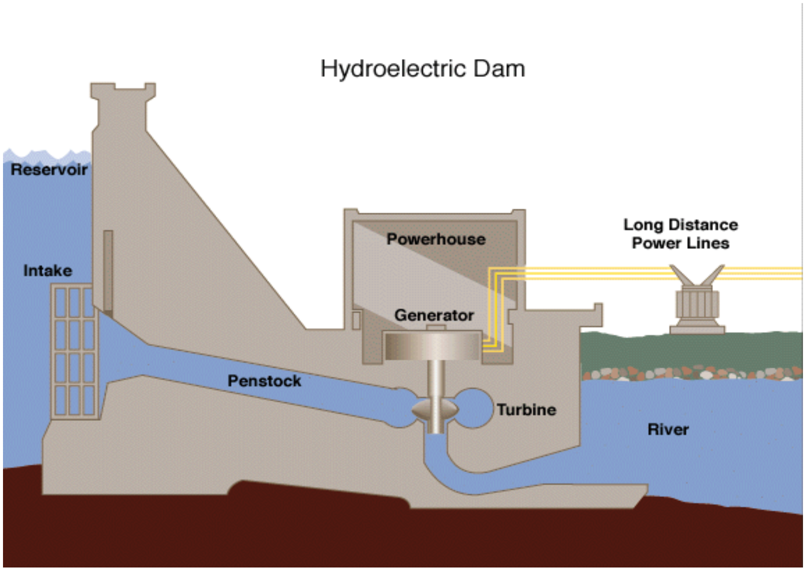


Figure 14 - Representation of a power plant[3]

- **Turbine**

The water is directed on the blades of a turbine which spins because of the force of the water (Fig. 15). The turbines' blades are attached through a vertical shaft to a generator. The most common type of turbine for hydropower plants are the Francis and the Kaplan.

[3] Source: http://www.tva.gov/power/hydro.htm

- **Generator**

A hydroelectric generator converts the mechanical energy into electricity. The operation of a generator is based on the principles discovered by Faraday: when a magnet is moved past a conductor, it causes electricity to flow. A generator consists of two parts: the rotor and the stator. The rotor contains electromagnets attached to the turbine shaft and is rotated at a fixed speed. The stator is a doughnut-shaped structure surrounding the rotor and contains the conductors. The movement of the magnet next to the conductor causes electricity to flow in the conductor.

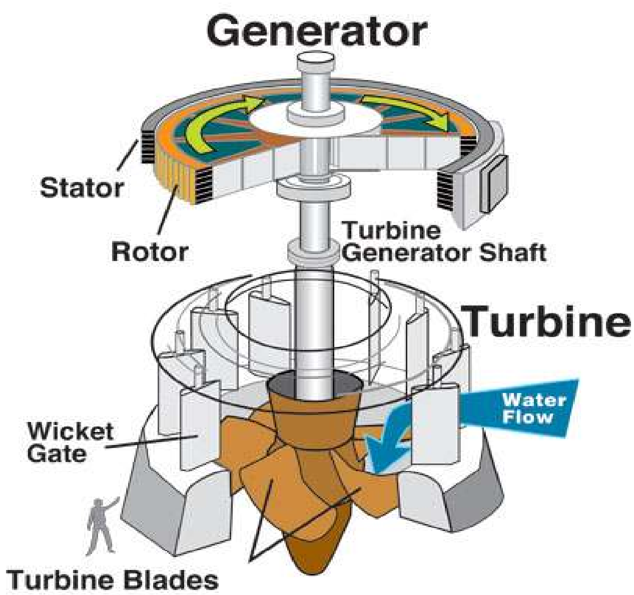


Figure 15 - Hydraulic turbine and electrical generator[4]

C - Pumped storage hydroelectricity

Pumped storage hydropower plants (Fig. 16) are a system of coupled reservoirs meant for load balancing. According to the pumped storage method, water, which is stocked in a lower reservoir located at the dam's outlet, is pumped back up to a higher reservoir. The pumping procedure is accomplished with the use of reversible turbine/generators assemblies, which function both as pump and turbine.

[4] Source: https://www.nwp.usace.army.mil/HDC/edu_genexcit.asp

The Francis turbines are most frequently used for this purpose. The pump-back procedure takes place mainly at night or over a weekend when there is an excess of electric load on the power network. Thus low cost off-peak electric power is used to pump the water. Although the electric and economic losses of the pumping procedure transforms the plant into a net energy consumer, the revenues from producing and selling excess electricity during periods of peak demand cover the pumping economic losses.

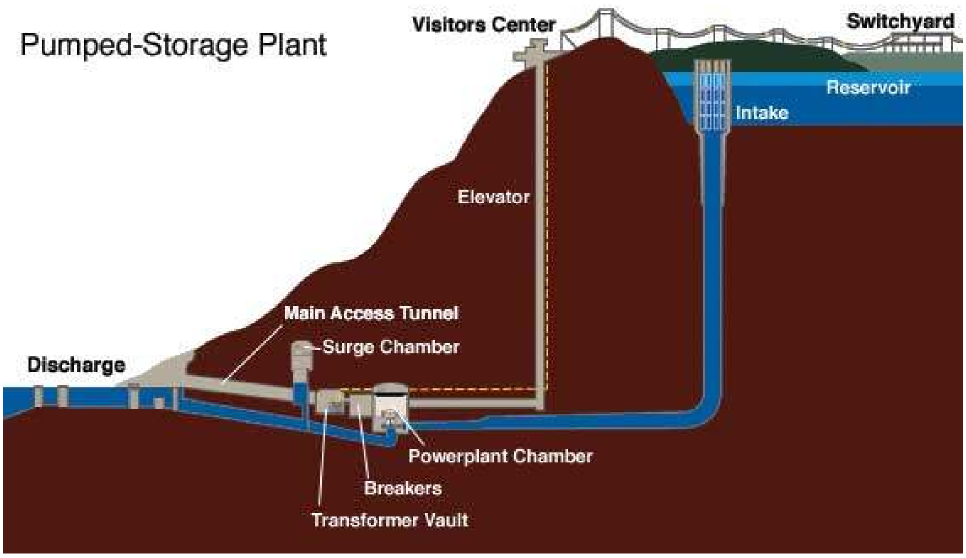


Figure 16 - Representation of a pumped-storage power plant[5]

The pumped storage hydroelectricity procedure is very efficient in terms of capacity. As much as 19.5 GW of pumped storage capacity were generated in United States in 2000, representing 2.5% of the national generated capacity (EIA, Annual Energy Review 2006[6]). In 1999 the EU had 32 GW capacity of pumped storage out of a total of 188 GW of hydropower, representing 5.5% of total electrical capacity in the EU.

The two existing dams on the Nestos, namely Thissavros and Platanovryssi are coupled using this system. It is planned that the future Temenos dam should be coupled to the upstream Platanovryssi dam in such a way. Pumped storage has many advantages but it is not easy to evaluate the advantages and to find out the characteristics which will lead to optimized pumping. One of these characteristics is the reservoir amplitude.

[5] Source: http://www.tva.gov/power/hydro.htm
[6] Source : http://www.eia.doe.gov/emeu/aer/pdf/pages/sec8_8.pdf

The required reservoir size fundamentally depends on expected operation of pumped storage, on the availability of pumping energy and on the duration of peak load (Nanahara and Takimito, 1994). Furthermore, there are cases where the off-peak load duration is limited or the peak load duration is too extended, thus the calculation of the optimum operation schedule of the pumped storage procedure during the two described cases involves linear programming methods (Jeng L.H. et al., 1996). New approaches based on neural networks have been proposed in order to determine an economical dispatching schedule for pumped storage hydroelectric plants (Liang R.H., 2000).

In all cases, the objective function to be minimized in hydro scheduling problem is the total fuel cost of thermal units and the practical constraints to be satisfied include power generation, load balance equations and available water limits, etc.

II-2-2 - Dam simulation

A – Initial developments of dam's simulation and optimization

In the 1930's, interest grew in estimating more accurately the quantity of water passing through a water power station. Until that time, calculations had been based on the nominal head capacity combined with the technical efficiency of the turbines and generators (Laurent, J., 1936). However, the efficiency of a turbine varies to a high degree with the load, so that this approach needed to be improved by a more accurate measurement of the flow passing through the turbines (Hartzell H., 1936). These accurate measurements were critical in order to maintain the stocked water in the reservoir at secure levels and prevent flood events, since the natural flow had been replaced with a regulated water discharge.

A few decades later in the early 70's, many detailed studies were conducted in an attempt to improve water resources systems, because of the enormous investments involved in their design and operation. Programming techniques, such as linear and dynamic programming, started to be used for optimum design and operation of water resource systems. However, these techniques were based on steady inflow and water demands and presented definite limitations when dealing with a natural stream flow with stochastic properties.

Further randomization of flow series using Monte Carlo techniques helped in this direction. Not only did they contribute to generate longer flow records than historical series, but also helped in estimating the probability of failure associated with any design or operational criteria (Askew A.J. et al., 1971). In addition, the problem of optimal planning of flows for a large number of relatively long time periods in multi-reservoir hydro-power systems was also addressed with the use of nonlinear programming techniques (Jacoby and Kowalik, 1971).

Finally, the optimization of the operation of a reservoir based on the coupling of reservoir simulation with hydrology was initiated in 1975. With this scheme, the first module is a system model which simulates and evaluates the operation of a reservoir system on a monthly basis for water supply, low flow regulation, power generation and recreation, with storage and release constraints for flood control. The second module is a catchment model which is usually meant for the simulation of short-time flow series meant to reproduce flood periods (Beard L.R., 1975). This coupled approach was initially tested on the operational optimization of the dam's complex in the Velika Morava basin in the former Yugoslavia (Djordjevic B. et al., 1975). It is nowadays the most common program structure adopted in dam simulation software.

B – The HEC-ResSim dam simulation program

The U.S. Army Corp of Engineers – Hydrologic Engineering Center developed in 1973 the HEC-5 program for the simulation of flood control and conservation systems. It was initially written for flood control operation of single flood events. The program was later expanded to multi-events floods and included basic water supply and hydropower analysis capabilities. Pumped-storage hydropower analysis capability was finally added in 1977. All versions were developed in FORTRAN and interfaced with the HEC-DSS data storage system.

HEC-5 recently evolved into the HEC-ResSim software with the addition of a graphical user interface (GUI). Its hydropower simulation capabilities include analysis of run-of-river generation, peak power generation, pumped storage and system power operation. To simulate hydropower operation, the reservoir releases are determined to meet power production goals which may vary on a monthly, daily, or hourly basis. Additionally, the hydropower component takes into account the penstock capacity and losses, as well as leakage parameters.

The model allows the user to define alternatives and run simulations simultaneously to compare results. Schematic elements in HEC-ResSim allow the representation of watershed, reservoir network and simulation data visually in a geo-referenced context that interacts with associated data. Additionally, HEC-ResSim is compatible with ArcGIS shape files, which can be used as a background layer and facilitate the better representation of the physical system. Watershed boundaries, reservoirs, channel networks, diversions, etc. can be superimposed over the shape file.

The HEC-ResSim program is divided into three modules (Fig. 17) which are respectively, the watershed setup, the reservoir network definition and the simulation scenario management.

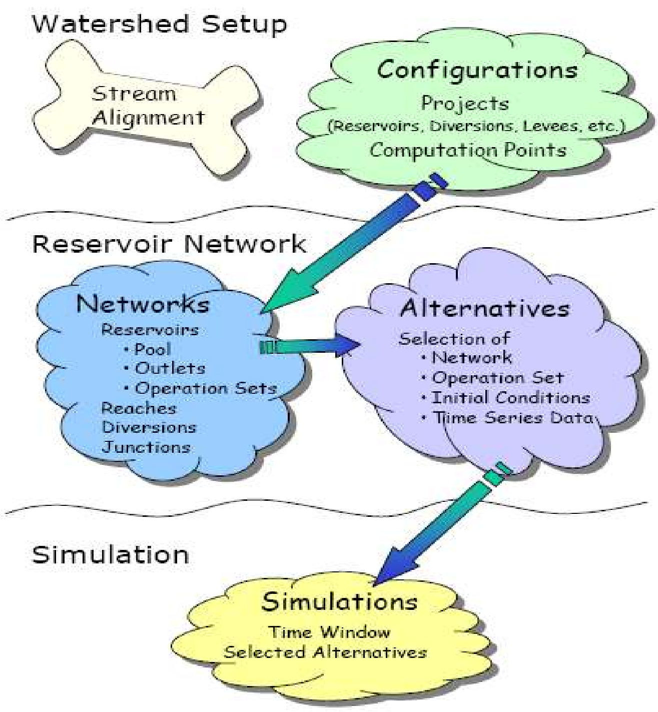


Figure 17 - Graphical illustration of the HEC-ResSim modules

- **Watershed setup**

The purpose of this module is to provide a common framework for watershed creation and definition. A watershed is associated with a geographic region for which multiple models and layers of information (idem, area coverages in ArcGIS) can be configured. A watershed may include all of the streams, projects, e.g., reservoirs, levees, gage locations, impact areas, time-series locations, and hydrologic and hydraulic data for a specific area. All of these details together, once configured, form a watershed framework.

- **Reservoir network definition**

The purpose of the Reservoir Network module is to isolate the development of the reservoir model from the output analysis. This module facilitates the creation of the network schematic, the description of the physical and operational elements of the reservoir model, and the definition the management alternatives to be analyzed. Reservoirs are further divided into multiple technical elements such the pool, the dam, and one or more outlets. The criteria for reservoir release decisions are drawn from a set of discrete pool heights, power production levels and release rules. Reservoirs are connected to the river network as well diversions or junctions. After finalizing the connection network schematic, physical and operational data for each network element are defined. Management alternatives are created to compare results using different model schematics, i.e. physical properties, operation sets, inflows, and/or initial conditions.

- **Simulation scenario management**

The purpose of the Simulation module is to isolate the output analysis from the model development process. Once the reservoir model is complete and the alternatives have been defined, the Simulation module enables the model to test various river flow hypotheses.

II-3 - **Climate models**

II-3-1 - Climate change concepts

The origins of the climate change concept can be dated back to the end of the 19^{th} century when the Swedish scientist Svante Arrhenius was interested in investigating what caused the end of the prehistoric ice ages (Weart S.R., 2004). He made speculated that gases in the atmosphere and especially carbon dioxide (CO_2) emitted from huge volcano eruptions, might have trapped the heat received from the sun which resulted in the augmentation of the global temperature and the end of the ice age. The entrapping of the Earth emitted heat by atmosphere gases is now known as the “greenhouse effect”.

In the late 1970s, concerns was expressed during the first “World Climate Conference” organized by the World Meteorological Organization (WMO) that “continued expansion of man’s activities on Earth may cause significant extended regional and even global changes to the climate” (IPCC Anniversary Report, 2004). At the same time, scientists revealed that apart from CO_2, other gases such as methane, emitted both by natural processes and human activities, strongly participate in the greenhouse effect.

In order to characterize climate parameters such as temperature, CO_2 concentrations and precipitation fluctuations over time, both direct measurements and indirect parameters have been used. Although reliable air temperature records near the Earth’s surface based on observations from thermometers are available back to about 1850, accurate precipitation records are available back to the beginning of the 20^{th} century, and CO_2 observations have been recorded since 1950 only. In the latter case the amount of available measurements is considered chronologically inadequate to evaluate the climate of previous decades. In order to compensate for this lack of information, indirect parameters also known as “proxy data” such as observations of ice cores and tree rings (Jacoby G.C. et al., 1997) are used in order to retrieve historical records and consequently expand our knowledge for the climate of previous centuries.

Evidence on the correlation between variations in the CO_2 concentration in the atmosphere and the Earth’s atmosphere temperature have only been confirmed since the middle 1980s after experimental measurements occurred in ice cores.

In particular, in 1985 during ice core experiments at Vostok Station in Central Antarctica, an ice core two kilometers deep representing a 150,000 years climate record was extracted (Weart S.R., 2004). Even though atmospheric CO_2 concentration was found to be of the same proportions as current records, the principal outcome of the experiment was that the CO_2 level had remarkably similar variations as that of the temperature deduced from measurements of the concentration in deuterium isotope (Fig. 18).

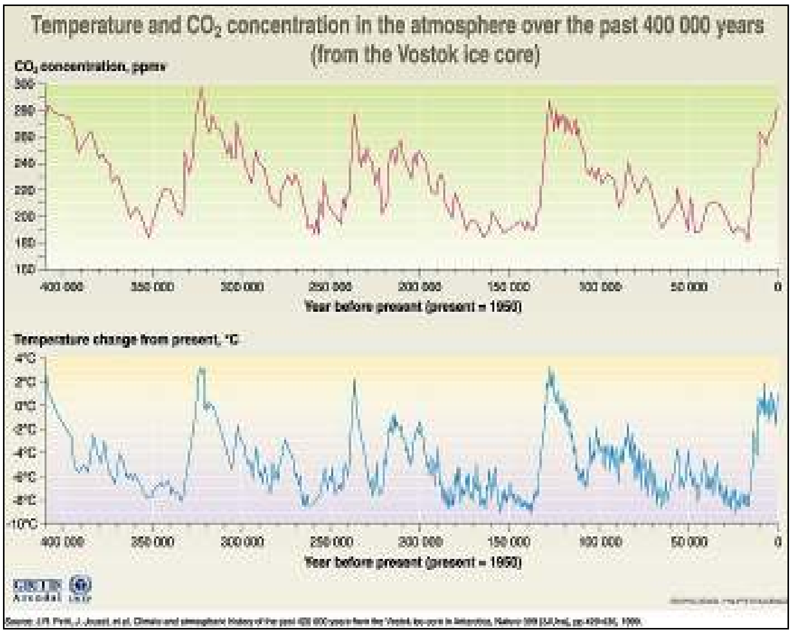


Figure 18 - Correlation between CO_2 concentration (in parts per million) and temperature (in Degree Celsius) the last 400,000 years (Pelit et al., 1999)

The experimental result convinced the scientific community that CO_2 augmentation due to human activities could be responsible for the recent rise of the temperature and thus drive changes in climate. Furthermore, scientists concluded that past climate data may no longer be a reliable guide for the future. It was decided that a coordinated international program was needed to collect systematic climate observations of present conditions, and to produce simulations of future climate conditions.

The World Meteorological Organization (WMO) is a specialized agency of the United Nations which was established in 1950 and has a network of 188 member states and territories. Thus WMO plays an important role in weather meteorology, climatology, hydrology and aeronomy observation, as well as in understanding the climate processes. This is done through the network of National Meteorological and Hydrological Services of its members. Other agencies are involved in global climate understanding such as the Computational and Information Systems Laboratory (CISL) Research Data Archive from the National Center for Atmospheric Research (NCAR) in the USA. It contains a large and diverse collection of meteorological and oceanographic observations, remote sensing datasets, along with ancillary datasets, such as topography/bathymetry, vegetation, and land use in order to support and facilitate atmospheric and geosciences research. Currently, climate observations are derived from about 7,300 monthly mean temperature stations, 5,100 monthly mean maximum and minimum temperature stations (Peterson T.C. et. al., 1998), and 6,700 rain gauge stations world wide (Global Precipitation Climatology Project data). Additionally, since the initial inception of satellite-based remote sensing technology in the 1970s, 15 meteorological satellites have been used. International cooperation in the field of oceanography as also brought the observations at sea from 100 moored buoys, 600 drifting buoys, 3,000 aircraft and 7,300 ships (WMO data). All measured data are nowadays stored in homogeneous form and are subject to quality control tests for reliability assessment (Peterson T.C. et. al., 1998).

The International Satellite Land Surface Climatology Project (ISLSCP) established by the World Climate Research Program (WCRP) is also investigating the land-atmosphere interactions and aims at producing global datasets (Schiffer and Rossow, 1983). Studies of energy, water, and biogeochemical cycles have been produced over the whole globe with a spatial resolution of 0.5 and 0.25 degrees since 1987. In particular, the Global Precipitation Climatology Project (GPCP) was established by WCRP to address the problem of quantifying the synoptic distribution of precipitation around the globe over a long period. The coupling of surface precipitation records with remote sensing data produced global precipitation datasets from 1979 to 2008 over a regular grid with a spatial resolution of 2.5 degrees.

The observed climate data obtained from the many sources mentioned above is used in climate simulation models both to define forcing conditions (idem, initial boundary conditions) and as reference data in order to conduct verification tests.

II-3-2 - The IPCC and its global change scenarios

Apart from coordinated efforts in climate data and dissemination, an intergovernmental mechanism has been set up in order to provide scientific assessments of climate change. The United Nations Environmental Program (UNEP) and WMO created in 1988 the Intergovernmental Panel on Climate Change (IPCC). The goals of the IPCC are related to the following topics:

- Identification of uncertainties and gaps in our present knowledge of climate change and its potential impacts, and preparation of a plan of action over the short- term in filling these gaps.
- Identification of information needed to evaluate policy implications of climate change and response strategies.
- Review of current and planned national/international policies related to the greenhouse gas issue.
- Scientific and environmental assessments to be transferred to governments and intergovernmental organizations as guidance in their policies on social and economic development and environmental programs.

Since its creation, IPCC has regularly prepared assessment reports on available scientific information on climate change and has proposed possible response strategies. The First IPCC Assessment Report (FAR) was presented in 1990 and was devoted to creating an inventory of climate change. The Second Assessment Report (SAR) was presented in 1995 and was coupled with the initial Special Report on future Emissions Scenarios (SRES). The future emission scenarios, also known as IS92, were subsequently used in climate simulation models in order to quantitatively assess their impacts. A follow-up Third Assessment Report (TAR) was presented in 2001 and the updated version of the SRES scenarios of the TAR were definitely adopted in the Fourth Assessment Report (AR4) which was presented in 2007.

The SRES scenarios have been developed to describe the effect of future human activities on the evolution of greenhouse gases emissions to be used as input data in climate simulation models, also known as Global Climate Models (GCM). The SRES scenarios describe at a global scale the relationships between the forces which may drive greenhouse gas and aerosol emissions and their evolution during the 21st century. A set of 40 scenarios have been regrouped into four storylines labeled A1, A2, B1 and B2.

Each storyline presents a possible set of demographic, social, economic, technological, and environmental developments. All the scenarios based on the same storyline constitute what is called a scenario "family" (ex: A1FI, A1T, A1B). The storylines are organized in four narrative storylines, as follows:

The A1 storyline and scenario family describes a future world of very rapid economic growth, a global population which peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. Subsequently, the A1 storyline group divides into three possibilities based on a particular technological emphasis: fossil energy intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). A1B balanced will be considered in this study, as it defines the situation of not relying too heavily on one particular energy source, and on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than for other storylines.

The B1 case describes a convergent world with a global population peaking in mid-century and declining similarly to the A1 storyline. But a rapid change in economic structures in envisioned toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, with intermediate levels of economic development, and slower and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The global CO_2 emissions for the six SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T are presented in Figure 19. The IS92a scenario derived from the Second assessment Report (SAR) is also presented. Obviously, the most optimistic scenarios are A1T and B1 where clean energy technologies are developed. One the other hand, the scenarios A1FI and A2 demonstrate a huge increase of CO_2 emissions since the economic development is not coupled with environmental friendly policies and technologies.

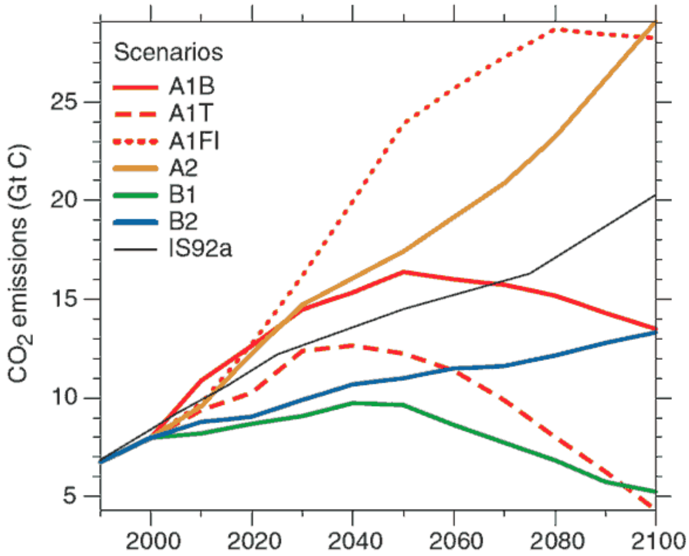


Figure 19 - CO_2 emissions of the TAR SRES scenarios A1B, A2, B1 and B2, A1FI and A1T.

The SAR SRES scenario IS92a is also shown (IPCC, 2001)

For the needs of my work on the Mesta-Nestos basin, the A1B, A2 and B1 scenarios have been selected and the corresponding climate simulation models results concerning temperature and precipitation records have been used in order to evaluate the impacts of climate change on the basin hydrologic regime.

It should be noted that the developing potential of the Mesta/Nestos basin region bears many similarities with the evolution described by the A1B and B1 scenarios. According to demographic statistics, both the Bulgarian part and the Greek part of the basin could experience an increase in population growth. Future economic growth is also expected.

In the Bulgarian part, apart from the injection of new EU funds dedicated to the region's infrastructures improvement, a number of investments in tourism activities are expected to help the local economy. In the Greek part of the basin, a number of private and public investments and the further exploitation of the agricultural potential of the region, suggest a lasting prosperity. On the other hand, both Bulgaria and Greece as EU members are obligated to implement environmental protection policies such as those stemming from the Kyoto protocol. In particular, the European Union has specified a target of 20% of its electricity consumption to be generated by renewable resources by 2010. This future development of clean and resource-efficient technologies is similar to the one hypothesized in the A1B and B1 scenarios. The A2 scenario which describes a much more pessimistic evolution has also been investigated in our work in order to evaluate the impacts in the Mesta/Nestos region under the worst possible conditions.

According to the results of the climate change models using the amount of CO2 emissions described in the six SRES scenarios as input data, the globally averaged surface temperature is predicted to increase by 1.4 to 5.8°C over the period 1990 to 2100 (Fig. 20). These temperature increases are estimated to be greater than those predicted in the SAR scenarios, which were about 1.0 to 3.5°C based on six IS92 scenarios. In Figure 19, the light gray shading represents the range of results for the 40 SRES scenarios taken separately, while the darker shading indicates the range of the temperatures obtained for seven specific storylines including IS92.

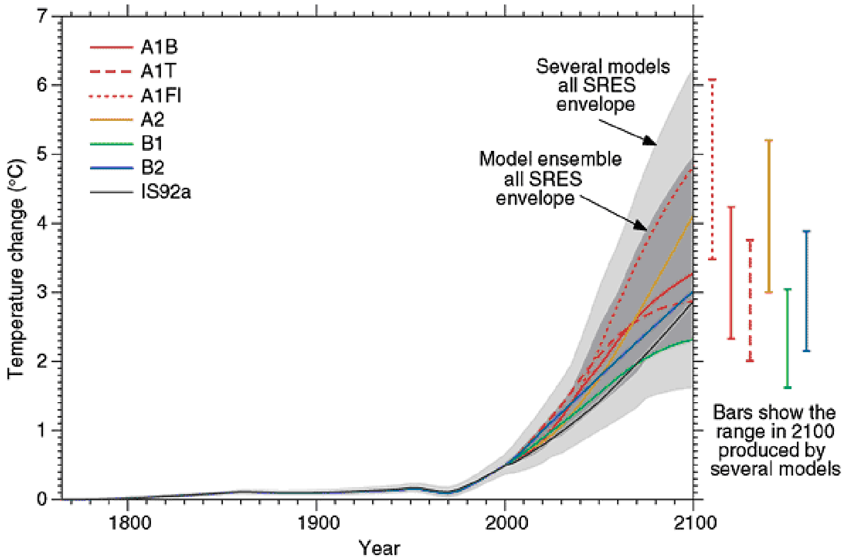


Figure 20 - Global mean temperature projections for the six SRES scenarios and the SAR - IS92a scenario (IPCC,2001)

The simulation results from global models (GCM) also indicate that the global predicted average water vapor concentration and precipitation should increase during the 21st century in the North Hemisphere and particularly in mid-high latitudes. At lower latitudes, the changes are less likely to be so large. Year to year variations in precipitation are also predicted to increase.

II-3-3 - Global climate models

A - Weather prediction models

Nowadays, weather prediction is based on a representation of the physical laws governing the atmosphere's behavior by mathematical equations. These are derived from the latest advances in fluid dynamics, thermodynamics and laws of motion. However, these non-linear partial differential equations can only be solved using approximate numerical solutions. These solutions are very sensitive to the correct setting of initial boundary equations.

These initial conditions, also known as “forcing” conditions, are deduced by actual measurements of temperature, humidity and wind speed fields. Weather prediction models work on a discrete grid which covers the whole Earth with a typical grid cell size of a few degrees. Thus “forcing” fields need to be “discretized” over the same grid using appropriate interpolation techniques.

One critical point about weekly weather prediction models is that they need to include the whole Earth atmosphere in their solution. For shorter time prediction, from several hours to about two days, simplified methods can be used such as the Limited Area Models (LAM), i.e. models used for weather predictions in local areas such as a national territory. They can produce detailed short range forecasts and are usually more computationally efficient. However, their forcing conditions (idem, boundary conditions) are influenced by the atmospheric conditions outside the area of interest and thus need to use global model results. This is the reason why global weather prediction models are a necessity. It is particular the case of the European Centre for Medium Range Weather Forecasts (ECMWF) model which is supported by 31 Members, in order to produce medium-range weather forecasts for distribution to the national meteorological services in Europe.

B - General Circulation Models

Climate simulation is conducted at a global scale using General Circulation models. Historically these models have been conceived to simulate the behavior of either the atmosphere or the ocean. More recently, these tools have been merged into atmosphere-ocean coupled general circulation models (AOGCM). However Global Climate Models (GCMs) such as those required to investigate the IPCC SRES scenarios need a more complete integrated approach with further coupling with other components, such as sea-ice, land-surface processes and chemical transport modeling.

General Circulation model solutions are based on a three dimensional grid which covers the globe (Fig. 21). These grids have typically a horizontal resolution of between 250 to 600 km with 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 underwater layers in the oceans (IPCC Task Group on Scenarios for Climate and Impact Assessment-TGICA). By adding the time dimension to the three spatial dimensions, these models can be considered as four dimensional.

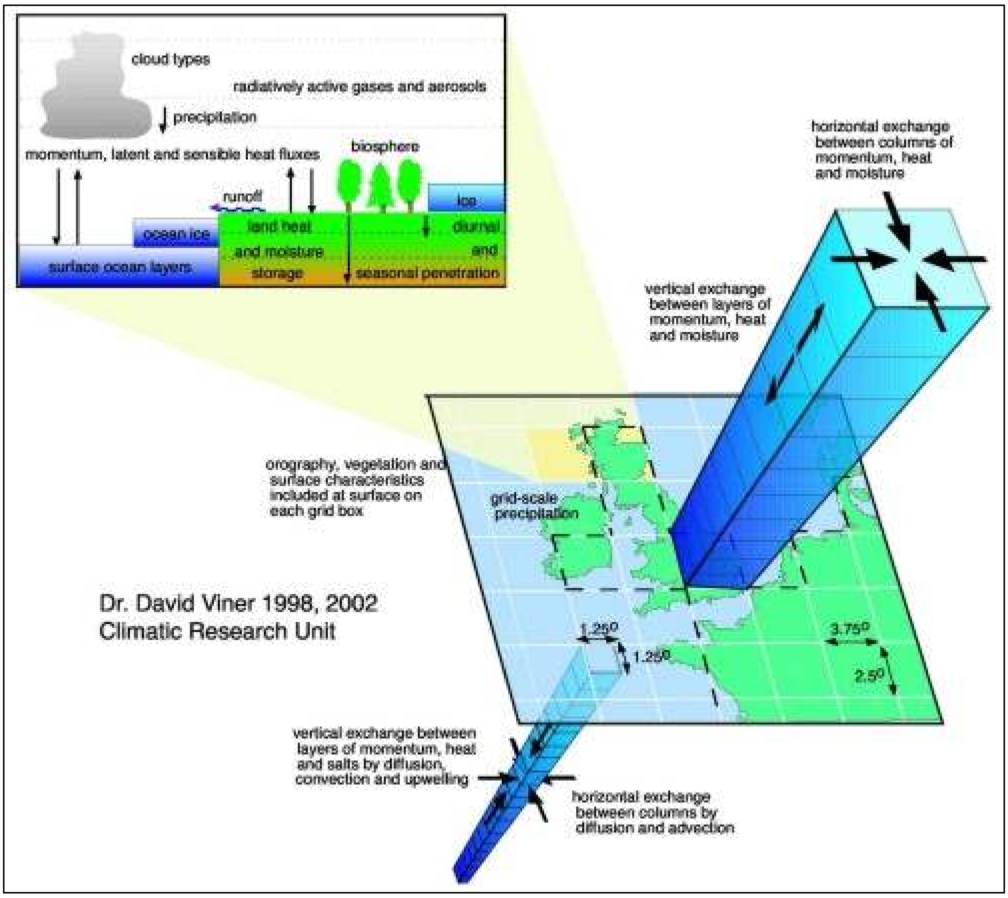


Figure 21 - Conceptual structure of a coupled atmosphere-ocean general circulation model. (Source: Viner and Hulme, 1998)

Grid types and sizes differ from model to model and depend upon the numerical method used to solve the climate equations. Two dominant techniques are implemented using either a finite difference method or a spectral method. In the case of finite difference methods, the grid can either be regular in latitude and longitude or they can use variable resolution cells. However in this case the gridlines converge towards the poles and in order to avoid computational instabilities, the model variables need to be filtered along the gridlines of latitude close to the poles. Spectral models are based on Gaussian grid systems which are determined by the type of analytical representation of the fields. They can use either triangular truncation (type T), or rhomboidal truncation (type R) or even Legendre polynomial truncation (type N). Near the poles, spectral models do not suffer from the same drawbacks as finite difference models do. However, the majority of AOGCMs mix both grid forms with a spectral method for the Earth surface dimensions while a finite difference method is used for the vertical axis.

C - The ECHAM series of global circulation models

The assessment of the possible effect of climate change on the hydrology of the Mesta/Nestos river basin has been conducted using precipitation results from two GCMs both developed by the Max Planck Institute for Meteorology in Hamburg:, the ECHAM4/OPYC3 and the ECHAM5/MPIOM coupled models.

ECHAM4 is an atmospheric Global Circulation model which has been developed from the initial ECMWF model code (therefore the first part of its name: EC) into a fully parameterized climate simulation package by the Max Planck Institute for Meteorology in Hamburg (therefore the abbreviation HAM). It is a spectral model using a T42 Gaussian grid with spatial resolution equivalent of 2.815° longitude × 2.815° latitude and a stack of 19 atmospheric layers (L19). The time-step of the model is 24 minutes, except for radiation which uses two hours.

In ECHAM4 (Roeckner E., et. al. 1992) the forcing conditions are defined as follows:

- The temperatures and sea conditions are taken from the COLA/CAC AMIP sea surface temperature and sea-ice data set.
- The mean terrain heights are computed from the high resolution US Navy data set.
- The fraction of grid area covered by vegetation is based on the Wilson and Henderson-Sellers (1985) data set
- The ocean albedo is a function of solar zenith angle and the land albedo is deduced from the satellite data of Geleyn and Preuss (1983).

The ocean model is an updated version of the isopycnal model (OPYC3) which was developed at the Max-Planck-Institute for Meteorology in Hamburg, Germany (Oberhuber J.M., 1993). It is based on the hypothesis of a conservative fluid. As this can only be representative of the deep ocean below the thermocline, a surface mixed-layer is modeled separately in order to improve the response time-scales to atmospheric forcing. A sea ice model is included and serves the purpose of de-coupling the ocean from extreme high-latitude winter conditions and provides a realistic treatment of salinity forcing due to melting and freezing in polar areas.

The ECHAM5 model (Roeckner E. et. al., 2003) is an updated version of the ECHAM4 spectral model using a T21 Gaussian grid with a spatial resolution equivalent of 5.6° longitude × 5.6° latitude and 19 atmospheric layers (L19). It is coupled with the MPIOM ocean-sea ice component (Roeckner E. et al., 2006; Jungclaus et al., 2006). MPIOM is a simplified equation model (C-Grid, z- coordinates, free surface) using hydrostatic and Boussinesq fluid hypotheses. It is an improvement from OPYC3 as it is modeling the ocean in one piece. In standard configuration it has 40 vertical levels, with 20 in the upper 600m. The horizontal resolution of MPIOM gradually varies between a minimum of 12km close to Greenland and 150km in the tropical Pacific.

The ECHAM5/MPIOM model has been adopted by IPCC as one of the models used for the simulation of the SRES scenarios of the Fourth Assessment Report (AR4). The precipitation results which it produced for the SRES A2 scenario produced have been used over the Mesta-Nestos basin.

D – The use of GCMs in hydrology modeling

Efforts in coupling GCMs and hydrology modeling at global scale have been promoted by the Global Energy and Water Cycle Experiment (GEWEX). GEWEX is a program initiated by the World Climate Research Program (WCRP) in order to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere, at land surface and in the upper oceans. GEWEX aims to reproduce and predict the variations of the hydrological regime at a global scale as well as the variations in hydrological processes and water resources at a regional scale under the scope of climate change. As the models developed in the framework of this project are in need of global precipitation and evaporation data, it is also linked to the Global Precipitation Climatology Project (GPCP).

In particular, the coupling of the Interface Soil Biosphere Atmosphere (ISBA) surface scheme with the hydrologic model MODCOU for the Rhone river basin (Habets F. et. al., 1999) is an example of an outcome of the GEWEX project.

II-3-4 - The simulation of local climate change

The results obtained from GCMs are very useful for evaluation of potential climate changes at a global scale. However, due to their coarse spatial resolution, they do not adequately take into account the local land surface characteristics, e.g. the topography. Thus specific methods need to be developed in order to adequately transfer the GCMs results at regional scales. They are known as "downscaling" techniques. They have initially been applied to study the impacts of climate change in the hydrology and agriculture of specific regions (Wilks and Wilby, 1999). Since then, a significant number of downscaling techniques have been developed which can be divided mainly into statistical and dynamical methods.

A - Statistical downscaling methods

Statistical downscaling involves the development of analytical relationships between large scale atmospheric variables, also known as predictors, and local surface variables, also known as predicands. Statistical downscaling techniques are classified into three general categories: weather generators, transfer functions, and weather typing.

Weather generators

A weather generator is a statistical model which generates time series of artificial weather data with the same statistical characteristics as the observations of a particular station or group of stations (Wilks and Wilby, 1999). The main advantage of the technique is that it can easily produce a large number of similar climate sequences and it has been widely used, particularly for agricultural weather impact assessment. Some weather generators are specialized in the representation of precipitation occurrence via Markov processes for wet-day/dry-day transitions. Auxiliary variables such as wet-day amounts, temperatures and solar radiation are often modeled conditionally on the precipitation occurrence (Wilby R.L., et al., 2004). For example, a weather generator has been used to simulate the precipitation changes in southeast Australia due to global warming (Watterson I.G., 2005).

Transfer functions

Transfer function downscaling methods rely on empirical relationships between predicands and predictors. The more common transfer functions are derived from linear and non–linear regression, artificial neural networks and canonical correlation analysis. The main strength of transfer function downscaling is its relative ease of application. The main weakness is that the models often explain only a fraction of the observed climate variability, especially in precipitation series. Transfer methods also assume a long term stability of the model parameters under future climate conditions. For example, an application of automated regression-based statistical technique has been applied to reconstruct the observed climate in eastern Canada (Hessami M., et al., 2008). This technique was inspired by the SDSM (Statistical Downscaling Model) software (Wilby R.L., et al., 2002). SDSM facilitates the rapid development of multiple scenarios of daily surface weather variables under present and future climate forcing.

Weather typing

Weather typing involves the grouping of local meteorological data in relation to prevailing patterns of atmospheric circulation at the global scale. They are founded on possible linkages between climate on the large scale and weather at the local scale. Their most serious limitation lies in the fact that precipitation changes produced by changes in the frequency of observed weather patterns are seldom consistent with the changes produced by the GCM generated weather patterns unless additional predictors such as atmospheric humidity are employed.

Statistical downscaling techniques are routinely used in order to evaluate water supply, agricultural production, environmental and social impacts to climate change at the regional scale, such as in the San Joaquin River Basin (Quinn N.W.T., et al., 2004). On the other hand, investigations are under way about the uncertainty in catchment-scale precipitation scenarios due to these downscaling methods (Vidal and Wade, 2008)

B - Dynamical downscaling with the Max Plank Institute CLM model

Dynamical downscaling occurs when the results produced by a Global Circulation Model (GCM) are used as boundary conditions (idem, "forcing") to dedicated Regional Climate Models (RCM) (Mearns L.O., et al., 2003). In my area of study, namely Greece and Bulgaria, predictive climate models which are constrained by local meteorological measurements do not yet exist, therefore the European scale CLM regional climate model has been used for dynamic downscaling.

CLM, which stands for Climate version of the "Local Model" (CLM), is a non hydrostatic European region climate model which can be used for simulations on time scales up to centuries and spatial resolutions between 1 and 50 km. The boundary conditions of the CLM are provided by the simulation results of the coupled atmosphere-ocean global climate model ECHAM5/MPIOM at 6 hours interval (see previous section).

The CLM regional climate model covers the west European region including the Baltic Sea and the most part of the Mediterranean Sea. For the European region two simulation datasets have been produced for IPCC scenarios investigation: one covers the present climate, i.e. from 1960 to 2000, and the other cover future predictions, i.e., from 2000 to 2100. The present climate of the 20^{th} century is simulated by three 20^{th} century realization runs, which are all based on the same control run, but set off at different initialization times. The climate of the 21^{st} century is modeled based on the A1B and B1 IPCC climate scenarios, and five more transient experiments are planned, since the result generation is still in progress. Scenario A1B connects to three and scenario B1 to two realization runs of the 20^{th} century climate. The CLM characteristics are illustrated in Table 4.

Data compilation	Model and Data Group (M&D) at MPI for Meteorology, Hamburg	
Model	CLM 2.4.11 (Climate mode of the Local Model of the DWD)	
	Dynamic model; drive: ECHAM5, non-hydrostatic	
Model region	Europe	
Simulation period	from 1960 to 2100	
IPCC emission scenarios	A1B, B1 (from 2001)	
Resolution	0.165° (data stream 2), 0.2° (data stream 3); approx. 20 km	
Structure	Rotated model grid (data stream 2 = DS2) or	
	Regular lat/lon grid (data stream 3 = DS3);	
Data format	netCDF or ASCII format	

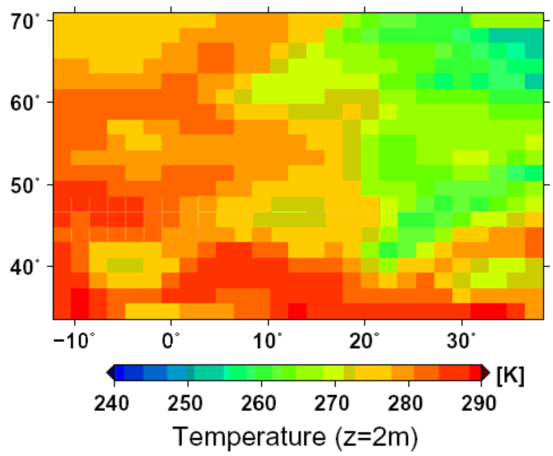
Table 4 - Synopsis of the CLM characteristics

The variables defining the boundary conditions (idem, "forcing" for CLM are interpolated as two-dimensional near surface fields and three dimensional soil and atmospheric fields, respectively. The soil fields are simulated on 10 different levels with a maximum depth of 15 meters. The atmospheric fields are given at 6 pressure levels (200, 500, 700, 850, 925 and 1000 hPa). The time interval of the output series ranges from 1 to 3 hours and includes daily output averages, depending on the respective variables. The overall output data of the CLM regional model is provided in netCDF format and is generated at two spatial resolutions (Table 5): a 0.165° spatial resolution on a rotated Gaussian grid (data stream 2) and a 0.2° spatial resolution on a regular geographical grid (data stream 3). My simulation work in the Mesta/Nestos basin has been conducted with the use of the latter.

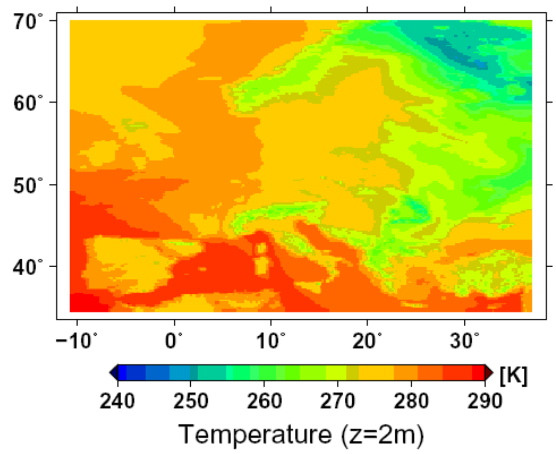
Parameters	Simulations	
Horizontal resolution	0.165º (data stream 2)	0.2º (data stream 3)
Simulated period	1960-2100	1960-2100
Initial-/boundary data	ECHAM5/MPI-OM1; 6 hourly	
Region [lat/lon]	center of grid cell	center of grid cell
North Pole	39.25 / -162	90. / 0
Lower left corner	20.8725 / -23.7275	34.6 / -10.6
Upper right corner	21.0375 / 15.8725	69.8 / 36.8
Number of grid points [lat/lon]	241/255	177/238
Number of vert. atm. layers	32	32

Table 5 - CLM model grid characteristics

A comparison has been carried on the temperature fields generated by ECHAM5/MPIOM and CLM for a same time and date (Fig. 22). The output clearly illustrates that CLM provides more spatially refined results than the ECHAM5/MPIOM model. A further analysis of the data also reveals that the average temperature produced by CLM on the whole domain is lower than that calculated by GCM. A linear least-square regression indicates a bias of about –2.5 K. For total accumulated precipitation, which is the sum of convective and large scale rain (intensive rainfalls both in duration and area coverage) plus snow fall, the average of the differences between CLM and ECHAM5/MPIOM values reveal also a positive bias of about 1 mm/day, i.e. CLM simulates more precipitation than the GCM.



a) Results from ECHAM5/MPIOM



b) Results from CLM

Figure 22 – Comparison of temperatures computed for a 2 meters height by a GCM and an RCM over Europe on 01-07-1984 at 06:00h

II-3-5 – Existing climate change studies in the area of investigation

For several years the subject of climate change and its influence on the area of south west Bulgaria (Alexandrov and Genev, 2003) and the Mesta in particular (Grunewald K. et al., 2008) have been investigated on the various aspects of mountain forest ecology and water resources.

The investigation of climate change scenarios in order to evaluate their possible impacts on the hydrology potential of the territory of Greece was initiated in the early 1990s. The Goddard Institute for Space Studies (GISS) model for carbon dioxide doubling was coupled with the US National Weather Service River Forecast System (NWSRFS) model in order to study the hydrological regime of the Messoshora mountainous catchment in central Greece. The results revealed a probable decrease in average snow accumulations as well as in average spring and summer runoff with an increase in winter runoff (Panagoulia, D., 1992).

A similar study followed in the late 1990s over central Greece. It predicted a decrease in stream flow and an increase of the temperature (Mimikou M., et. al., 1999). The climate change scenarios outputs used were derived from two GCM-based models produced by the UK Meteorological Office, respectively: HadCM2 and the UK Meteorological Office High Resolution model (UKHI). The hydrologic modeling was carried out with the WBUDG conceptual model.

At the same time, a more local study was conducted on the impacts of climate change on reservoir storage capacity and hydroelectric production of the Polyfyto dam on the Aliakmon River was realized (Mimikou and Baltas, 1997). Two scenario results were derived from the UKHI and the Canadian Climate Centre model. It was speculated that depending on the GCM used, a diminution of respectively 12% and 38% could occur on the long run during the 21st century. More recent results using the same methods (Baltas and Mimikou, 2005) have confirmed these results.

Another local study has also been published about the impact of climate change on several critical water quantity and quality issues was accomplished in the Ali Efenti Basin, also situated in central Greece. A decrease in stream flow and an annual reduction of the nitrogen flux to the water body have also been predicted (Varanou E. et al., 2002).

Similar studies have also been conducted in the mountainous region of southwestern Bulgaria. One of them involved the coupling of a GIS-based distributed hydrologic model and two climate change scenarios run by the HadCM2 and CCC models. This study demonstrated a possible seasonal drift of the maximum runoff period of several months from end of spring to the beginning of the spring. However, the mean annual runoff could remain stable (Chang H. et al., 2002).

III – MODELLING THE MESTA-NESTOS BASIN

III-1 – **Hydrology data management**

Data management in hydrology is an issue of importance as it is the basic preliminary phase before initiating any project. When "modern" hydrology first began in the early 1950s, data management meant a form of standardization of the information to be recorded. Later on, with the emergence of computer technology in the early 1970s, it evolved toward the development of methods for data organization, digitization of data using punched cards and storage in file systems. Currently, managing information on the quality and quantity of water information in order to understand hydrological processes lends itself to automated computer techniques. Database management and geographic information systems are nowadays linked to automated analytical tools such as statistical packages, surface and ground water models, and various spatial analysis modules.

III-1-1 - Historical evolution of hydrology data management

In the beginning of modern hydrology the aim of data management was the standardization of the hydrologic measurements which needed to be recorded (Smetana J., 1951). The main concern at that time was the definition of a common "strategy" for recording data. These standards were meant to facilitate data exchanges such as in the case of transboundary water bodies or when comparing different geographic regions.

In the 1970s the development of computer technology changed the perception of computing capabilities and furthermore the concept of data management. Information was initially stored in data files on disk or most often on magnetic tapes. Before storage, data needed to be normalized and prepared for transfer in digital form via punched cards (Fig. 23). Thus, the data management concept changed from the standardization of the hydrologic characteristics to storage of those measurements.

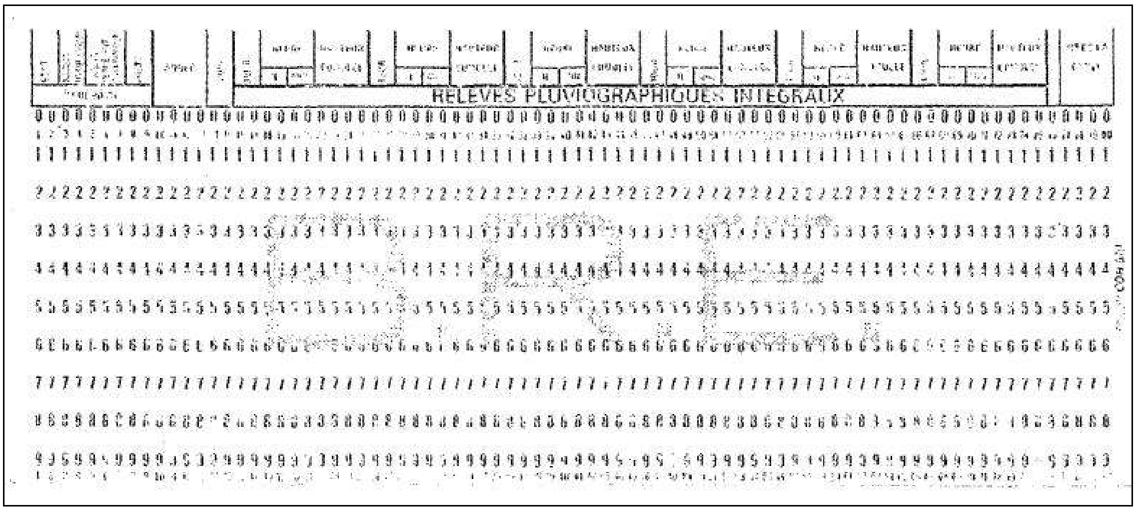


Figure 23 - The normalized punched cards selected by the Hydrological Service of ORSTOM in order to store data from rainfall records (Girard and Chaperon, 1971)

Since then the progress in software and data base structures has considerably modified the methods and procedures for managing hydrologic data. New techniques have been developed for estimating missing portions of hydrologic records or generating synthetic hydrologic data (Beard L. R., 1972) using computer programs and statistical methods. In terms of data management challenges have shifted to the data handling of hydrologic parameters at a global scale and in data bridging between the myriads of computer software and models which have been developed both in hydrology and climatology.

III-1-2 – The HEC-DSS hydrologic database

The Hydrologic Engineering Centre of the U.S. Army Corps of Engineers has developed the Hydrologic Engineering Centre Data Storage System, or HEC-DSS. This software has been used for the Mesta-Nestos basin study. It is a database system designed to efficiently store and retrieve scientific data that is typically sequential. HEC-DSS not only permits the plotting, tabulation and editing of data, but also the manipulation of stored data using a collection of mathematical functions.

HEC-DSS was initially conceived as a response to the needs which emerged in the late 1970s. At the time the passing of data from one analysis program to another was functional but not productive, since it was mostly accomplished in manual mode.

In particular, the fact that each program had its own data format, the passing over of data from one program to the next proved to be time consuming. Thus, the initial version of HEC-DSS provided an orderly approach to the proper management of input data and the analysis of the results.

The basic concept underlying HEC-DSS is the organization of data into records containing a series of values of a single variable over a particular time span. Each record is identified by a unique name called a “pathname” and along with the data it holds descriptive information about the nature of the data, such as units or time intervals (Fig. 24). Furthermore, data stored in HEC-DSS are compatible with the application modules developed by HEC such as HEC-HMS for hydrologic simulation and HEC-ResSim for dam simulation.

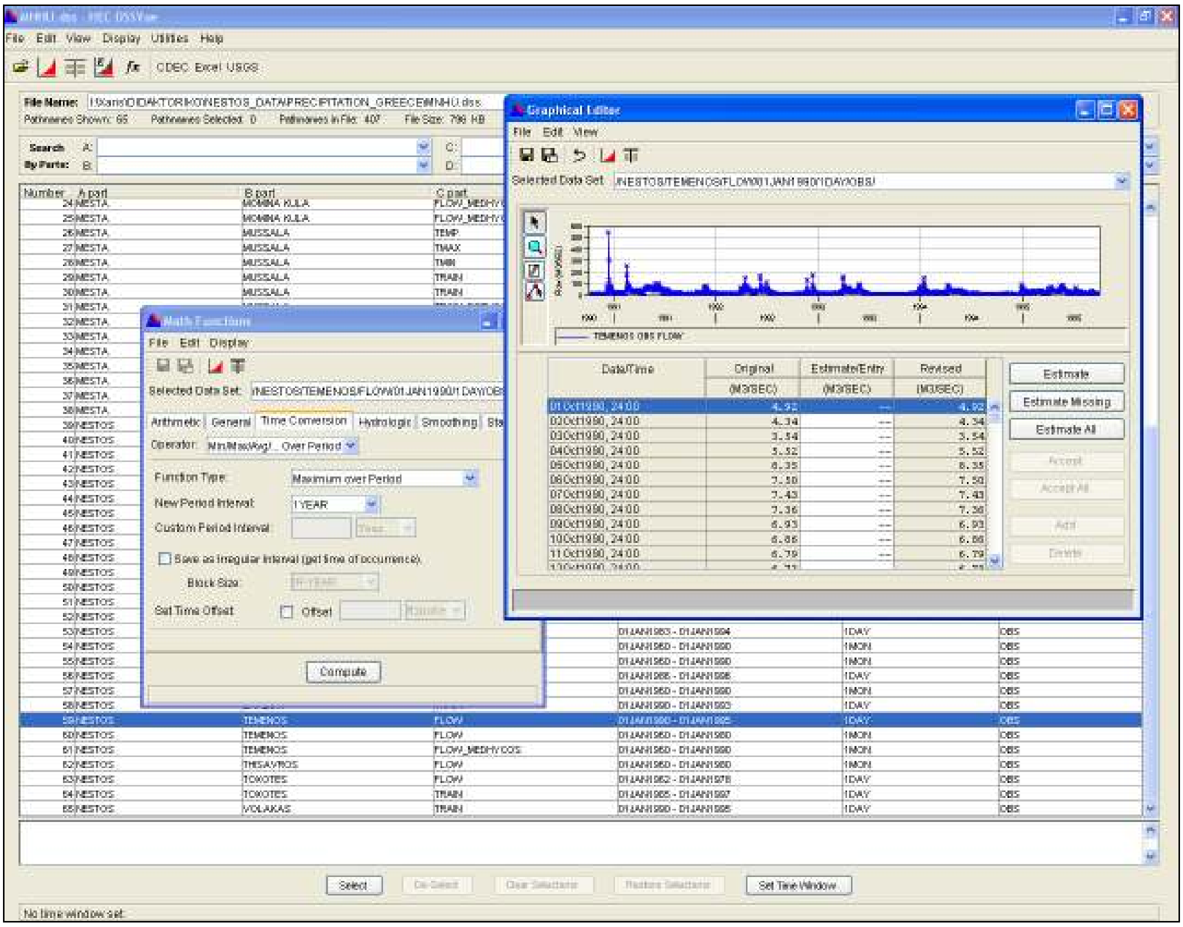


Figure 24 – Display from the HEC-DSS data base system illustrating storage, visualization and application of math function capabilities.

Apart from database management, HEC-DSS provides a large number of mathematical functions which can be applied in order to modify and combine the stored data time series. These functions are organized as follows:

- **Arithmetic:** Add, Subtract, Multiply, Divide, Exponentiate, Absolute Value, Square Root, Log, Log Base 10, Sine, Cosine, Tangent, Inverse (1/X), Accumulation, Successive Differences, and Time Derivative.

- **General Functions:** Units Conversion, Round to Nearest Whole Number, Truncate to Whole Number, Round Off, Estimate Missing Values, Screen Maximum and Minimum, Screen Using Forward Moving Average, Merge Time Series, Merge Paired Data and Generate Data Pairs.

- **Time conversion:** Shift in Time, Change Time Interval, Irregular to Regular, Min/Max/Avg…Over Period, Snap Irregular to Regular, Regular to Irregular, To Irregular Using Pattern and Extract Time Series.

- **Hydrologic Functions:** Muskingum Rooting, Straddle Stagger Routing, Modified Plus Routing, Rating Table, Reverse Rating Table, Two Variables Rating Table, Decaying Basin Wetness, Shift Adjustment, Period Constants, Multiple Linear Integral, Conic Interpolation, Polynomial, Polynomial with Integral and Flow Accumulator Gage Processor.

- **Smoothing:** Centered Moving Average, Olympic Smoothing Average, and Forward Moving Average.

- **Statistics:** Basic Statistics, Linear Regression and Cyclic Analysis.

III-2 – **Mapping river basin parameters**

III-2-1 - Mapping activities in hydrology

As one can expect the cartography of rivers and of theirs tributaries has been at the origin of mapping in hydrology. But since hydrology developed as a science in the beginning of the 1900s, associated mapping activities broaden their scope to study and represent spatially the factors governing the flow of water in rivers. These factors include, climate conditions, terrain relief, geology and pedology and well as land use.

In the early stages of hydrology science development mapping was used in order to better understand the spatial distribution of meteorological parameters, i.e. rain, and evapotranspiration. This is for example the representation of rainfall over the whole Italian territory (Central Hydrographical Service of Italy, 1948). In this type of activity the mere record of the geometric shape of geographic objects evolved toward the development of interpolation methods enabling the description of spatial fields after they are recorded over a discrete and often limited set of gauge stations.

Since the 1970s the drawing skill of cartographers has been replaced by mathematical interpolation instruments such as "Kriging". The cartography of the evapotranspiration field was also developed at an early stage in order to help evaluate water demands in agriculture (Darlot and Lecarpentier, 1963).

At an early stage, another need for mapping hydrology factors also started in geology or in phenomena related to geology, such as pedology and soil erosion (Fournier F., 1954). However a specialized activity later emerged in the cartography of groundwater bodies and flows. It introduced a new style of hydrogeology mapping, namely the integration in one cartographic document of multiple factors such as lithology, fractures and other properties of rock formation defining the groundwater circulation along with hydrometric data concerning precipitation and temperature defining the surface conditions (Albinet M. et al., 1973).

The introduction of land use mapping for a better understanding of the surface conditions such as runoff and evapotranspiration benefited in the 1970s from remote sensing technology, which was then emerging. Remote sensing from satellite uses measurements of the electromagnetic spectrum to characterize the landscape and provides its data in a raster form which is particularly suitable for mapping. Currently, remote sensing is widely used in climatology modeling and in particular for the computation of energy budgets at the Earth's surface (Ottlé C., 1989).

Spatial data storage and manipulation is now conducted using computer tools known as Geographic Information Systems (GIS). GIS technology was introduced in the 1960s and later evolved from a variety of technological developments including database systems, computer mapping, surveying and photogrammetry (Males R., 1992). Water resources GIS most often integrate map data (idem, coverage data) related to hydrology networks, terrain, land use, land cover, geology and soils.

III-2-2 - Geographical Information Systems in hydrology

A - Background on GIS technology

Since their creation, GIS technologies have been divided into a "polygon-based" (idem, vector) approaches derived from traditional cartography and a "grid-based" (idem, raster) inherited from the mapping activity of planners primarily in the United States of America. The vector approach provides an accurate representation of mapped information but proves to be difficult when used in spatial analysis. The raster approach is based on a regular matrix layout which is easy to handle by algorithms but does not provide very precise representation of objects. The coupling of the two previous techniques in a seamless GIS proved be difficult and is still a matter of software research. Further challenge is still present in the seamless handling of 3D information such as Digital Terrain Models (DTM) and the inclusion of time, the fourth dimension of nature.

The further evolution of GIS technology was influenced by a) the utilization of remote sensing data for the generation of grids and b) the development of the "polygon overlay" concept, in which two representations of an area mapped as polygons could be combined to generate a third representation showing the intersection of the two main ones.

However, terrain and network data storage and analysis, both of high significance in hydrology, were not handled by the GIS technology of that era, because terrain data was difficult to manage by both the polygon and the grid approach and network data was considered an issue related to the transportation planning sector. Only recently has GIS technology produced complete toolkits for the management of data relevant to hydrology.

B - Water Resources Applications of GIS Technology

One of the typical applications of GIS in water resources is the use of DTMs for the extraction of hydrologic catchment properties, such as elevation matrix, flow direction matrix, ranked elevation matrix, and flow accumulation matrix.

Moreover, probably the most important application of GIS technology to hydrology lies is the combination of derived information (Fig. 25) obtained by topographic, geological, soil type, land use and vegetation in order to construct unique outputs, e.g. the combination of land uses maps with soil maps provide as an output a Curve Number grid, which determines the loss rate parameters in the amount of runoff from a rainfall event in a particular area. Similarly in other situations, flow velocities and isochrones can be derived (Skop and Loarciga, 1998).

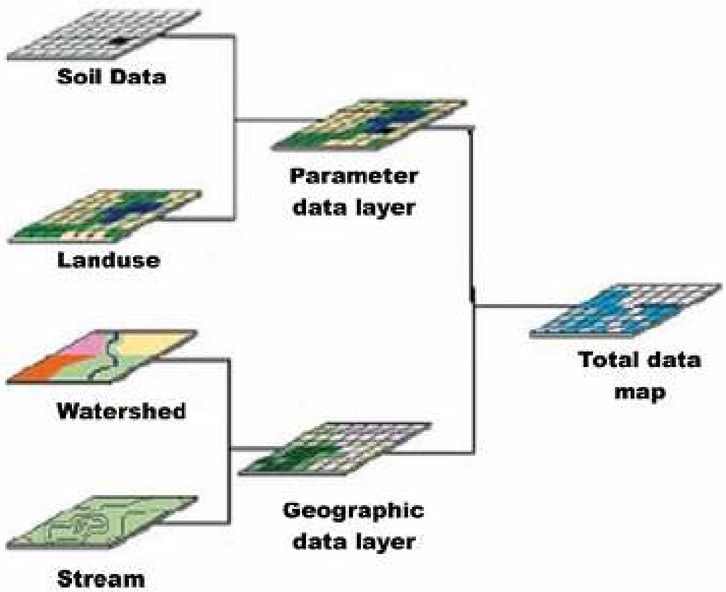


Figure 25 – Typical GIS structure in water resources applications (Skoulikaris, 2004)

On the other hand, the use of GIS in hydrology is not restricted to the management or storage of data. First attempts at coupling GIS with hydrologic modeling technology were made by the US Army Corps of Engineers (USACE), where GIS served as a database to 'feed' the models used (Phase I, Oconee Basin Pilot Study, 1975). Nowadays, this type of coupling is routinely performed. The most critical part of this operation is the capability of GIS to properly structure the data in order that it may be adequately processed by models. An example is the ability to perform spatial analysis for the development of lumped or distributed parameters over a particular river basin.

Recently, attempts have also been made for the construction of a complete hydromodeling system from a GIS package. However, the outputs of such systems are still judged to be inaccurate (Sui D.Z. et al., 1999).

III-3 - **Data structuring for models**

The construction of a spatially distributed hydrological model requires the integration of numerous thematic datasets such as topography, soil types and the vegetation classes. One of the most effective ways to represent this type of data is to use a grid raster structure format also called "raster". This format developed in the Earth sciences with the introduction of remote sensing techniques. The raster data structure has also evolved from simple lat-long matrices to more efficient systems such as triangular meshes or progressive grids also known in computer science by the term "quadtree".

III-3-1 - Grid data structures

In the representation of the terrain relief or other similar variables the selection of a particular grid type and grid element is a matter of compromise between several criteria. In the case of terrain the selected grid size will for example depend upon the degree of realism needed to represent slopes. For an area covering both steep mountainous areas and flat zones the selection of a unique uniform grid size will be difficult. The choice of a particular grid type will often involve criteria such as file size and computing power which greatly vary with the application. The three of the most common grid structures are the following (Fig. 26):

- Square or rectangular equal area cells.
- Mesh of triangulated surfaces (also called Triangulated Irregular Networks -TINs).
- Irregular curved cells match the contours lines or other bidimensional functions.

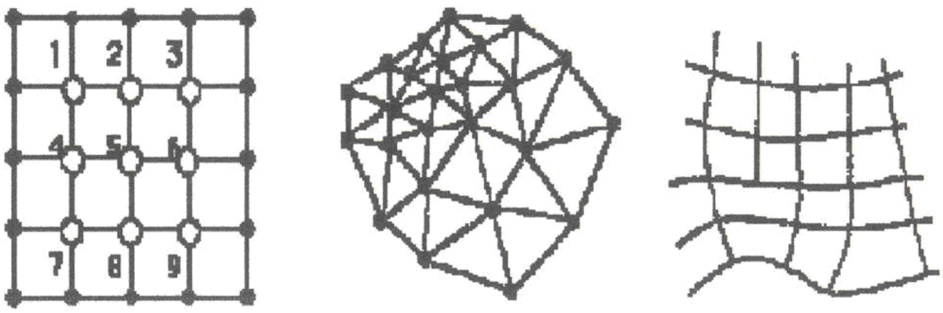


Figure 26 - Different types of meshed structures

Regular square or rectangular grids (idem, raster) are the most frequently used because they easy to store and process facilitates. They are the standard GIS structure when dealing with remote sensing data and terrain data in the form of DTMs are also structured in normal grids-raster. One of the advantages of the raster structure is that it holds an implicit definition of point topology where the neighboring cells at a particular point can be found by simple addressing without additional computation. On the other hand, one of the disadvantages of this grid structure is the inability to store detailed relief changes in rough terrain (Rahman A. A., 1994). Furthermore, the raster structure tends to store a high amount of redundant of data for flat terrain. Triangular mesh or other polygon shaped cells can represent the terrain relief much more accurately, but they fairly elaborate in their production and manipulation thus needing large amounts of computing power.

Apart from the simple raster data structure format, variable size square grids, also called quadtrees, has recently received considerable attention in GIS and DTM applications.. Some GIS software packages such as the Tydac Technology SPANS use the quadtree data structure for their internal manipulations instead of the regular raster structure (Wheatley D. et. al., 2002). One of the advantages of quadtree structure is that it can be more efficient than a simple raster format for the storage of thematic data such as soil types. This is because in the case of most thematic maps large contiguous pixel regions bear the same code.

However, quadtree is often inefficient in the case of DTM data, because in this case neighboring cells do not often have identical values. Quadtree data structures have already been used in hydrology (De Silva, R. P. et. al., 1999) and have been selected to build the meshes structure of the MODSUR hydrology model used in my study for the Mesta-Nestos river basin.

III-3-2 - Terrain modeling for hydrology

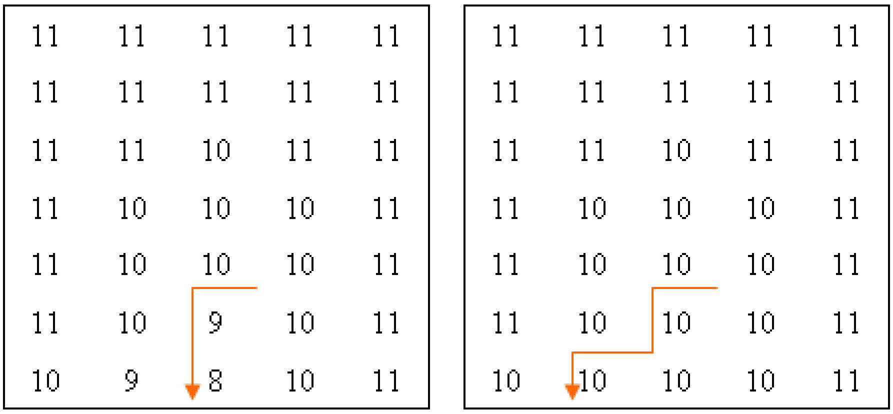
In hydrology, DTM data is subjected to specific spatial analysis algorithms for the automatic delineation of river streams and extraction of morphology characteristics of watersheds such as flow direction, drainage area and stream hierarchy, also called “Strahler” order.

A - Principles of hydrology features extraction from a DTM

Computation of flow direction

Flow direction corresponds to the direction of the vector joining a particular cell with its neighboring cell with the smallest lower altitude. Cells for which all neighboring cells having a higher altitude are termed “pool” cells. But it is obvious the vector of flow is undetermined in the case when all the neighboring cells have the same altitude as the center cell. This is the case of “flat area” indetermination.

Because of the problems cited before, flow determination algorithms use a more sophisticated approach involving a wider cell environment than its immediate neighbors. The distance of investigation is usually equal to r * amplitude of a cell, where r is the radius of investigation where r varies from 2 to 10. Nevertheless the results of this type of algorithms are almost always improved manually in order to solve the ambiguous areas (Fig. 27).



a) Flow path exists, automatically derived b) No flow path, manual correction

Figure 27 - Determination of the flow path, a) automatically b) manually

Moreover, if the results obtained from the previous method do not prove to be satisfactory, the flow direction can be manually imposed by digitizing the vectors which represent the flow direction from upstream to downstream. Of course, this can be done only if topographic maps of the area or other ancillary data are available.

Drainage area

The drainage area is obtained by taking into account the crest points of the DEM. The crest cells are those that do not have a neighboring cell at a higher altitude.

Hydrographic network

The hydrographic network includes all the cells whose upstream drained surface exceeds a threshold value. This threshold value is calibrated so that the network corresponds to the desired level of detail, which is often compared with existing topographic maps using a GIS.

Stream and watershed delineation

The stream delineation is based on the concept of the Strahler order (Fig. 28).

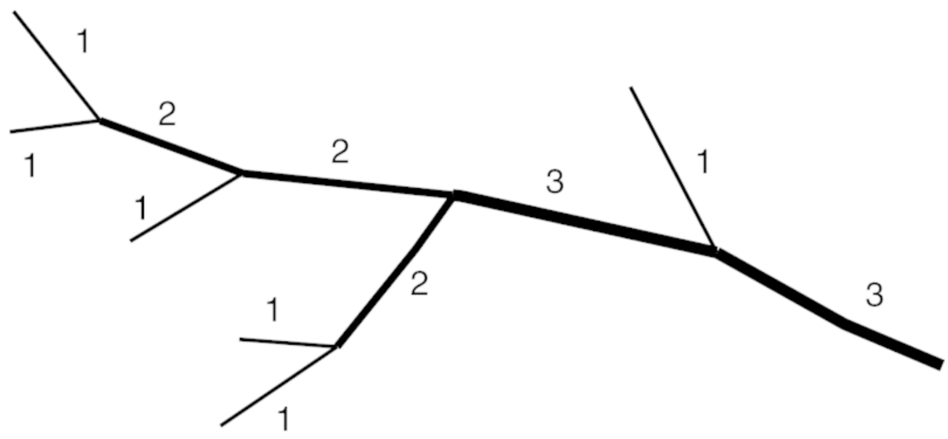


Figure 28 - Strahler stream order principles

According to the Strahler order stream classification, when two streams are joined they form a stream which is either:

- 1) the order immediately higher than that of the two streams if they have the same order;
- 2) the order of the stream with higher order if the two streams do not have the same order.

Once the full stream network has been classified using Strahler order it can be used to divide the main watershed into sub-watersheds on the basis of the given Strahler order threshold (Fig. 29).

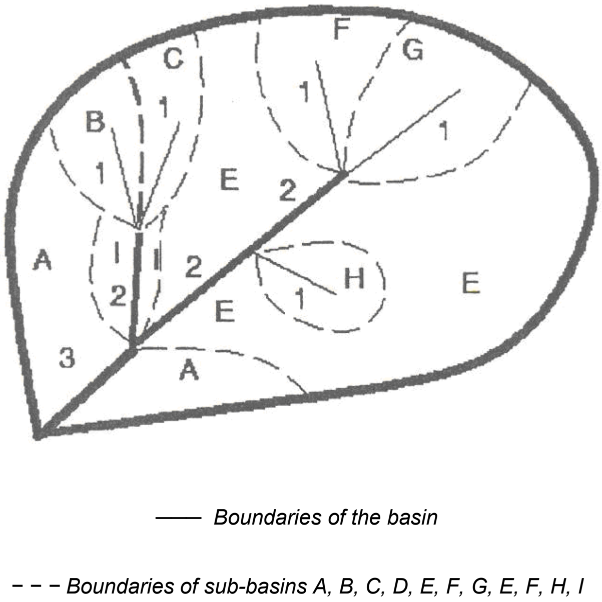


Figure 29 - Division of the basin into sub-basins based on the Strahler stream order

The stream labeling or ordering based on the Strahler order concept is one of the basic concepts behind river network oriented models such as SENEQUE, which originally was called RIVERSTRAHLER. The SENEQUE model is broadly used in European research programs such as the PIREN-Seine program (Programme Interdisciplinaire de Recherche sur l'Environnement de la Seine), (Servais P. et al., 2007), or in the case of surface and groundwater resources management in the Bistrita river basin, Romania (Trifu M. et al., 2007).

B – DTM processing in the Mesta-Nestos basin

For the determination of the river networks and associated parameters such as sub-watersheds, flow accumulations etc.., the Mesta-Nestos river basin terrain parameters have been processed using two types of tools: the Geospatial Hydrologic Modeling Extension HEC-GeoHMS (USACE) and HydroDEM (Leblois E., et al., 1999).

HydroDEM is a system for structuring hydrographical networks in a hierarchical way (Sauquet E., 2000). Using discharge observations and a DEM, it allows an effective reconstruction of the variation of mean annual runoff along the river network in a basin. It produces the topographic and structural information necessary to the construction of a MODSUR hydrology model grid.

The Geospatial Hydrologic Modelling Extension (HEC-GeoHMS) is a geospatial hydrology tool integrated with the ArcInfo GIS. It allows the visualization of spatial information, the delineation of streams and sub-basins and streams and the construction of inputs to the HEC-HMS hydrology model (Fig. 30).

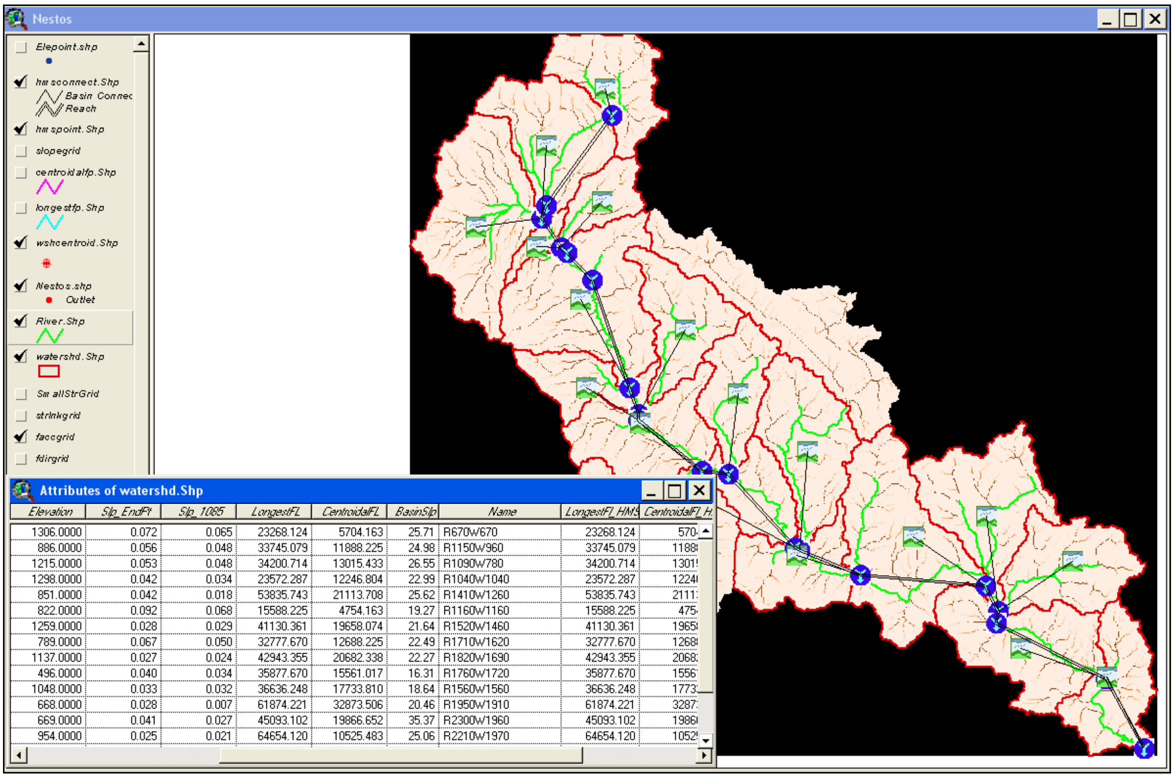


Figure 30 - Representation of the Mesta/Nestos watershed and computation of the hydrologic parameters with the use of HEC-GeoHMS

Apart from the basic basin parameters, Geo-HMS produces a number of topographic characteristics, such as river length and slope, watershed slope and area, basin centroid location and longest flow path, which are used for estimating the hydrologic parameters.

III-3-3 - Quadtree grid in the MODSUR hydrology model

Gridding is a data structuring problem common to many models used to simulate time varying natural phenomena using differential equations. Since the parameters relevant to hydrologic modeling and derived from GIS technology and remote sensing have also grid data structure, it is logical that techniques were developed to adapt this GIS data to the structure needed by hydrology models. Currently, there are computer programs dedicated to this type of coupling such as ARGUS One (Pinder G. F., 2002) or SIGMOD (Golaz-Cavazzi, 1995).

The MODSUR hydrology uses a progressive quadtree structure, which originates from the gridding method introduced at CIG-ENSMP in the early 70s in order to simulate ground flow (Besbes M. et al., 1976). The program initially called SAMMIR and later renamed NEWSAM is still the ground flow instrument used at the Ecole des Mines de Paris. The MODSUR modeling procedure is based on the spatial discretization of the surface. The creation of a grid was initially accomplished by coupling different methods and tools, such as the Idrisi GIS tool and the HydroDEM DTM processing program. This coupling method is now known as SIGMOD.

SIGMOD input data consist of seven different layers of information derived from the GIS module. Five of the layers are derived from the elevation model using HydroDEM: flow direction, drainage area, hydrographic network, stream delineation and watershed delineation. The last two layers contain the soil types and the land use information. All the information included in the seven layers is distributed over the terrain model raster grid, i.e. over a large number of cells with the same size. SIGMOD produces a quadtree grid with variable size square cells which are regrouped from the initial raster grid elements on the basis of specific criteria. The criteria can be distinguished by their “topology” and “hydrology” nature. They are aimed a maintaining the hydrology properties of the sub-basins and the isochrones during the regrouping procedure. The decrease in the number of cells, i.e. meshes regrouping, aims to diminish the calculation time of the hydrologic model compared with similar hydrology modules such as MODFLOW which do not use a similarly parsimonious grid system.

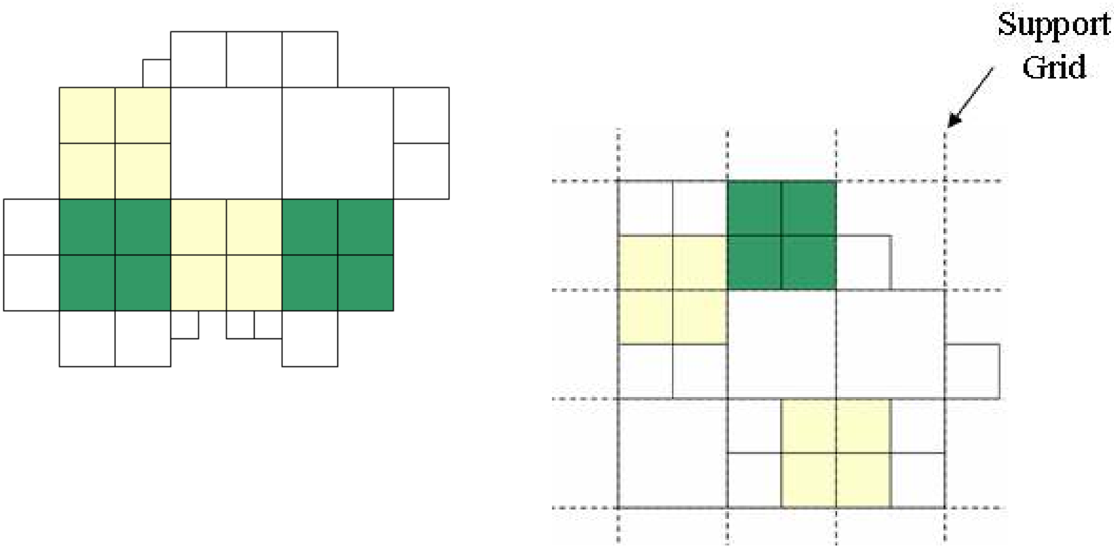
A - Topology criteria

The topology criteria used in MODSR for regrouping cells are the following:

1) The four candidates for regrouping cells should have the same size.

2) The regrouping procedure should respect the neighboring rules: four (4) cells of size *n* can be regrouped only if the size of their neighboring cells is not equal to *n-1* (Fig. 31a).

3) In every phase *n* of the mesh regrouping procedure, a support grid with a size equal to $2^{\{n\}}$ * (amplitude of the DTM's grid) is stacked over the mesh. Only the group of cells that are found completely inside the cell of the support grid can be regrouped (Fig. 31b).



a) restructuring based on criterion 2

b) restructuring based on criterion 3

Cells authorized to be restructured

Cells not authorized to be restructured

Figure 31 – Topology regrouping in MODSUR model grid

B - Hydrology criteria

The regrouping hydrology criteria used for the regrouping are the following:

- The river cells, i.e. the cells that represent the extent of the river are at the origin of the process one quaqrter of the size (idem, half width) compared to the cells of the DTM. This results in an accurate representation of river streams and their possible exchanges with the underground domain.

- Four (4) cells can be regrouped only if they belong to the same sub-basin. In this way, stream flow transfers from one sub-basin to another are excluded.

C - Cells regrouping parameters

- The regrouping of four (4) cells produces a river cell as its output if at least one of the four cells is a river cell.

- The flow direction of the 4 regrouped cells depends on the presence of at least one river cell:

    - If no river cell exists in the group, the flow direction of the regrouped cells adopts the flow direction of the cell that had the largest drained area downstream before the regrouping procedure.

    - If at least one of the cells is a river cell, then the flow direction of the regrouped cells adopts the flow of the river direction of the river cell that had the largest drained area downstream before the regrouping procedure.

III-4 - **The physical characteristics of the Mesta/Nestos basin**

The present thesis work has benefited from a large GIS and satellite imagery database (Monget J-M et al, 2005) which has been accumulated over several years. It started at the Democritus University of Thrace (DUTH) by the building of an environmental multithematic Arc View GIS which covered the whole Mesta-Nestos basin (Viavattene C., 2001) and a more focused database dedicated to the problems of the Nestos delta (Fallon A., 2001). It was complemented by the construction of an initial MODSUR hydrology model at Ecole Nationale Supérieure des Mines de Paris (Chaunut Le Donge D. et al, 2001). Through the years, this database was transferred to the ArcGIS system and partly broadcasted on-line on the Internet using the Mapserver system (Karakos A. et al, 2003).

Overall the database occupies now about 10 Gigabytes of data which are managed at the Aritristotle University of Thessaloniki (AUTH) under the umbrella of the HELP-UNESCO program (Ganoulis et al, 2007). The GIS layers have received contributions for Greece from admisnistrations (Prefecture of Kavala, the Greek Geological Survey-IGME) and universities (DUTH and AUTH); for Bulgaria from the Bulgarian Academy of Sciences and the Technical University of Dresden; for the whole basin from European programs (TRANSCAT, Corine Land Cover). The remote sensing images were contributed by DUTH in Greece, the Bulgarian Acacdemy of Sciences in Bulgaria and for the whole basin from the West Virginia University (WVU) in the USA.

III-4-1 - Geology and pedology of the basin

As can be seen from Figure 32, a large part of the inland part of the Mesta-Nestos basin is covered by granites formations (in pink color) which are in the northern part, the cretaceous Rila-Pirin region granitoids and in the center part, the Rhodopes Paleozoic granites. These are interwoven with metamorphic gneisses and Paleogene volcanic formations.

The same orogeny has also produced massive marble reliefs in the Bulgarian Pirin region in the North and the Greek Lekani mountains, in the South, boarding the Quaternary alluviums of the Nestos delta. The Lekani karst aquifer system has an annual potential of $105*10^6$ m^3 and connects to about 25 cold springs, many of them used as a source of drinking water for the towns and communities of the region.

It is thought that this groundwater system is connected with the Nestos stream but so far no definite observations of this have been made.

The Mesta/Nestos basin belongs to the so-called Rhodope geotectonic zone which covers East Macedonia and Thrace as well as the southern part of Bulgaria. It has been marked by several tectonically active periods, the last being the Alpine orogeny. Today the area is still tectonically active with moderate seismicity compared with neighboring areas of Sofia to the North and along the Struma river to the West.

The Nestos delta forms part of the Tertiary basin of Prinos-Nestos (Xeidakis G. S. et al., 2002). During the Quaternary the Nestos delta area is estimated to have been subjected to a tectonic subsidence of 100 m. It covers a deep graben structure with sediments with a thickness estimated at 2500 m (Psilovikos A., 1990). At the surface the accumulation of delta sediments consists mostly of gravels, sands, silts and clays. This area of loose sediments is susceptible to erosion and rapid retreat of the coastline in particular, since the dams on the Greek Nestos side of the river have considerably reduced the sediment load in the stream.

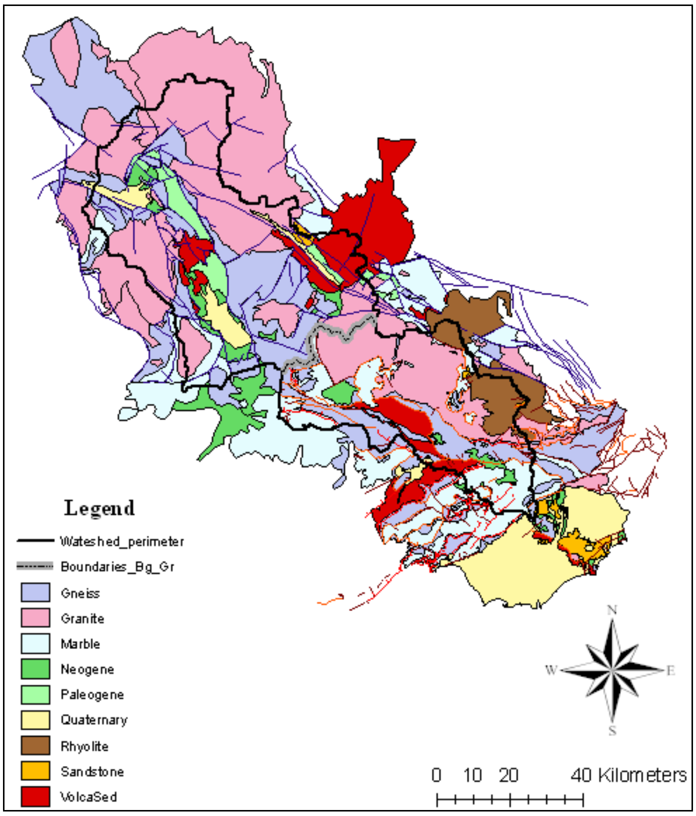


Figure 32 - Geology of the broader area of the Mesta/Nestos basin

As my work includes the effects of the development of agriculture projects in the areas downstream from Toxotes, pedology information was gathered for the lower part of the Nestos river stream namely the Nestos delta and its neighboring Xanthi plain. However, the Nestos basin lacks a detailed map of soil types. The only available document is a simple map mostly obtained by generalization of the few pedology sections made in the area (Nakos G., 1997). The soils are classified in five broad groups (Table 6) and the map is provided at a scale of 1:50000 (Fig. 33).

Figure 33 - Soil types in the Greek part of the Mesta/Nestos basin (Nakos G., 1997)

Soil class	Legend Color	Humidity (cm/month)		Field Capacity (bar)		Permanent Wilting (%w.d.s)		Hydraulic Conductivity (m/s)	
		min	max	min	max	min	max	min	max
Argillaceous to argillaceous-loamy	**Grey**	0.38	0.41	0.26	0.37	0.15	0.31	5.5e -07	7.2e-07
Argillaceous-loamy to loamy	**Red**	0.41	0.43	0.185	0.26	0.085	0.15	7.2e-07	2.9e-06
Silt-loamy to loamy	**Yellow**	0.43	0.45	0.18	0.24	0.085	0.09	1.2e-06	2.9e-06
Loamy- sandy to sandy	**Green**	0.41	0.43	0.05	0.12	0.04	0.05	4.1e-05	8.3e-05
Silt-argillaceous-loam to loamy-sandy	**Magenta**	0.41	0.46	0.12	0.31	0.06	0.19	1.9e-07	1.2e-05

Table 6 - The five soil types of Fig. 33 and the range of values of the parameters

The distribution of the best soils (in Magenta) indicates that although the entire expanse of the Nestos Delta is appropriate for intensive agriculture, the Xanthi plain has a more limited capacity, particularly on its eastern edge which is bordered by low relief of rocky gneiss hills.

III-4-2 - Hydrology characteristics

A – Upstream Mesta basin in Bulgaria

In the North part of the basin a significant number of high altitude lakes in the upper Rila Mountain (2,424 m) are supplying the primary tributaries with water. In the west part, although the Pirin Mountain reaches about the same altitude, the karstic nature of its marble formations provides fewer significant outflows.). The junction of the Biala Mesta and Cherna Mesta streams above the town of Jakorouda gives birth to the main Mesta River which then runs down and enters Greece at 388 m above sea level. The biggest tributary to the main course is the Dospatska River, also known as the Dospat, which flows into the Nestos on Greek territory (Fig. 34).

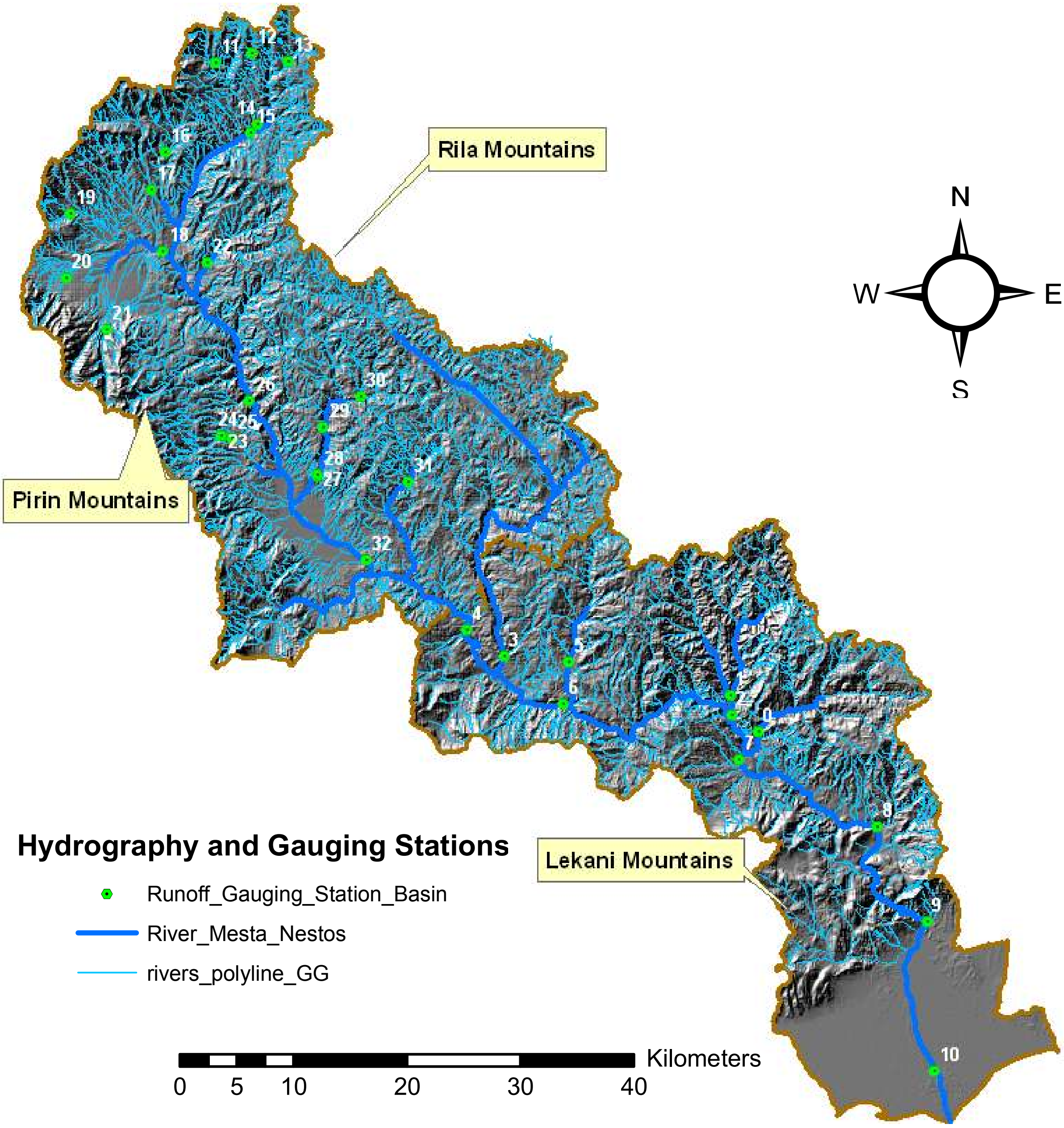


Figure 34 - Hydrographical network of the Mesta/Nestos river basin. The green dots represent the runoff gauging stations

In the Bulgarian part of the basin, the Mesta River has twenty five tributaries, twelve of which are significant (Table 7).

River	Catchment area (km²)	River Length (m)	Annual Runoff Qavg (m^3/s)
B.Mesta	56.7	10,207	1.628
Leevestitsa	13.2	6,794	0.287
Cherna Mesta	33.2	8,335	0.746
Biala Reka	33.8	18,341	0.288
Demianitsa	35.7	11,061	1.439
Iztok	361.0	14,202	6.538
Kanina	231.0	33,740	2.889
Bistritza	82.4	32,283	1.339
Dospatska	236.0	82,863	3.158

Table 7 - Main tributaries of the Mesta River, their catchment area, the river length and the average annual runoff (Ganoulis et al., 2004)

As for the available hydrological information, the first gauging station in the Mesta basin was completed in 1927 at Momina Kula. Initially, it was only a rainfall gauging station but since 1936 runoff data have also been recorded. Currently, in the Mesta basin there are 23 hydrometric gauging stations. They all belong to the national river-monitoring network of the Ministry of Environment and Water (MOEW). In addition, there are 35 rainfall gauging stations covering the total extent of the basin, and 3 gauging stations recording the transfer of sediments. Access to all of this data is still restricted to Bulgarian institutions except for the Momina Kula station which is freely available as part of the WMO program.

The hydrological study performed in 1972 (Moutafis N., 1991) estimated a mean annual runoff of 433 mm for the Mesta basin which corresponds to a mean annual inflow at the border with Greece of 47.2 m^3/s. Part of that water is diverted from the Dospat reservoir to the River Vacha. The area of the Mesta basin drained by this diversion project was determined to be of 565 km^2 (Moutafis N., 1991), thus resulting in the diversion of a mean annual flow of 7.76 m^3/s. Consequently the mean annual flow at the border had been reduced since the construction of the Dospat dam in 1964 to a mean annual flow of 39.43 m^3/s.

B – Downstream Nestos basin in Greece

In the Greek part of the basin, the Nestos River has six main tributaries, which are presented in Table 8.

Tributary	Catchment area (km²)	Tributary	Catchment area (km²)
Diavolorema	356.4	**Mulorema**	93.1
Arkoudorema	283.3	**Kastanitourema**	60.9
Despatis	118.9	**Rema**	45.7

Table 8 - Main tributaries of the Nestos River and their catchment area (Ganoulis et al., 2004)

According to the Power Public Corporation of Greece (PPC) the mean monthly flow for the period 1965-1990 of the Nestos stream was rarely measured above 150 m^3/s while the minimum flow was often lower than 10 m^3/s. Nowadays, the regime of flow downstream of the dams is artificial but it is maintained above 6 m^3/s for environmental conservation.

As for the available hydrological information, 11 hydrometric gauging stations exist in the Greek part of the basin. Most of them are located upland with the exception of the "Erimonisi" gauging station which is located in the delta area (Table 9). The Ministry of Agriculture (MINAGR) monitors quality and quantity parameters at six points on the river and the rest of the gauging stations belong to PPC. Although the data of MINAGR stations is available in digital form from 2001, the use of the PPC measurements is more restricted, historical measurements still being stored in paper form. The Temenos station data is freely available as part of the WMO program, however the measurements stopped after the start of operation of the dams in 1997. It is also to note that the station started in 1964 which is much later than the Bulgarian station of Momina Kula which started operation in 1936.

The delta and its coastal zone are more regularly monitored by a variety of institutions such as the National Agricultural Research Foundation (NAGREF), the Democritus University of Thrace (DUTH) and EPO-Living Lakes, a local NGO (Jerrentrup et al, 1988). Groundwater monitoring of the Nestos delta area is also available over a 20 year period for an array of about 20 piezometers and 100 wells under the auspices of the Institute of Geology and Mineral Exploration (IGME) and DUTH. The various karstic freshwater springs situated at the periphery of the Lekani mountains have also been monitored over a long period.

Gauging station	Agency	Years observed
Arkoudorema	PPC	1986 - 2001
Thyssavros	PPC	1964 - 2001
Platanovryssi	PPC	1964 – 1983 and 1999 - 2001
Despatis	MINAGR	1990 - 1993
Village of Delta	MINAGR	1979 - 2001
Mpousda	PPC	1994 - 2001
Papades bridge	MINAGR	1964 - 1993
Temenos	**PPC**	**1964 - 1997**
Stavroupoli bridge	MINAGR	1974 - 2004
Toxotes	MINAGR	1974 - 2004
Erimonisi	MINAGR	1974 - 2004

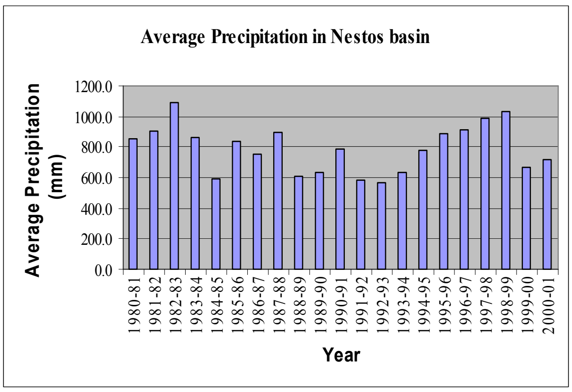
Table 9 - The runoff gauging stations of the Greek part of the Mesta/Nestos basin

III-4-3 - Local climatology

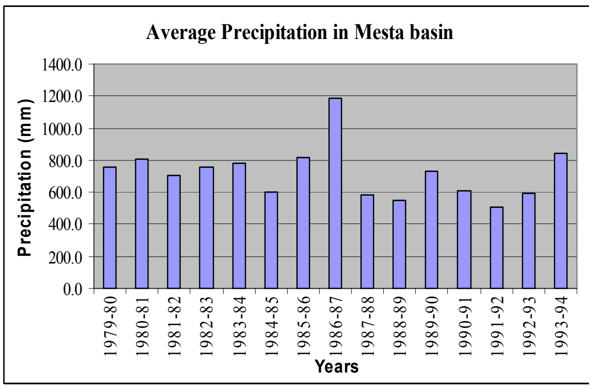
The climate of the upper part of the Mesta/Nestos river basin in Bulgaria differs from the climate of the downstream part which is situated in Greece. The climate of the upstream part can be characterized as sub-alpine or transitional Mediterranean, while the southern part of the catchment is characterized as a Mediterranean climate. Thus, in the mountainous part of the basin, the temperature is low in winter and moderate in summer, while in lowlands the winter is mild and the summer dry and hot.

A - Precipitation

In the Bulgarian part of the basin, the mean annual rainfall is approximately 810 mm/year. The driest months are August and September, with monthly rainfall precipitation varying between 25 mm and 38 mm. The tributaries of the north western part of the Mesta are influenced by the mountainous climate in Rila and Pirin with its high precipitation and prolonged snow cover. In the Greek part of the basin, the annual rainfall is of 790 mm with 86.3 days of rain annually and a mean humidity 70 to 72%, November, December, and January being the wettest months. Figure 35 shows the mean average rainfall in the upstream and downstream part of the basin.



a)



b)

Figure 35 - Mean average rainfall a) in the Greek part of the basin, 1980-2001, b) in the Bulgarian part of the basin, 1979-1994 (source: UNESCO/INWEB[7]).

[7] UNESCO/INWEB: http://www.inweb.gr/

A fair number of rainfall gauging stations exist on both sides of the catchment. Table 10 presents the gauge stations of the Bulgarian part of the basin, while Table 11 presents the precipitation stations of the Greek part.

Name of Station	Code of rainfall station	Years of observation
Dospat	45080	1948-1993
Kourtovo	47680	1951-1995
Semkovo	61020	1951-1995
Belitza	61030	1947-1995
Bansko	61040	1931-1995
Goze Delchev	61120	1914-1995
B.Mesta	61430	1954-1984
Jakorouda.leeve	61440	1949-1995
Razlog	61470	1914-1993
Predel	61480	1948-1995
Gostoun	61520	1952-1984
Osenovo	61530	1954-1995
Vicheritza	61540	1948-1984
Gospodinovzy	61550	1947-1995
Dikchan	61560	1948-1995
Satovcha	61570	1947-1995
Balkosel	61580	1940-1995
Beslet	61590	1948-1995
Breznitza	61660	1954-1995
Kovatchevitza	61710	1940-1989

Table 10 - Rainfall stations of the Mesta basin in Bulgaria

Station	Source
Achladia	PPC
Chryssoupoli	HNMS
Kariofyto	PPC
Kechrocampos	PPC
Lekani	PPC
Likodromio	PPC
Livadero	MINAGR
Livaditis	NAGREF-FRI
Maggana	MINAGR
Makriplagi	PPC
Messochori	PPC
Mikromilia	PPC
Paranesti	MINENV
Potamoi	PPC
Prassinada	PPC
Ptelea	PPC
Semeli-Petrochori	MINAGR
Sidironero	PPC
Stegno	PPC
Thyssavros	PPC
Toxotes	MINENV
Volakas	PPC

Table 11 - Rainfall stations of the Nestos basin in Greece

B - Temperature

The temperature differs between the northern and more mountainous part of the basin and the downstream part of the catchment. A difference of 5 °C between Sofia and the Greek part is apparent (Fig. 36).

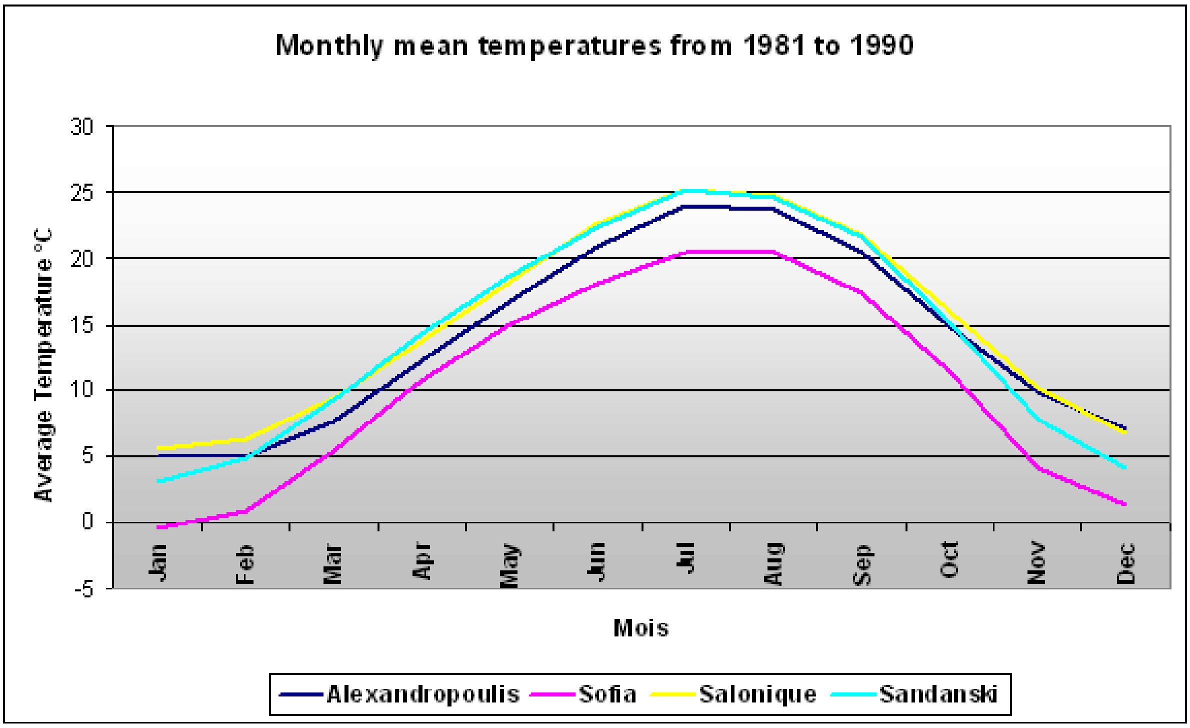


Figure 36 - Comparison of temperature data between Greek stations (Thessaloniki, Alexandroupolis) and Bulgarian stations (Sofia, Sandanski)

In the Greek part, mean annual temperature is 15.4° C. November, December, and January are the wettest months with an average number of 11 days of frost, while the driest month is July. Average minimum air temperatures occur in January (4.1°C - 5.3°C) while average maximum temperatures occur in July (23.3°C - 25.9°C). According to available data for the Nestos basin, there is also a difference of 5 °C between the mountainous region and the delta region of the basin (Table 12).

Station	Mean Average Temperature (°C)	Mean Max. Temperature (°C)	Mean Min. Temperature (°C)	Station Altitude (m)
Messochori	13.1	20.3	5.8	135.5
Sidironero	11.8	16.9	5.2	600
Livaditis	8.4	12.5	3.3	1240
Maggana	14.2	19.6	8.8	4.5
Chryssoupoli	14.2	20.7	7.5	18.1
Semeli-Petrochori	10	14.9	20.5	9.1
Oraio	13.1	17.5	8.8	656.4
Gerakas	13.7	19.2	8.2	308.3
Genisea	10	14.3	20.1	8.3
Prosotsani	13.8	-	-	140
Kato Nevrokopi	10	11.1	18.6	3.7
Leukoyeia	10.7	17.3	4.1	600

Table 12 - Mean average, maximum and minimum temperatures for fourteen stations in the Greek part of the basin

III-5 - The Mesta-Nestos MODSUR model implementation

III-5-1 - Building the MODSUR grid from a DTM

The hydrographic network has been determined from the GTOPO30 DTM (Digital Terrain Model) from USGS[8]. The GTOPO30 is a global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer). The subset related to the area of study (Fig. 37) was retrieved from the original DTM data and geometrically rectified to the Hellenic Geodetic Reference System (HGRS 87) at a one km resolution using the TeraVue system. It was then linearly interpolated on a 250m grid in order to achieve compatibility with the Corine Land Cover digital map available over the area. This process of grid refinement by linear smoothing is leads to the computation of less ambiguous terrain slopes and is often favorable to the automatic determination of crests and valleys in the DTM which is followed by the extraction of the river network.

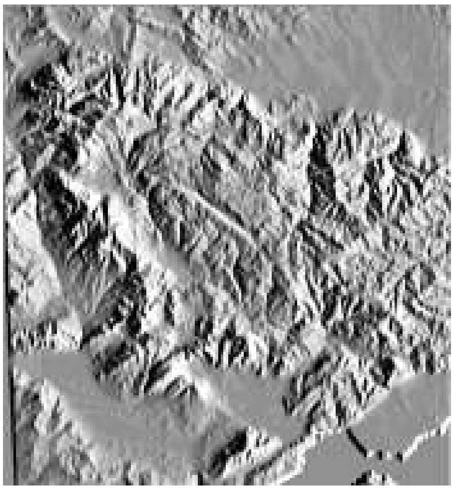
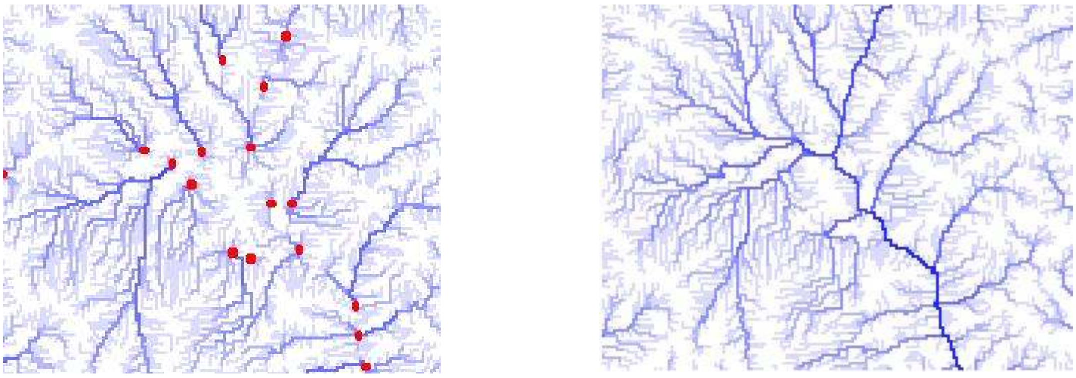


Figure 37 - Shaded relief image of the DTM used in the project (1km refined to 250m)

The MODSUR grid has been constructed using the HydroDEM automated system developed by E. Leblois as an extension to the Idrisi GIS followed by the use of the SIGMOD module. HydroDEM enables to interactively improve the network determination by editing litigious points were local slope conditions in the DTM lead to ambiguous connecting decisions (Fig. 38).

[8] GTOPO30 DTM (Digital Terrain Model) from USGS - (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html)



a) Litigious connection points automatically marked by the DTM analysis software

b) Improved version of the network determined by the analysis software after "manually" connecting the problematic points

Figure 38 - Process of network editing in the Leblois system in the upper Mesta drainage area

Overall, nine drainage sub-basins have been determined in order to build the MODSUR grid, eight of them are related to existing hydrographic features (Fig. 39):

- 1 - Lower Nestos in Lekani mountains area
- 3 – Arkoudorema Nestos tributary
- 4 – High Nestos watershed
- 5 – Diavolorema Nestos tributary
- 6 – Dospat river
- 7 – Lower Mesta watershed
- 8 – Cherna Mesta tributary
- 9 – Bela Reka tributary

The sub-basin numbered 2 by the system is a model artifact which is related to ambiguous local relief conditions in a flat area downstream Temenos where DTM derived stream connectivity is difficult.

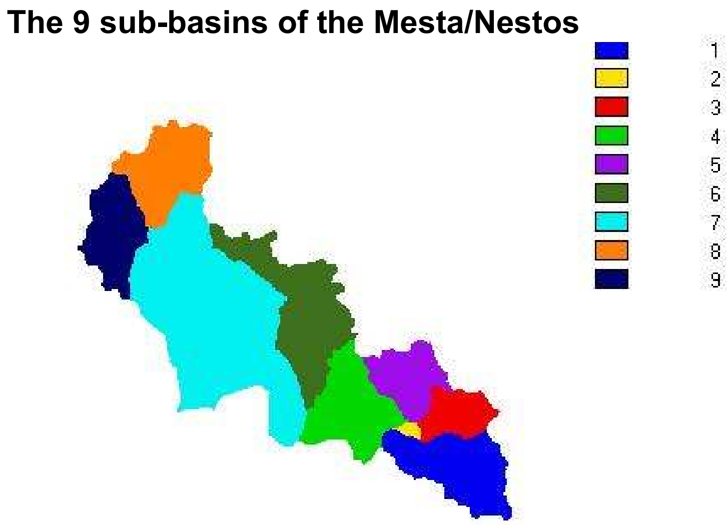
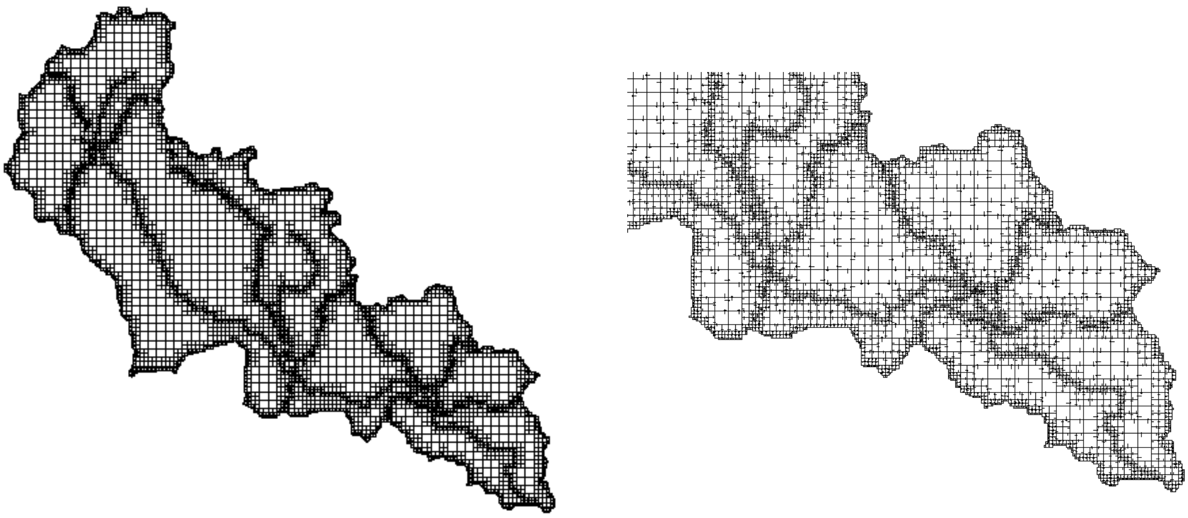


Figure 39 - Main drainage systems determined by the automated DTM analysis

The final variable size quadtree MODSUR grid contains 9212 elements (Fig. 40) with sizes ranging from 250m for the smallest to 2000m for the largest. The most refined parts of the model grid are essentially located at the border line of the watershed, on the crest lines separating two sub-basins and along the main river streams.



a) MODSUR model grid for the Mesta-Nestos basin (9212 elements)

b) Detailed view of the local drainage represented by MODSUR

Figure 40 – The Mesta-Nestos MODSUR distributed hydrology model

In the MODSUR model grid, the so-called "river cells" are model elements which are specifically dedicated to open channel flow simulation. They are in particular suitable for the coupling with other models such as the HEC-ResSim dam simulator. A certain degree of realism needs to be maintained for the placement of these "river cells" regarding the main river branches in the watershed. In the present case (Fig. 41) the various river branches which have been retained are: 1) the Cherna Mesta and Bela Reka confluence forming the main Mesta stream, 2) the Dospat river branch and 3) the branching of the Diavolorema and the Arkoudorema tributaries with the main Nestos stream. These last tributaries are of particular significance because their confluence points are situated respectively upstream and downstream from the Temenos dam project.

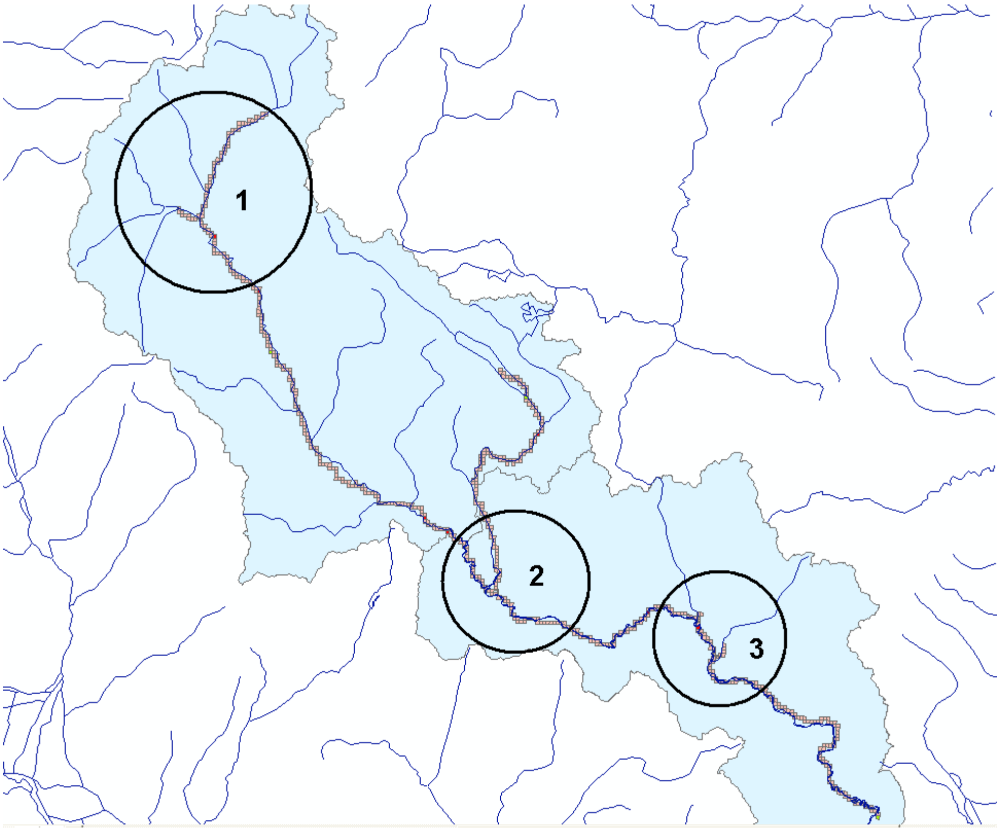


Figure 41 - "River" cells in the Mesta-Nestos MODSUR model grid.

Tributary channels: 1) the Cherna Mesta and Bela Reka confluence, 2) the Dospat river branch and 3) the branching of the Diavolorema and the Arkoudorema tributaries

III-5-2 - The integration of rain data

On the Greek side, rain values are based on the data set provided by the Department of Civil Engineering, Democritus University of Thrace, Xanthi. It consists of monthly rain data compiled from various sources (PPC-DEH, HNMS …). After an initial spatial correlation study between available stations in order to avoid excessive redundancy it was decided to retain six rain stations for the period of 1 Aug 1991 to 31 July 1995, namely:

- 1 - Achladia
- 2 - Potamoi
- 3 - Sidironero
- 4 - Ptelea
- 5 - Kechrokampos
- 6 - Mesohori
- 7 - Prasinada

Monthly rain data for the Bulgaria stations has been transferred from a recent comprehensive evaluation of the basin hydrology (Mimides et al., 2005). In Bulgaria, the following 11 stations were added:

- 17 - Bansko
- 14 - Beslet
- 9 - Breznitsa
- 12 - Dikchan
- 10 - Gospodintsi
- 18 - Jakoruda
- 15 - Kurtovo
- 11 - Osenovo
- 16 - Predel
- 13 - Satovcha
- 8 - Valkosel

The Bulgarian data covers a reduced time period from 1 Aug 1991 until 31 Dec 1995. Exact day calendar has been used with HEC-DSS database thus leading to a total period of 1614 days. However, original station data sets for Bansko, Breznitsa, Gospodintsi and Dikchan were missing some data periods. These have been filled using a linear regression with neighboring stations using the S-PLUS statistical package.

Furthermore, two more stations were introduced for the peaks Mussala and Vihren in order to improve the geographic coverage of the rain stations. However, the only rain data available at these locations is the monthly Mussala data stored at the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research Research Data Archive (RDA) in Boulder, Colorado[9]. Unfortunately, this set contains only scattered monthly measurements available for the period 1963-1969

In order to generate realistic artificial rain series for Mussala and Vihren peaks, another linear regression analysis was performed with the S-PLUS program using the neighboring station data of Jakorouda (less than 20 km) for which a long term monthly rain series is available (Fig. 42). The underlying argument is that statistically, when it does not rain in Jakorouda it should also not rain in Mussala, and thus the regression has been conditioned to the value of intersect being null (intersect a in the regression formula MUSSALA = a +b*JAKOROUDA (Fig. 43).

[9] Computational and Information Systems Laboratory at the National Center for Atmospheric Research (CISL) Research Data Archive (RDA) - (http://dss.ucar.edu/)

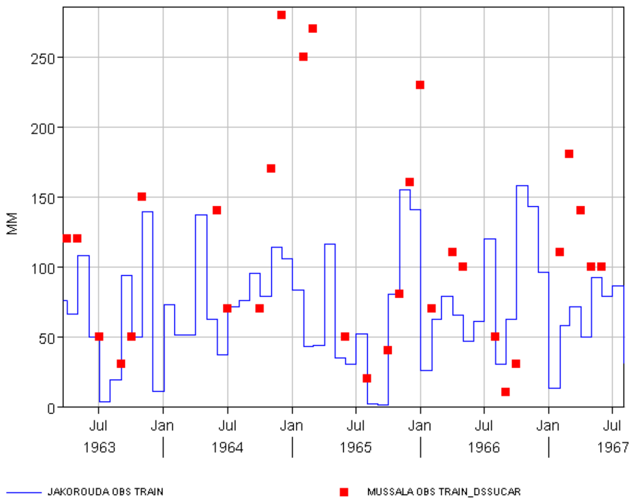
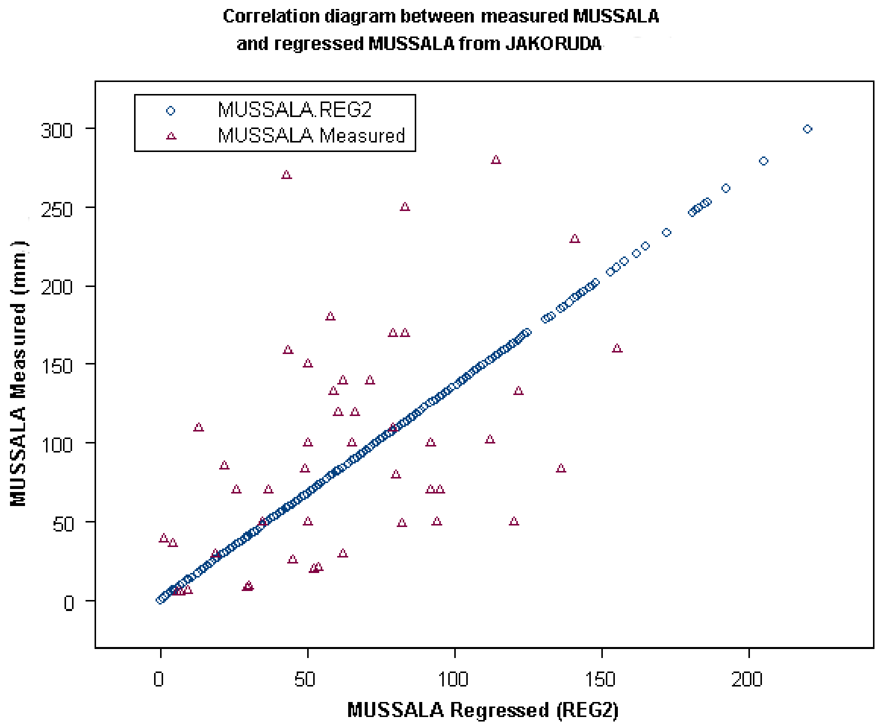


Figure 42 - Comparison between monthly measurements available during the period 1963-1969 for the Mussala station (DSS-CISL) and Jakorouda station (Mimides et al., 2005)



*Regression equation determined with S-PLUS: MUSSALA = 1.36 * JAKOROUDA*

Figure 43 – Mussala-Jakorouda regression line compared to scattered monthly measurements available for the period 1963-1969 for the Mussala station

Finally, each station rain data has been assigned to the neighboring MODSUR model grid cells using the geometry of Thiessen polygons which were determined using ArcGIS (Fig 44).

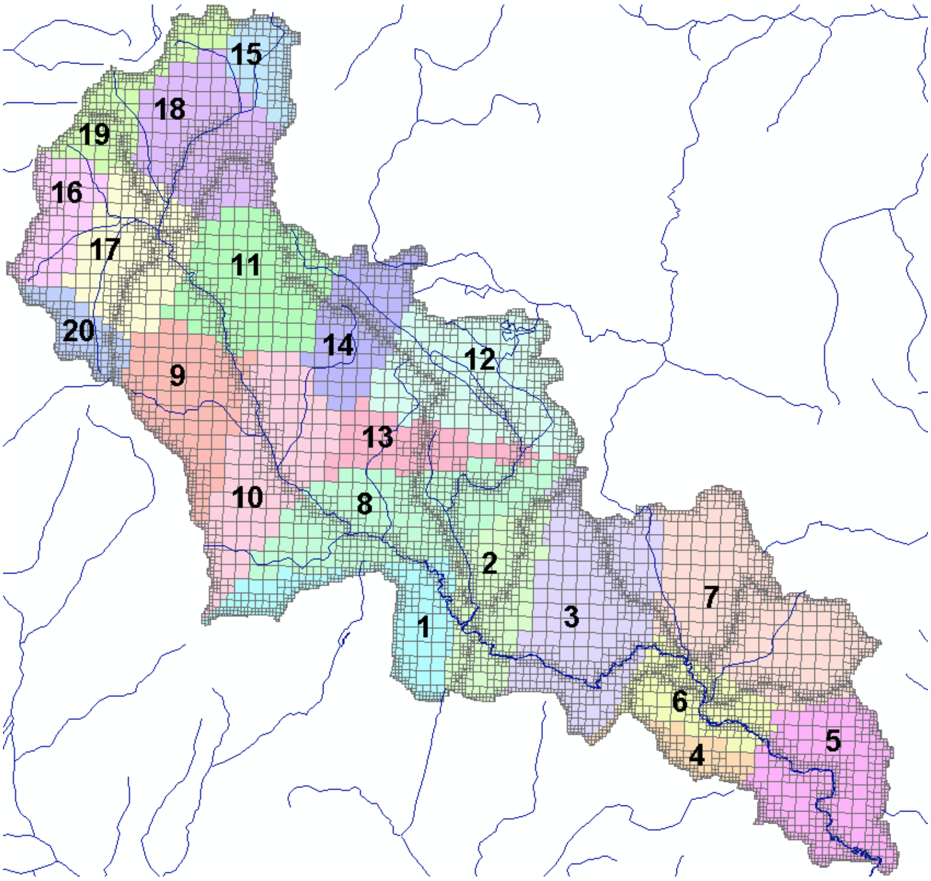


Figure 44 - Thiessen polygons (influence zones) for the complete set of twenty rain stations covering Bulgaria and Greece

III-5-3 – The determination of PET parameters

As a first hypothesis, it was decided to define the Potential Evapotranspiration (PET) using a unique average monthly curve over the entire Mesta-Nestos basin. After comparing various data sources, the Thornthwaite PET calculated at Nevrokopi (Upper Drama basin) by A. Dimadi (Table 13) was selected (Dimadi A., 1988, pp 99).

Average monthly PET in Nevrokopi	
Month	**PET (in mm)**
Aug	96.0
Sep	76.0
Oct	49.0
Nov	28.0
Dec	5.0
Jan	1.0
Feb	9.0
Mar	24.0
Apr	44.0
May	69.0
Jun	87.0
Jul	98.0

Table 13 - Annual average Thornthwaite PET calculated at Nevrokopi (Upper Drama basin)

However, from the initial results produced by MODSUR runs, it was apparent that the flow amount downstream of Momina-Kula needed to be reduced to insure a better fit with measured values. Evapotranspiration being one of the major factors controlling the river flow "production" it was speculated that the Nevrokopi PET curve was too low, in particular during the winter. It was thus decided to experiment with average monthly evapotranspiration curves with higher values such as those computed for Thessaloniki and Alexandroupolis using the Turc formula and which are published in the European Solar Radiation Atlas (ESRA, 1984) (Fig. 45).

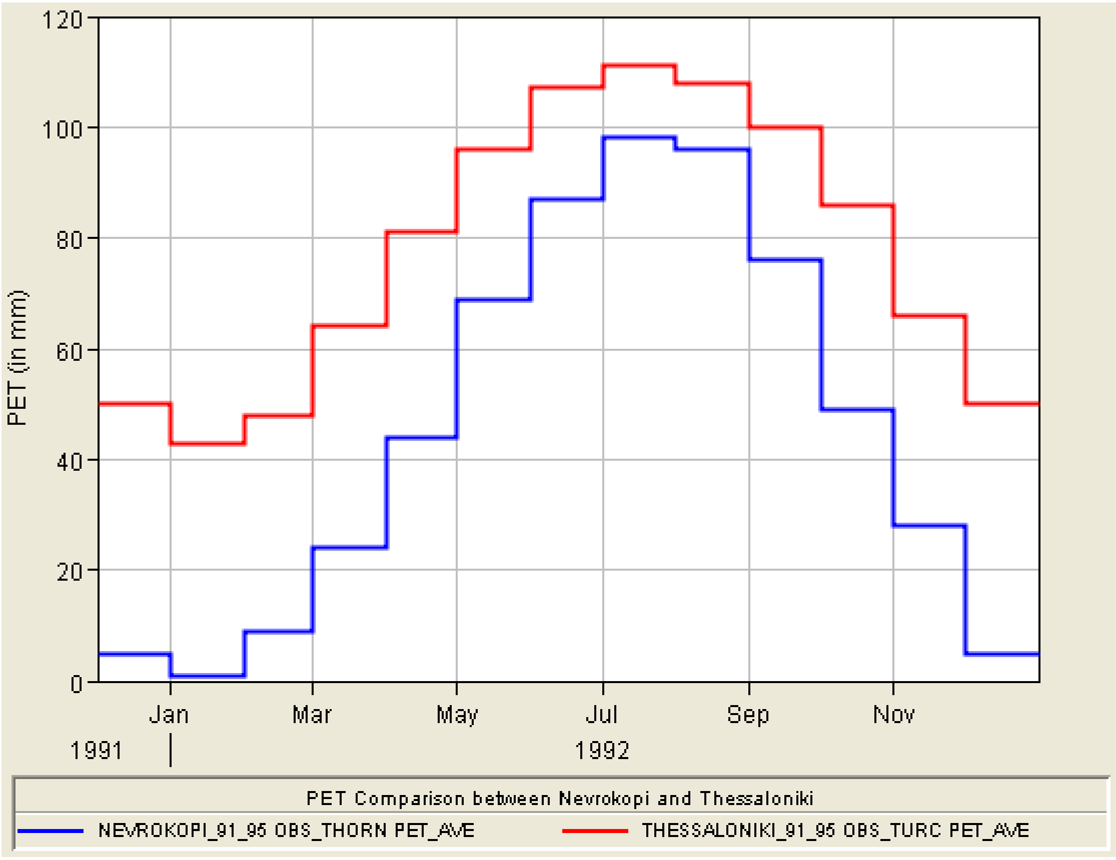


Figure 45 – Comparison between average monthly PET published for the two stations of Nevrokopi and Thessaloniki both situated in Northern Greece.

Finally, on the basis of observed climate contrasts, it was decided that the Nevrokopi PET should be applied to the northern portion of the Mesta-Nestos basin in Bulgaria and that the Thessaloniki PET would better fit the climate conditions of the southern part situated in Greece. However, due to the important basin relief, compared with the flat area conditions of PET computations, the available evapotranspiration values were divided by a "form factor" of 1.414 in order to account for the marked topography of the basin, trending North-South (Fig. 46).

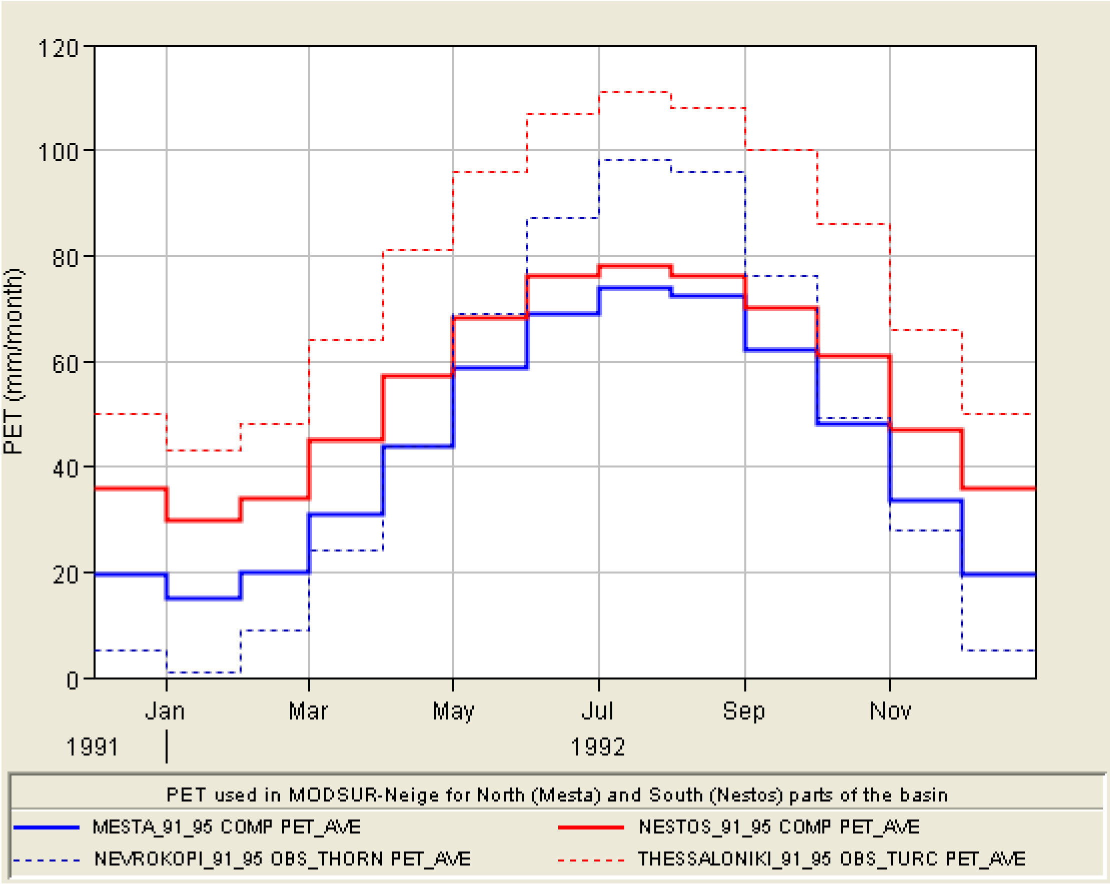


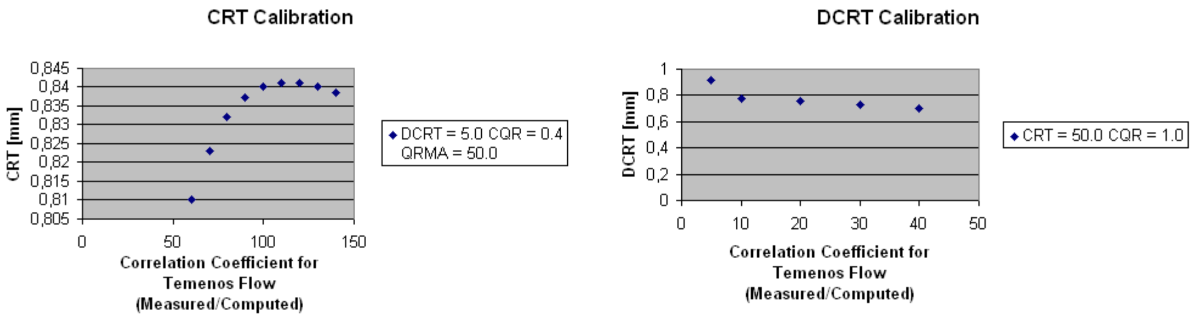
Figure 46 - Adapted PET selected in MODSUR for the Bulgarian (Mesta) and Greek part (Nestos) of the basin

III-5-4 - The calibration of the MODSUR "production functions"

The calibration of MODSUR has been conducted over the period raging from 1 August 1991 until 31 July 1995. A first hypothesis was made of a uniform "production function" for which the infiltration was set to zero (*FN* = 0.0). On this basis, systematic variations of other parameters were tested in order to evaluate the sensitivity of MODSUR to these parameters and eventually identify an optimum in their determination.

A – Initial calibration exercise

The following illustrations (Fig. 47) display sensitivity analyses results for the *CRT* (midlevel in top soil reservoir) and *DCRT* (minimum amount of moisture in top soil reservoir) parameters. They tend to show that best correlation between measured and computed flows at Temenos are obtained with *CRT* = 84 mm and *DCRT* = 8 mm, when each of these parameters are varied independently.



a) Abacus of sensitivity to CRT *b) Abacus of sensitivity to DCRT*

Figure 47 - Calibration experiment conducted on the upper soil reservoir parameters (*CRT-DCRT*)

Initial best parameters setting for the uniform "production function" was finally determined as:

CRT = 115 mm, *DCRT* = 5 mm, *R* = 0 mm, *FN* = 0 mm, *CQR* = 0,2 mm and *QRMA* = 8 mm

The corresponding MODSUR results for the Temenos flow station (Fig. 48) display a good correspondence between measured and computed flows in terms of seasonal variations. However, the computed flow is systematically in excess. Lower initial values during the first computed semester (idem, Aug-Dec 1991) are merely an artifact due to the fact that top soil reservoir is empty at the start of MODSUR (R = 0.)

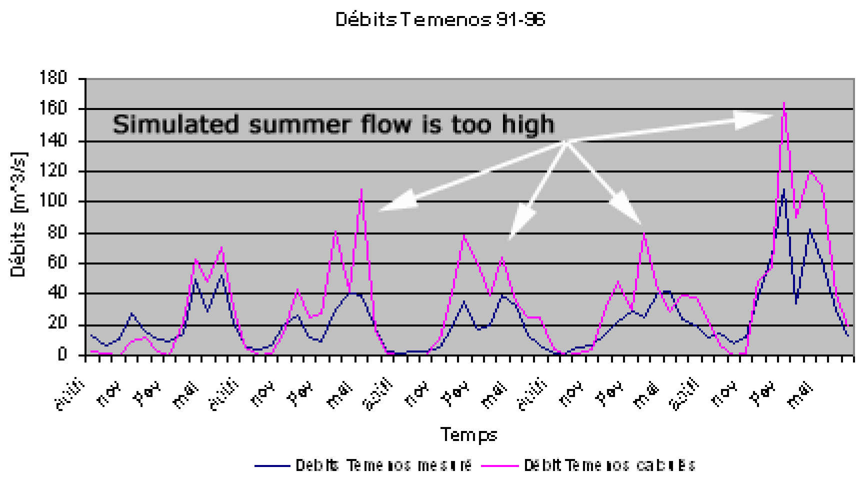


Figure 48 - Comparison between measured (blue) and computed (magenta) flow values at Temenos for the period Aug 1991 to Aug1996 after initial calibration

The simulation results for Momina-Kula (Fig. 49) are less satisfactory. In particular, the computed flow goes to zero during summer periods while measured summer flow is sustained, probably under the influence of either snow stock melting or ground water discharge.

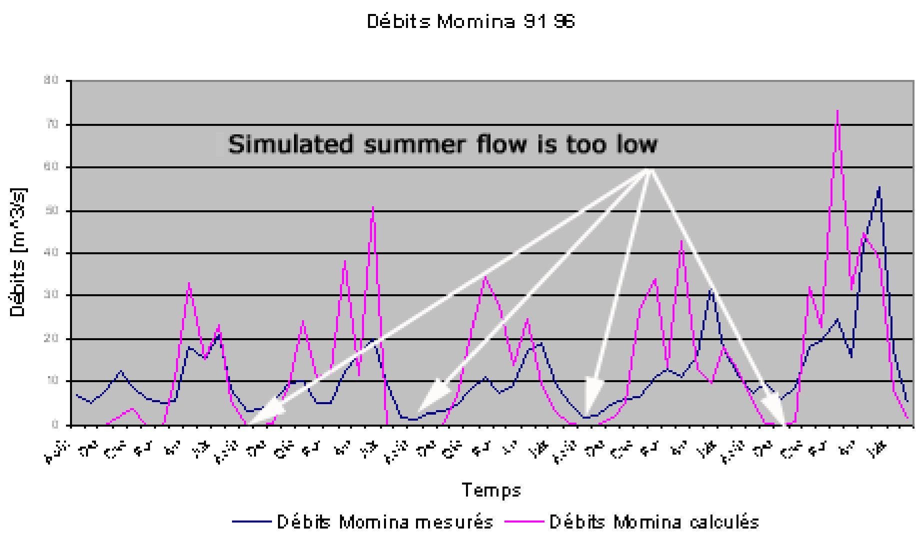


Figure 49 - Comparison between measured (blue) and computed (magenta) flow values at Momina-Kula for the period Aug 1991 to Aug1996

When looking at the differential flow between the Temenos and Momina-Kula stations (Fig. 50), the excess flow computed on the corresponding sub-watersheds is even clearer. It is to be noted that the near zero flow during summer periods for both computed and measured sequences is also a clear indication that during this season, the river flow is maintained exclusively from the contribution of the Momina-Kula headwaters in Bulgaria.

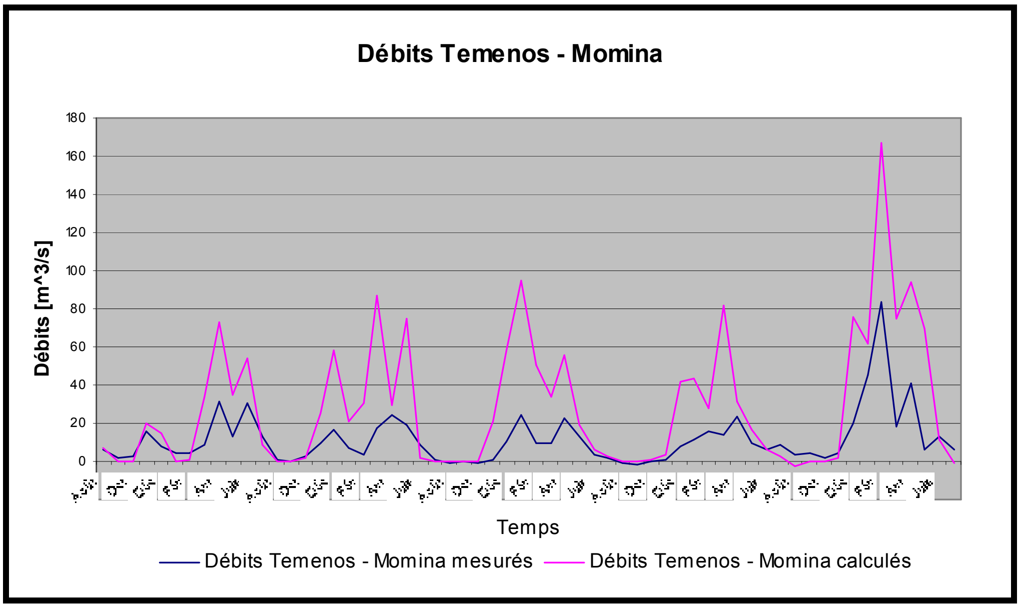
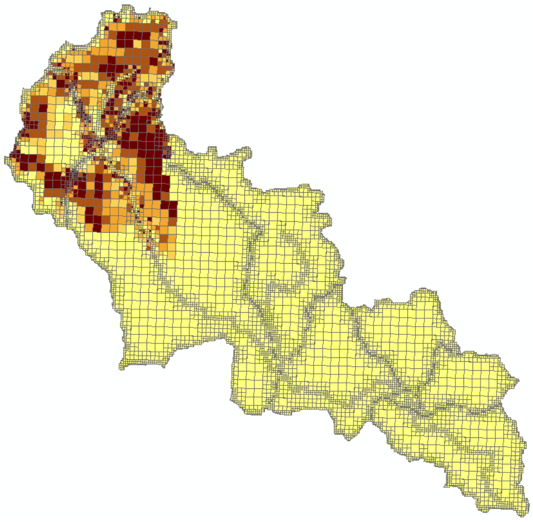


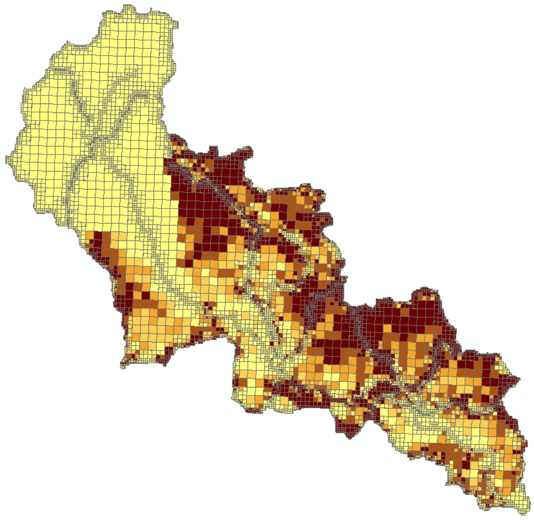
Figure 50 - Comparison between measured (blue) and computed (magenta) flow differences between Temenos and Momina-Kula for the period Aug 1991 until Aug1996

B - Taking into account the actual land use and terrain characteristics

In order to better apprehend the land use and landscape contrast existing between the Bulgaria and Greece parts of the basin, two sets of production functions (PDs) have been created for each of the following two sub-basins groups: 1-drainage of Momina-Kula and 2-Remaining Mesta-Nestos+Dospat. These PDs are produced by regrouping Corine Land Cover classes into 4 themes: Bare, Agriculture, Grass and Forest and computing the percentage of each of these classes for each element of the MODSUR grid using the ArcGIS program (Fig. 51).



a) Production function map for "Forest" class in the Momina-Kula sub-basin



a) Production function map for "Forest" class in the Dospat, Nestos sub-basins

Figure 51 - Example of production function deduced from Corine Land Cover

C - Allowing infiltration to shallow groundwater

The initial calibration of MODSUR has shown that excessively low values in the summer remained for the simulated Momina-Kula flow. This is a major limitiation because as it has already been illustrated in section B, the flow at Temenos in the summer is essentially maintained by the flow incoming from Bulgaria. It is also a critical contribution to the flow of the Nestos in the summer if a minimum "ecological" flow needs to be maintained.

Thus it was decided to introduce a "shallow" aquifer in the Momina-Kula sub-basin part. This was done in MODSUR using the intermediate infiltration reservoir defined by parameters *QIMA*, *CQI* and *RNAP* (see Chapter II). The retention parameter *CQI* is of particular importance since it defines the amount in mm per time step (here, by day) released from this intermediate reservoir. The *RNAP* parameter is also set to a null value which means that there is no transfer to the deeper aquifer. In this case, whatever is released from the intermediate reservoir goes back to run-off. With these infiltration settings the low flow in summer is correctly maintained with however a slight shift in time of about one month for the lowest flow event.

Furthermore, infiltration was limited to the forested area "production function" (PD) which forms better conditions for the presence of a shallow aquifer rather than bare lands or grasslands which are more prone to quick surface runoff (Fig. 52). The following parameters were selected:

CRT = 115 mm, *DCRT* = 5 mm, *R* = 150 mm, *FN* = 10 mm, *CQR* = 0.2 mm, *QRMA* = 8 mm, *CQI* = 0,01 mm, *QIMA* = 100.0 mmm and *RNAP* = 0.0

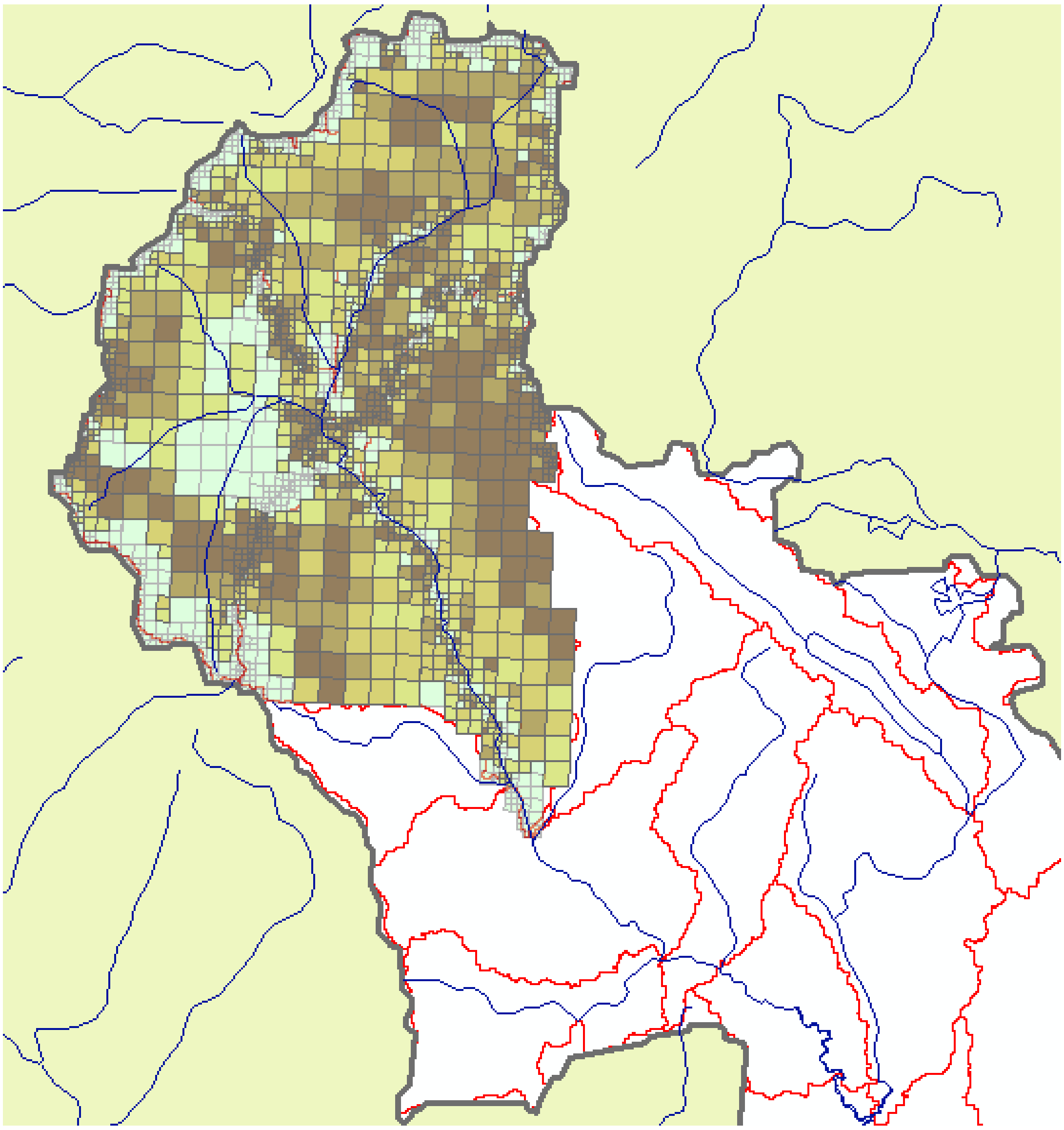


Figure 52 - Map of infiltration density modeled by MODSUR in the Momina-Kula sub-basin

III-5-5 - Snow cover simulation in the upper mountain part

Regarding the climate phenomenology of the upper part of the Mesta basin it sounded reasonable to introduce snow storage capacities in the model. This has been done using the MODSUR-NEIGE module. After initial experiments with this program, it was decided to restrict the area concerned with snow storage to the highest parts of the head of the basin, namely the Mussala and Vihren Thiessen polygon areas. In order to run the MODSUR-NEIGE program one needs to take into account the daily temperature as well as the precipitation and the PET.

Monthly and daily temperature records have been acquired from different sources. In Greece they were provided by the Ministry of Environment (MINENV or YPEXODE) and the Hellenic National Meteorological Service (HNMS) (Table 14). In Bulgaria, the data for Bansko and Mussala were provided by various scientific sources.

Station name	Altitude(m)
Semeli-Petrochori	70
Messochori	130
Sidironero	629
Bansko	936
Mussala	2925

Table 14 - Meteorolgy stations used for surface temperature determination

A systematic correlation study between stations has been conducted (Fig. 53). It displays a marked linear correlation between stations as well as a systematic variation of temperature with the station altitude. In particular the temperature lapse coefficient corresponding to the transition between the city of Bansko (936 m) and Mussala peak (2935 m) is evaluated by linear regression to be equal to 5.6 °C/km. This is markedly similar to results obtained by other groups in other mountainous areas (Jain S.K. et al., 1998).

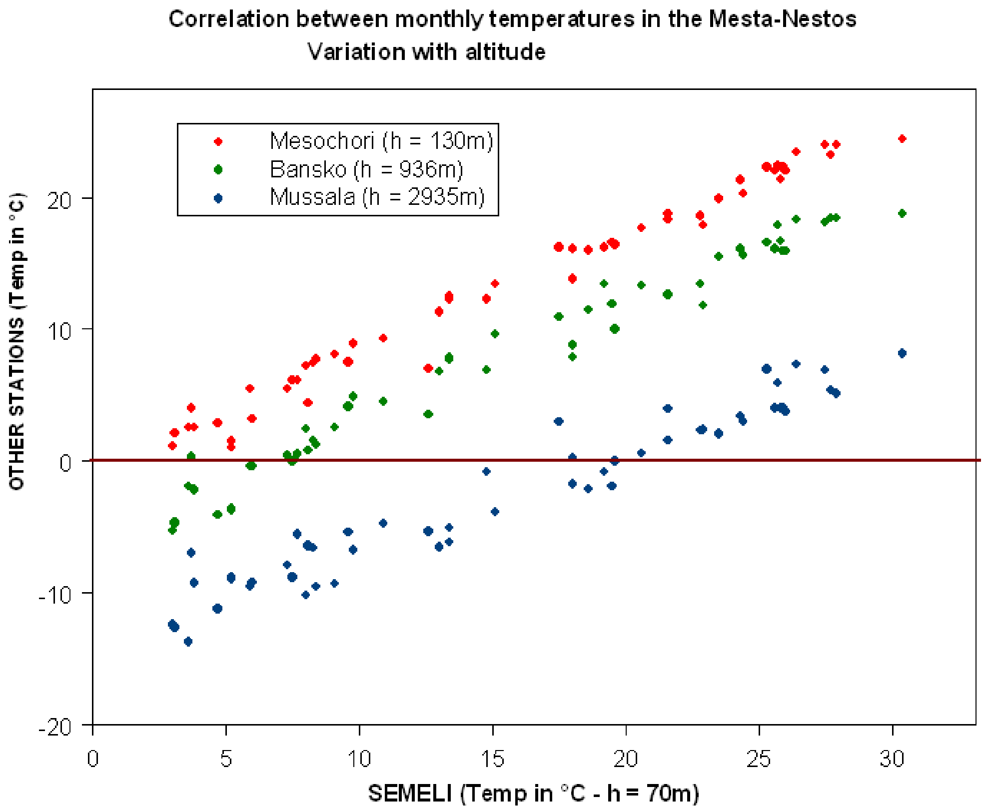


Figure 53 - Temperature correlation study between stations as a function of station height (h)

In the MODSUR model, the temperatures of each station are assigned to the grid cells belonging to the corresponding Thiessen polygons. Thus the average altitude of each of the two polygonal zones corresponding to Mussala and Vihren peaks have been used in order to use the temperature-altitude regression. Thus starting from the average monthly temperatures measured at Mussala Peak, the temperatures assigned to the cells of the Mesta-Nestos MODSUR-NEIGE model belonging to polygon 19-Mussala have been increased by 7.2 °C and those assigned to the cells belonging to polygon 20-Vihren have been increased by 4.8 °C (Fig. 54).

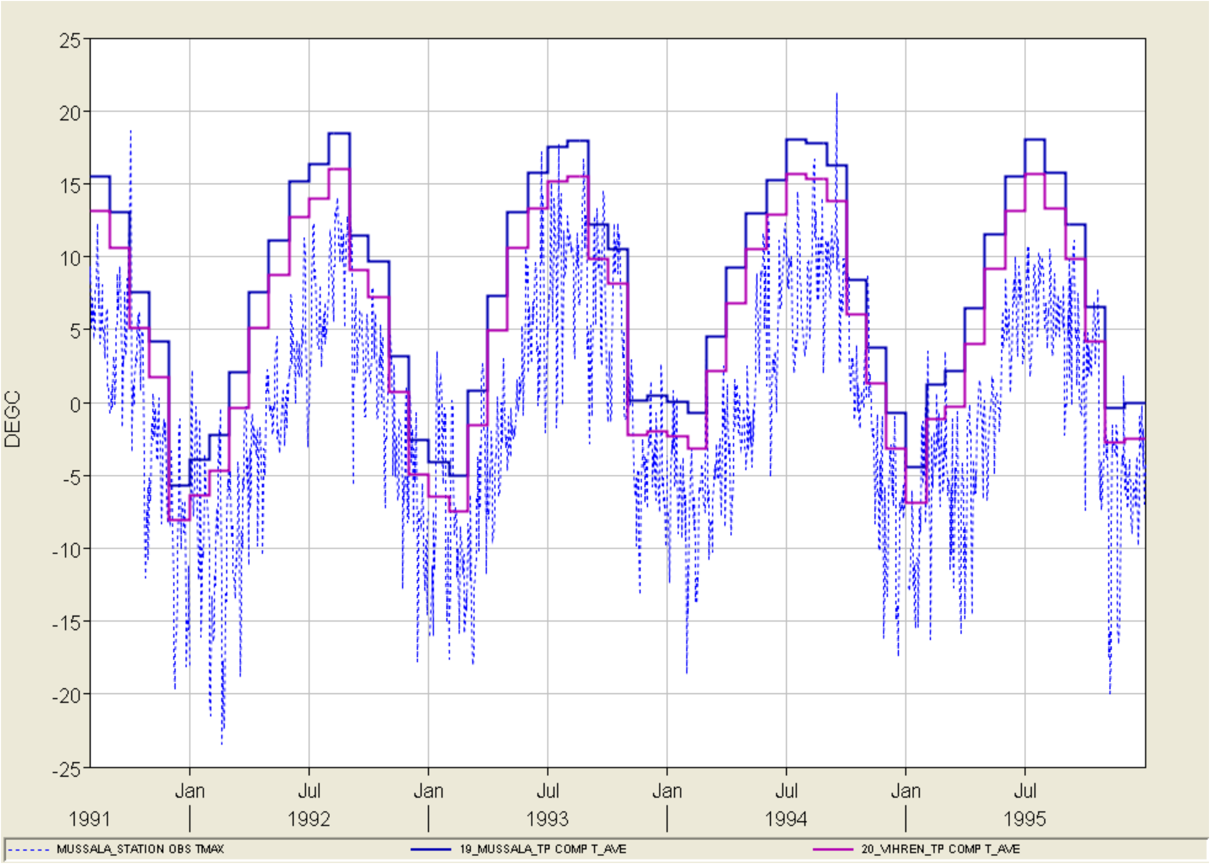


Figure 54 - Monthly temperatures assigned to the 19_MUSSALA (Blue) and 20_VIHREN (Purple) zones as compared to the daily temperatures measured at peak MUSSALA (Dotted blue)

The daily temperatures of for the other stations numbered 1 to 18 have been set to a constant of 25 °C. This is a model artifact which enables the restriction of snow storage simulation part in MODSUR-NEIGE to the geographic zones covered by the 19_MUSSALA and 20_VIHREN Thiessen polygons.

II-5-6 - Final calibration run and interface with HEC-ResSim

On the basis of the difference existing in stream flow behavior, climate, geology and land use between the high mountain part and the rest of the basin, the MODSUR basin has been finally separated between 4 different zones (Fig 55):

- 1) Greek part: High PET without snow storage;
- 2) Mid-basin in Bulgaria: Low PET without snow storage;
- 3) Lower Momina-Kula sub-basin: Shallow groundwater table in the forested areas and low PET without snow storage
- 4) Higher Momina-Kula sub-basin: Snow storage with low PET and no infiltration

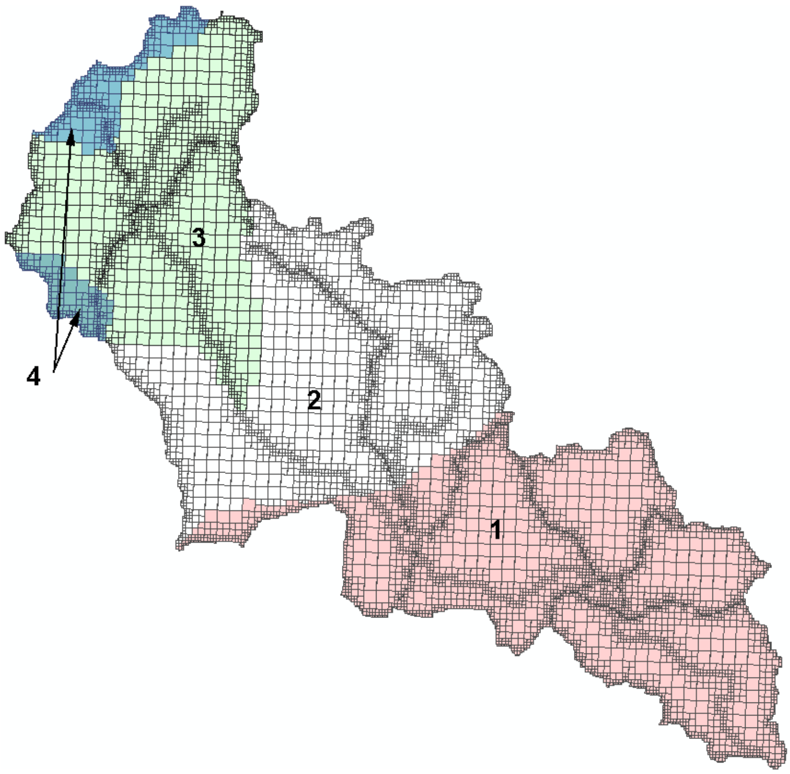


Figure 55 - Areas of the MODSUR grid concerned by different phenomenologies

Some concern is caused by the fact that in this MODSUR model, all the flow from the Dospat branch was received in Greece, despite the fact that it is well known that the Dospat dam diverts all its water to the Maritza basin. Thus it was decided to add an outflow point (*éxutoire*, in French) at the Dospat dam location. Furthermore, in order to adapt the results of the model to the needs of the Temenos dam project simulation with HEC-ResSim, three other sub basins have been created with outflows at Momina Kula, Temenos and Toxotes (Fig 56). These artificial sub-watersheds provided more modularity in the management of the data transfer between MODSUR-NEIGE and HEC-ResSim. This transfer is performed via the HEC-DSS data management system.

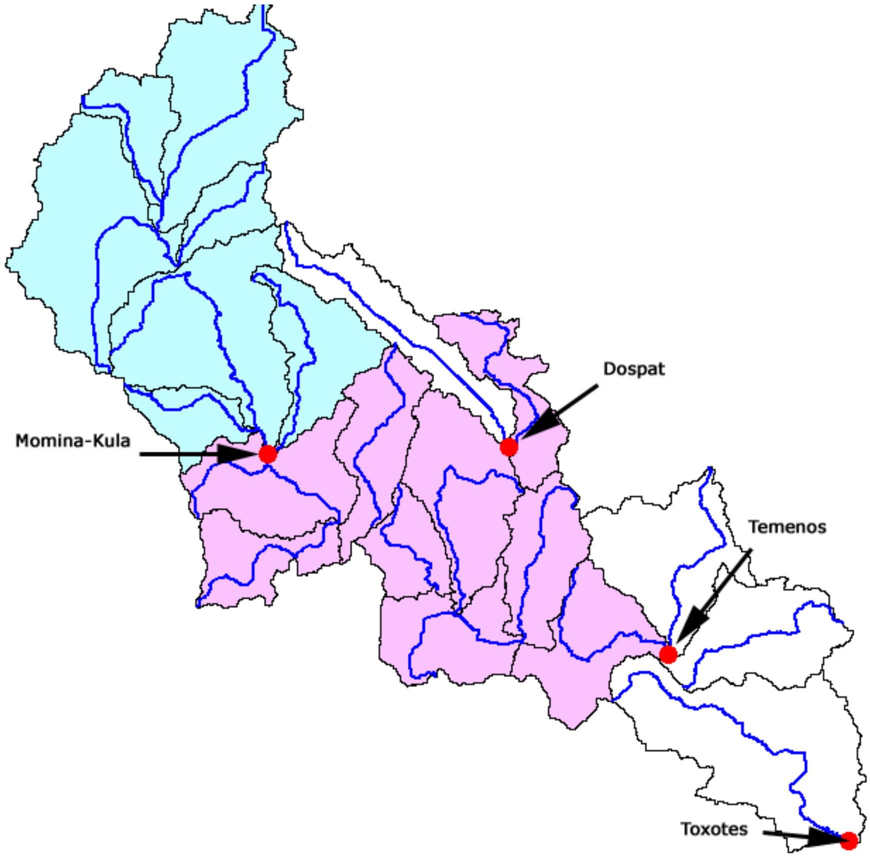


Figure 56 - Separation of the MODSUR model into separate areas for Momina-Kula, Dospat dam, Temenos and Toxotes final outflow

Several flow measurement cells have also been added to the MODSUR model in order to facilitate the evaluation of past and future dam projects in Bulgaria and Greece. These flow measurement cells provide an automated mean of reconstructing the simulated stream flow at the following geographic points:

- 1 - Mesta dam
- 2 - Gostoun dam
- 3 - Barutin dam
- 4 - Illinden dam
- 5 - BG-GR Border
- 6 - Thissavros
- 7 - Platanovryssi
- 8 - Temenos
- 9 - Arkoudorema

Final model performance has been evaluated by direct comparison between the calculated and measured monthly flows at Momina-Kula in Bulgaria and Temenos in Greece. Figure 57 presents such results for the Momina Kula station and compares the final calibration run (V10M1) with the results obtained the initial calibration run (V2Bis) which used a uniform PET and the same "production function" over the whole basin. The improvement should be noted concerning the values of the low flow in the summer period.

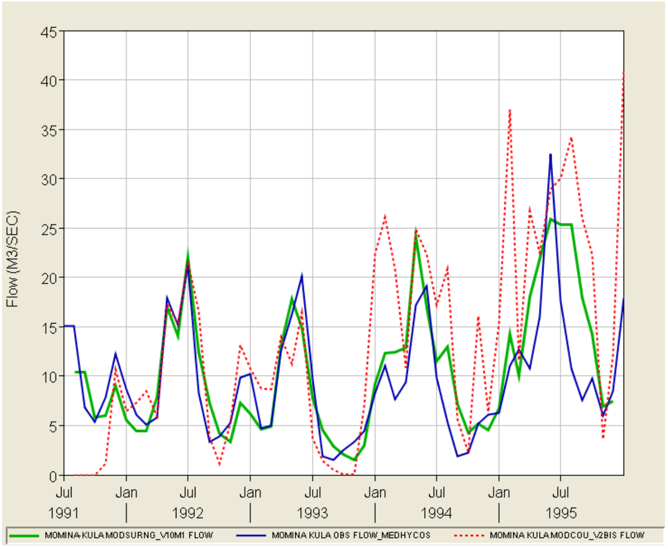


Figure 57 - Comparison of MODSUR simulation results for the Momina-Kula station

Blue = Measured flow, Dotted red = Initial run V2Bis, Green = Final simulated flow (Run V10M1)

For the Temenos station (Fig. 58) a similar agreement is illustrated between observed and simulated flow values obtained from the final calibration run (V10M1).

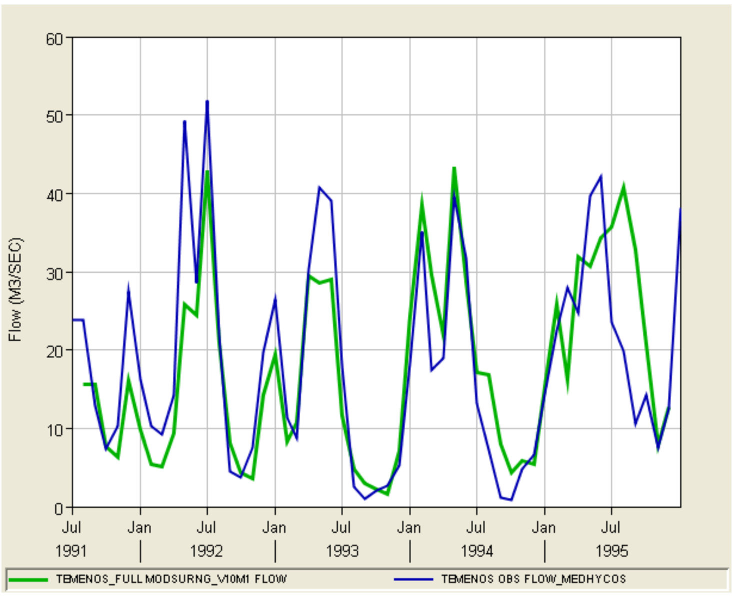


Figure 58 - Comparison of MODSUR simulation results for the Temenos station

Blue = Measured flow, Green = Final simulated flow (Run V10M1)

III-6 - **Modeling the Nestos dams complex with HEC-ResSim**

The modeling of the Nestos dams' complex using HEC-ResSim was carried out in a three phase process: the design of the Nestos equipment network, the parameterization of the dams' components and the simulation of the different operational scenarios.

III-6-1 – The Nestos watershed network setup

The initial phase of the modeling concerns the tracing of the connected flow elements of the river watercourse between the Greek border and the Toxotes dam where water is distributed between the irrigation networks and the last Nestos stretch down to the delta mouth (Fig. 59). Apart from the main course, the modeling includes the placement of inflow segments gathering the water drained from the various watersheds nourishing the Nestos river. Most of these watersheds divide the basin into lumped areas contributing water to the sections of the river situated between the various simulated dams with the exception of the first one which represents the lumped water contribution from the Mesta river (idem, the Bulgarian side of the basin). The first inflow has been artificially placed in order to simulate a possible reduction of the Mesta river flow in strict compliance with the bilateral flow treaty between Bulgaria and Greece. The total of five watershed inflow points is placed as follows:

- Border inflow: This point receives the flow from the Mesta watershed and determines the quantity of water which enters the Greek part of the basin from Bulgaria.

- Thissavros inflow: It gathers the water drained between the Bulgarian border together with the remaining flow of the Despatis (idem, Dospat) downstream from the Dospat dam in Bulgaria.

- Platanovryssi inflow: It receives the water drained by the watershed part situated between the Thissavros and the Platanovryssi dams. It is mostly contributed by the Diavolorema tributary.

- Temenos inflow: Gathers the water drained between the Platanovryssi dam and Temenos dams. It is a small watershed with no major drainage. It is of note that the Arkoudorema tributary reaches the Nestos beyond the future location of the Temenos dam.

- Toxotes inflow: It receives the water drained by the last portion of the Nestos watershed between Temenos and the Toxotes. The main contribution comes from the Arkoudorema right at the beginning of this watershed portion. Downstream from this confluence the mainstream crosses karstic marble formations with very little flow contribution.

All the necessary natural flow series which are fed into HEC-ResSim for each of these points are obtained from the results of the MODSUR-NEIGE basin simulation using the HEC-DSS program as a mean of data transfer.

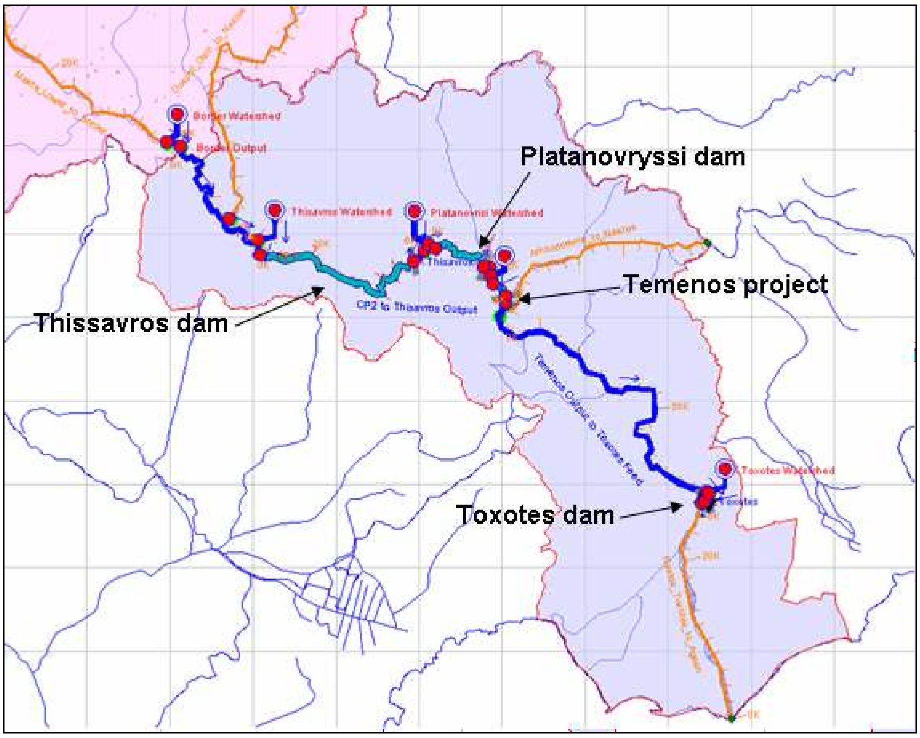


Figure 59 - Representation in HEC-ResSim of the five lumped watershed inflow points (indicated by red dots surrounded by a white strip) along
with the three existing dams as well the Temenos project dam.

II-6-2 – The parameterization of the Nestos hydropower dams

Following the geographic placement of the HEC-ResSim elements including main stream segments, inflow points, dams with their connections to the main river stream as well as irrigation canals, the next step of the HEC-ResSim set-up is the definition of the technical parameters defining for each dam: the geometric properties of the pool, the capability of the hydropower plant if appropriate and the definition of the various management constraints regarding the electric power production, the regime of released flow and the operation in conditions of flooding.

The physical and operational elements used for the hydropower dam settings are based on data published by PPC for the existing Thissavros and Platanovryssi equipments as well for the future Temenos project (Table 15).

Operational parameters	Thissavros	Platanovryssi	Temenos
River floods catchment (Km^2)	4263	4655	4666.4
River flow catchment (Km^2)	3698	4090	4101.4
Mean discharge (1964-65/1982-83) (m^3/sec)	38.84	43.14	45.22
Upper operation level (UOL) (m)	380	227.5	154
Lower operation level (LOL) (m)	320	223.5	147
Volume in UOL 10^6 m^3	750	84	11.35
Useful volume 10^6 m^3	565	11	6.00
Reservoir surface in UOL (Km^2)	18	3.25	1.05
Height of Tailrace Tunnel (m)	226	151	127
Height of plant intake	309	190	137.8
Upper spillway level	385.82	229.95	159.5
Height of crest dam (m)	390	230	160
Height (m)	175	95	45
Number of units	3	2	3
Total power (MW)	300	100	19.5
Produced energy (GWh):			
Primary	285	167	50
Secondary	140	73	22
Total	425	240	72

Table 15 - Technical and power generation characteristics of the Nestos hydropower dams' complex

As an illustration of how HEC-ResSim dam parameters have been set, I present here the detailed process followed for the Thissavros dam (Fig. 60). The settings for the two other hydropower dams of Platanovryssi and Temenos are not illustrated in detail because they quite similar both in terms of technical performances and rules of operation.

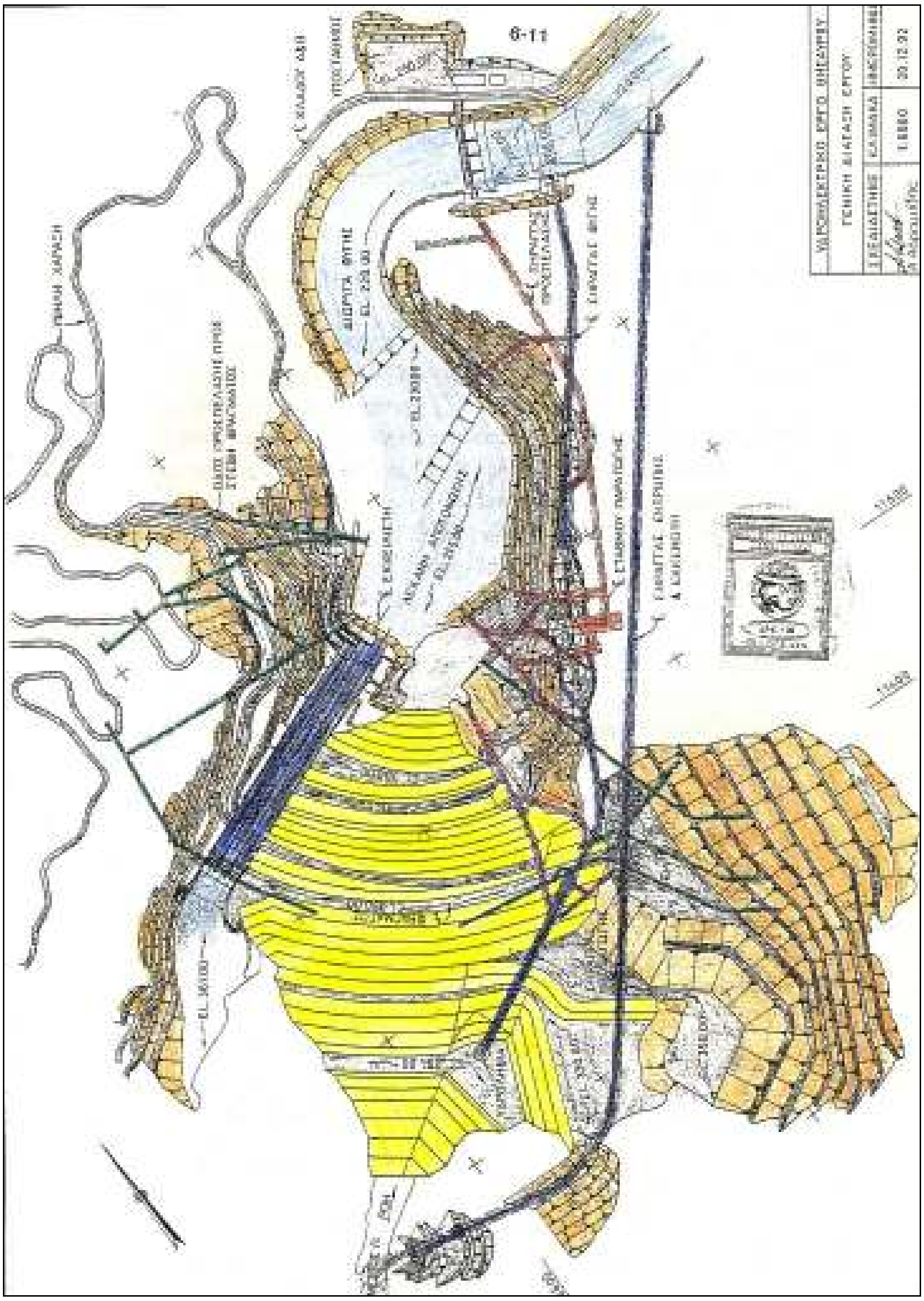


Figure 60 - Design of the Thissavros dam and its construction characteristics at an original scale of 1:60.000 (source: PPC)

A – Definition of the pool parameters

For the Thissavros reservoir characteristics, the height of the bottom duct (idem, tailrace tunnel) is 226 m. This defines the lowest elevation from which it is possible to release water. Below this level the storage capacity of the reservoir is considered to be equal to zero since the stored water cannot be used. When the upper operation level is reached at 380m, the volume of the stored water is 750 million m^3 and the area covered with water is 18 km^2. HEC-ResSim provides various models of relation between pool area and water height. In the case of the Mesta-Nestos runs, a linear variation has been selected for all the modeled dams. Using this hypothesis (Fig. 61), it is deduced that when the crest of the flood overflow spillway is reached at 385.82 m, the Thissavros lake is holding 800 million m^3 of stored water for a total lake area of 19 km^2.

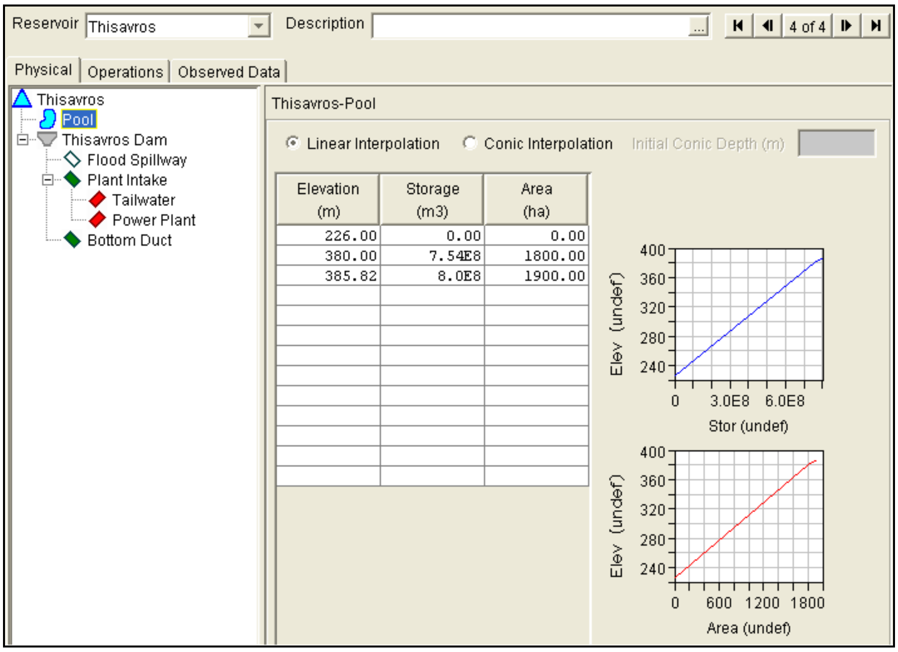


Figure 61 - The storage capacity and the reservoir surface in different elevationsof the Thissavros reservoir

B – Parameters of the hydrotechnical equipment

The next group of parameters which needs to defined concerns the various hydrotechnical equipments, namely: the flood spillway, the plant intake and the bottom duct (idem, tailrace tunnel). All these outflows have hydrodynamic properties which need to be set.

The flood spillway

In case of flood, the spillway starts to operate when the water level is 380m but as the flood presses on, water outflow speed increases until the maximum level of operation of the spillway is reached, namely 385.82 m. If the water would go higher, the whole dam would be over-topped and in danger of collapsing. This is why the maximum spillway flow is usually set to a very high value. In the case of Thissavros, the engineering limit is set to 6000 m^3/sec.

This far above the maximum daily flow ever measured for the Nestos which has been around 800 m^3/sec. As the HEC-ResSim done for my study has been performed on a daily basis, the control variables cannot be modeled at a finer time scale. This is unfortunate, because operating at maximum engineering spillway flow of 6000 m^3/sec would empty the whole Thissavros lake in one day.

This is why the maximum daily spillway flow had to be set to a “realistic” daily average. The relation between the elevation of water in the spillway and the flow intensity (Fig. 62) was set by analogy with published cases of HEC-ResSim runs (McKinney, D. C., 2005) and consequently the maximum daily flow was set to 432 m^3/sec.

Elevation (m)	Outflow (cms)
380.0	0.0
382.0	54.0
383.5	152.8
384.7	260.0
385.0	280.8
385.82	432.2

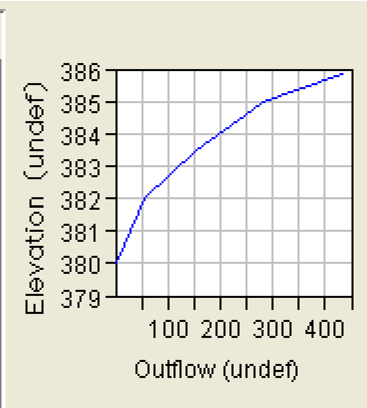


Figure 62 - Spillway outflows settings for the Thissavros reservoir

The plant intake

The plant intake setting is concerned with the relation between the elevation of the water in the lake and the flow intensity in the pipe reaches the turbines. This intake is in operation as soon as the water level reaches 309 m. Although no engineering details were published by PPC on the subject, it was decided to set the maximum flow in the pipe at 200m^3/s based on similar published hydropower equipment performance. Le law of variation has been set to be linear (Fig. 63) up to the maximum charge when the dam is reaching the flood spillway level.

Elevation (m)	Max Capacity (cms)
309.0	0.0
380.0	200.0
385.82	200.0

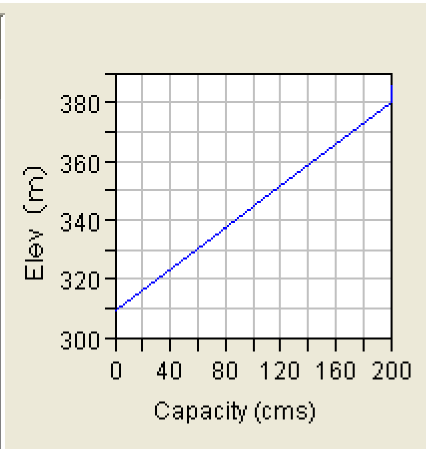


Figure 63 - The Plant Intake component of the Thissavros dam in HEC-ResSim.

The bottom duct

The hydrodynamic properties of the bottom duct need also to be defined. A maximum flow capacity of 100 m^3/s has been selected, the opening of the duct starting as soon as the level of the lake is below the plant intake level. The flow decreases linearly with lake elevation down to the opening hole of the duct (idem, tailrace tunnel) which is situated at 226 m (Fig. 64). At that height, the lake is empty and the flow is null.

It is to note that since the Thissavros plant was put in operation in 1996, the PPC managers have indicated that the bottom duct has never been opened. This means that so far the lake has received enough water for its plant to operate using the plant intake.

Elevation (m)	Max Capacity (cms)
226.0	0.0
309.0	100.0
385.82	100.0

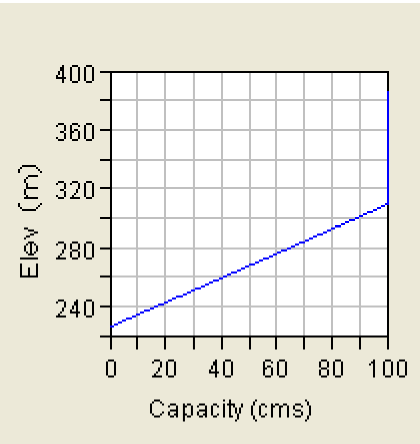


Figure 64 - The Bottom Duct component of the Thissavros dam in HEC-ResSim.

C – The power plant parameters

In HEC-ResSim, the power plant module is used in order to define the electric power generated by the turbines. The total installed capacity of the Thissavros plant is 300 MW. However, 100 MW are used for the pump storage operation when water is daily pumped back from the Platanovryssi pool. Thus the installed capacity has been set to 200 MW. As the simulation performed in my study was set to a daily time interval, it was not possible to explicitly simulate the back pumping operation. But the use of the differential capacity is a way to account for the "useful" power produced by the Thissavros dam, which is the installed capacity diminished by the power used by the daily operation of the pumped storage.

D - Operational parameters

In HEC-ResSim, the dam operation is defined by three typical operation modes, also called “zones”, which are called respectively: Flood control, Conservation and Inactive. These “zones” of operation are based on specific reservoir elevations and contain a set of rules that describe the goals and constraints that should be followed when the reservoir's pool elevation is within a particular zone (idem, the lake level is situated between prescribed levels).

For each mode of operation (idem, zone), the rules are ordered by priority. The HEC-ResSim algorithm attempts to fulfill the requirements of the highest priority rule, if these are successfully reached, the program switches to the next rule and will proceed in the same fashion.

The flow requirements for irrigation and environmental constraints

As my study is primarily aimed at studying the possible benefits of the Temenos project in terms of improvements to the agriculture of the Nestos delta and the Xanthi plain as well as the sustainability of a good ecological status for the Nestos waters, particular focus has been put on the flow requirements necessary to meet these goals.

Regarding the state of the environment, it has been assumed since the early days of the planning of the Nestos dams that a minimum environmental flow to the delta mouth of $6.0m^3/s$ was needed in order to fulfill the needs of the ecosystem.

As for the agricultural demand in irrigated water the Prefecture of Kavala regularly publishes the monthly requirements of the existing combined irrigation network serving the Kavala side of the delta and the existing upper Xanthi side. The statistics published in 2000 have been retained in order to define the rules of operation of the Nestos dams (Table 16). They illustrate in particular, the peak demand in July which is the very period when the natural flow of the Nestos in minimal.

Months	April	May	June	July	August	September
Required water volumes (m^3/s)	11.5	15.7	18.5	20.9	20	13.0

Table 16 - Water demand for the present state of the irrigation in the Nestos Delta (source: Prefecture of Kavala, 2000)

The water demand of the future extension of the irrigation network to the Xanthi plain after the construction of the Temenos dam has been evaluated using a coefficient of proportion equal to the ratio between the existing irrigated land and its future extension (As for the agricultural demand in irrigated water the Prefecture of Kavala regularly publishes the monthly requirements of the existing combined irrigation network serving the Kavala side of the delta and the existing upper Xanthi side (Table 17). More details about these evaluations are found in Chapter IV.

Months	April	May	June	July	August	September
Required water volumes (m^3/s)	5.7	7.8	9.2	10.4	10	6.5

Table 17 – Evaluated water demand for the future extension to the irrigation of the Xanthi plain

Flood control mode of operation

Two rules were used in order to define the Flood control mode which is triggered when the water in the lake reaches 385.82 m (the height of he crest of the overflow spillway). The first rule which was called "Plant Flood" simply states that power continues to operate with a plant intake flow of $200m^3/s$. The second rule is called "Duct Closed" and specifies that the door of the tailrace tunnel remains closed. A similar set of rules is applied in case of flood to the other two hydropower dams, namely Platanovryssi and Temenos.

Normal (idem, Conservation) mode of operation

For the normal mode of operation, also know as the Conservation mode, priority is given to sustain both the irrigation water demand and the ecological flow. If these requirements are met, the power plant is left to operate at its maximum possible power.

For Thissavros, the Conservation mode is triggered when the level of the lake is situated between the upper operational level of 380 m and the empty level reached at 226 m. The operation of the dam in the conservation zone is determined by the three following rules by decreasing order of priority: "Plant ToDay", "Plant Schedule" and "Duct To Day_Flow".

The "Plant ToDay" is the highest priority rule (Fig. 65). It is defined so that to maintain a minimum flow equal to the requirements of the irrigated land (Table 16) augmented by the ecological monthly flow of $6.0m^3/s$. It is of note that the supplemental requirements of the Xanthi plain have not been considered here as they are supposed to be coming from the operation of the future Temenos dam.

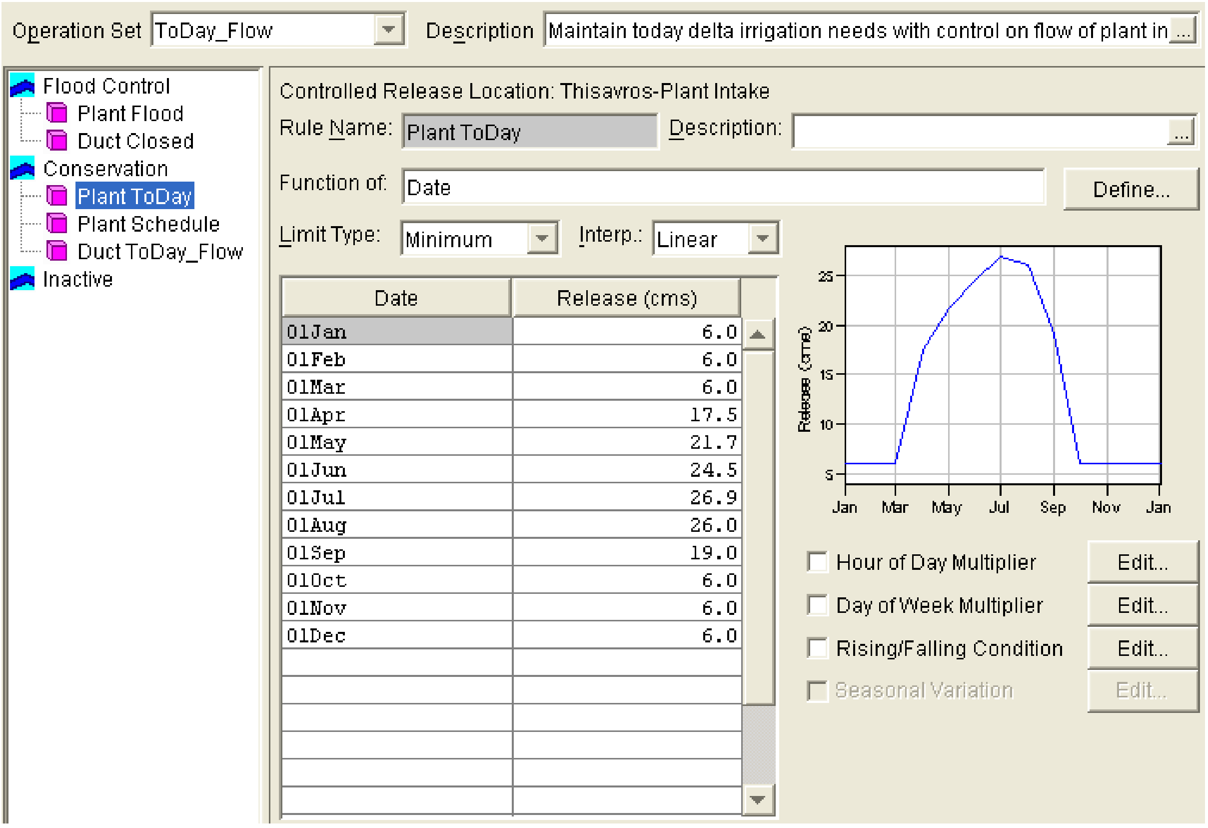


Figure 65 - Determination of the "Plant ToDay" rule of the conservation zone of the Thissavros dam operation

The "Plant Schedule" rule follows in priority and specifies that the power plant should operate at is the maximum possible level of 200 MWh on a daily basis. It does not mean that this level will always be reached as it requires that the plant intake delivers it maximum flow of 200m^3/s. This condition is not always possible.

Finally the "Duct toDay_Flow" rule (Fig. 66) defines the mode of operation which is triggered if the flow coming out the power plant is not sufficient to meet the requirements of agriculture and good ecology status. Table 18 displays the details of the flow specifications for the bottom duct. In effect, the monthly values are set so that when the power plant intake decreases, the doors of the bottom duct are opened so as to compensate for the loss. When the level of the lake drops under the height of the plant intake which is 309m, the bottom duct delivers the full required amount of water. This defines the conditions of operation under extreme drought or insufficient natural flow upstream from Thissavros. Similar rules are set for the other hydropower dams of Platanovryssi and Temenos.

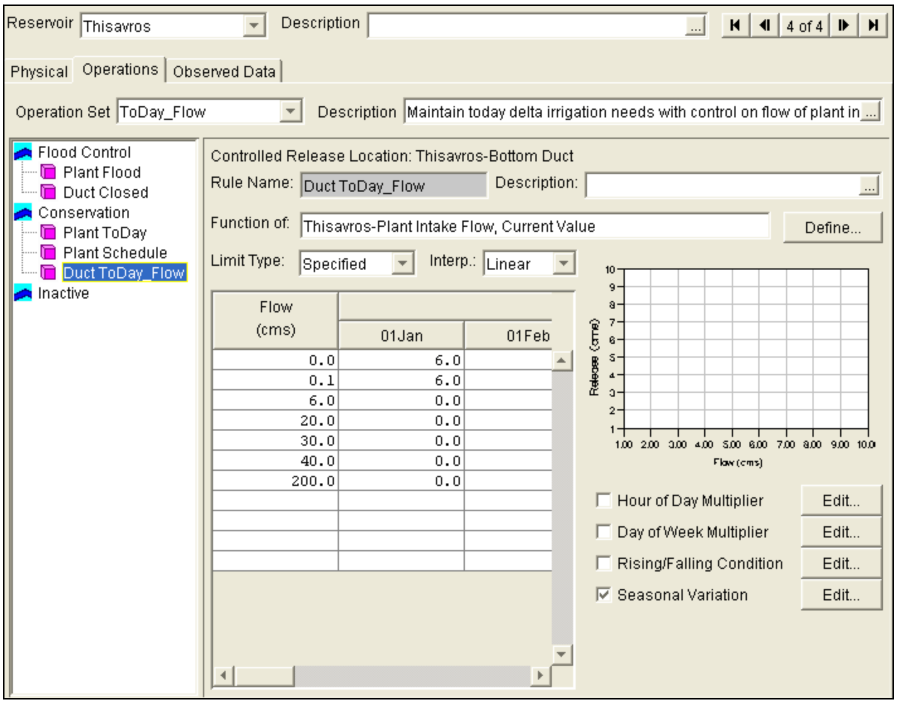


Figure 66 - The "Duct toDay_Flow" rule for estimating the excess water quantities for the agricultural and environmental flow demand.

Intake Flow (m^3/sec)	Releases (m^3/sec)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	6	6	6	19	21.7.	24.5	26.9	26	19	6	6	6
0.1	6	6	6	19	20.2	23	26.9	26	19	6	6	6
6	0	0	0	13	17.2	18	22.4	22	15	0	0	0
20	0	0	0	0	3.2	6	8.4	8	1.2	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	1.5	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0

Table 18 - Determination of the water releases in correlation with the plant intake flows addressed to power generation.

III-6-3 – HEC-ResSim parameters for the Toxotes irrigation dam

The Toxotes dam is located at the neck of the Nestos delta (Fig. 67). It is dedicated to water regulation and is equipped with a spill over levee bordered by two diversion channels serving the irrigation systems of the Nestos delta.

It is a relatively small dam with a maximum reservoir capacity of 30 million m^3 of water when the reservoir elevation is equal to 16.95 m. The maximum flood spill output is 2200 m^3/s which is considered safe for the Nestos river. The HEC-ResSim maximum output flow for the diversion channels has been set to 200 m^3/s (Table 19).

Reservoir Elevation (m)	Released capacity to Nestos outlet (m^3/s)	Released capacity to delta (m^3/s)	Released capacity to Xanthi (m^3/s)
10.0	0.0	0.0	0.0
11.0	60.0	60.0	60.0
12.0	160.0	80.0	80.0
14.0	500.0	150.0	150.0
16.95	2200.0	200.0	200.0

Table 19 – Relation between pool elevation and released water volumes for the Toxotes reservoir

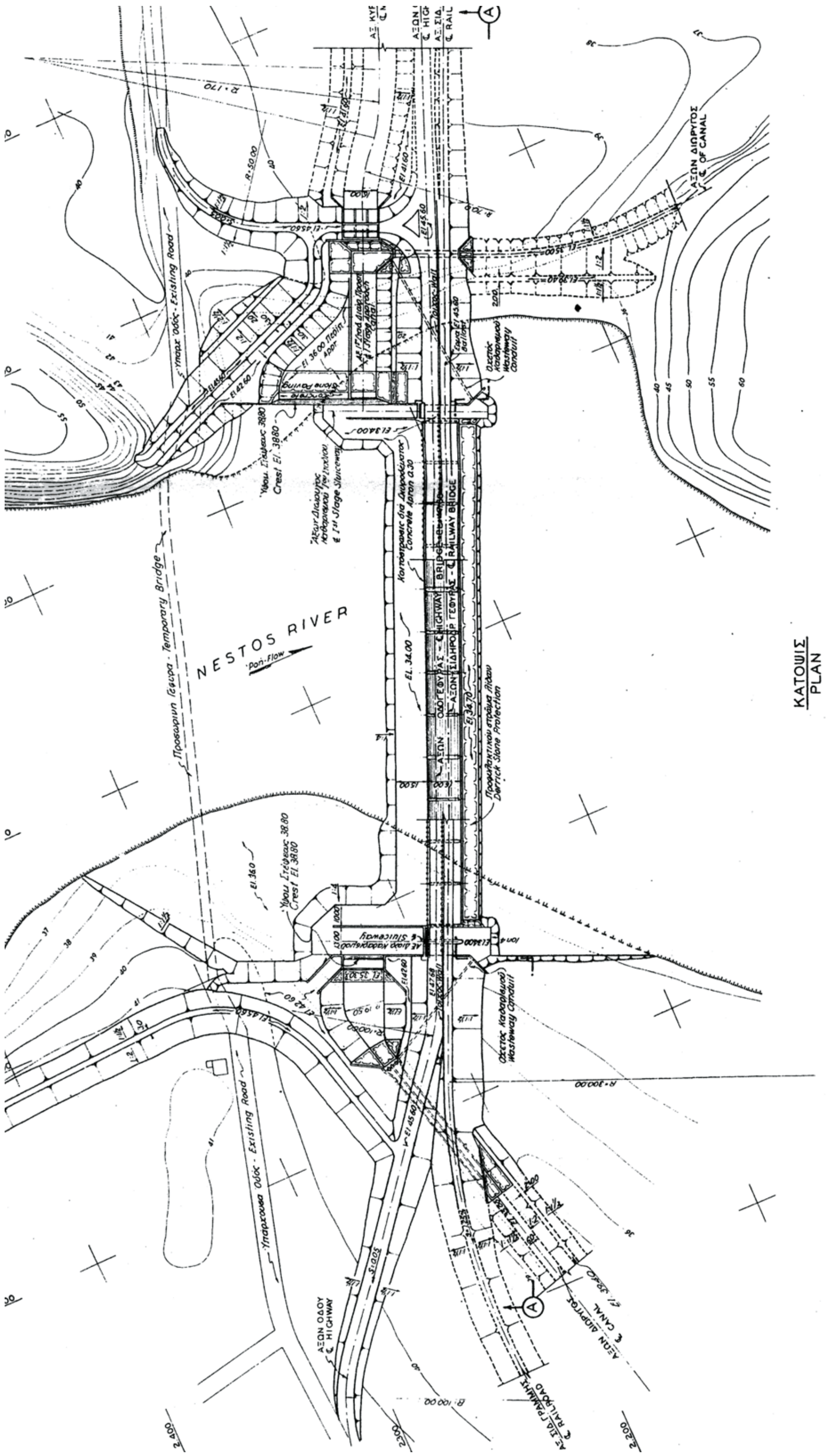


Figure 67 - The Toxotes dam schematics (PPC, 1994).

B - Operational parameters of the Toxotes dam

For the Toxotes dam operation, the highest priority has been set to the sustaining the environmental flow in the main Nestos outlet (Fig. 68). The water demand of the existing irrigated area in the Nestos delta was set at the next priority level and the demand for water of the future development in the Xanthi plain has been set at lowest level.

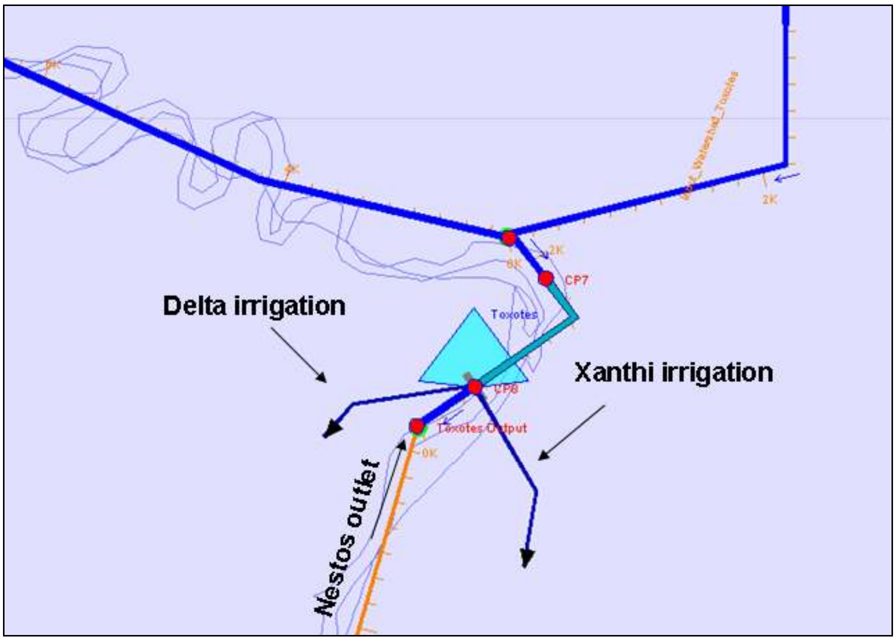


Figure 68 - The Toxotes dam representation in HEC-ResSim and its two diversions to the left and right bank of the Nestos River

The Conservation mode is triggered between the flood level of 16.95 m and the bottom level of 10 m. The operation of the dam in mode is determined by three rules of decreasing priority: the "Nestos EcoFlow", the "Delta Requirements" and the "Xanthi Requirements".

The "Nestos EcoFlow" rule is set to be constant and equal to minimum ecological flow of 6.0m^3/sec. The "Delta Requirement" rule is based on the flow requirements listed in Table 16 and the "Xanthi Requirements" rule uses the flow requirements defined in Table 17.

Furthermore, because of the fact that the existence of the upstream de facto eliminates any flood event downstream, Flood Control mode has been set identical to the Conservation mode.

III-7 – **The implementation of the climate change scenarios**

In order to study the possible impacts of future climate change on the Nestos dams complex including the new Temenos project one needs to be able to evaluate the hydropower and irrigation performances of the complete dam network along a full life cycle which typically in the industry extends over 50 years. For the present study, this period is 2010-2065. Furthermore, impacts are evaluated through a comparison between the performances which are expected under present climate conditions (also known under the name of "baseline scenarios") with those which would be determined for future climate conditions under various IPCC scenarios.

In order to run the simulation of the Nestos dams complex using HEC-ResSim one needs to input into this program, the flow at the border between Bulgaria and Greece as well the flow of the Nestos river sub-watersheds (also called differential flow) collected by the existing dams at Thissavros, Platanovryssi and Toxotes and the future dam at Temenos.

For the IPCC scenarios, climate parameters such as monthly precipitation intensity, air temperature and evapotranspiration (PET) are available for the period 2010-2065 for a variety of climate models. As previously indicated (see, Section II-3-4) I have selected the runs of European regional climate model CLM from Max Plank Institute for the A1B and B1 IPCC scenarios. After appropriate adaptation, these time series are used as input to the MODSUR-NEIGE hydrology model and the output Flow series are processed through HEC-ResSim

Paradoxically, for the Mesta-Nestos basin the situation is much more complex when dealing with the present climate conditions (idem, "baseline scenario"). The difficulties come from the fact that no consistent measured rain data set is available for this area for a period of 50 years. The only long term record concerns the monthly river flow measured over 27 years at the Temenos station from 1968 to 1995. As no MODSUR-NEIGE run is possible due to the lack of rain data, an ad-hoc simplified method needed to be developed in order to feed HEC-ResSim with flow data which would realistically represent flow conditions under 50 years of climate similar to the one recently experienced in the area.

III-7-1 – Building baseline scenarios based on past climate

A – Determination of a simplified rain-flow regression

There exists a common period of the observation for both flow stations in Momina Kula and Temenos, namely form 1 Jan. 1968 until 31 Dec. 1995 (27 years). These two flow sequences have been retained as representative of contemporary climate conditions (Fig. 69).

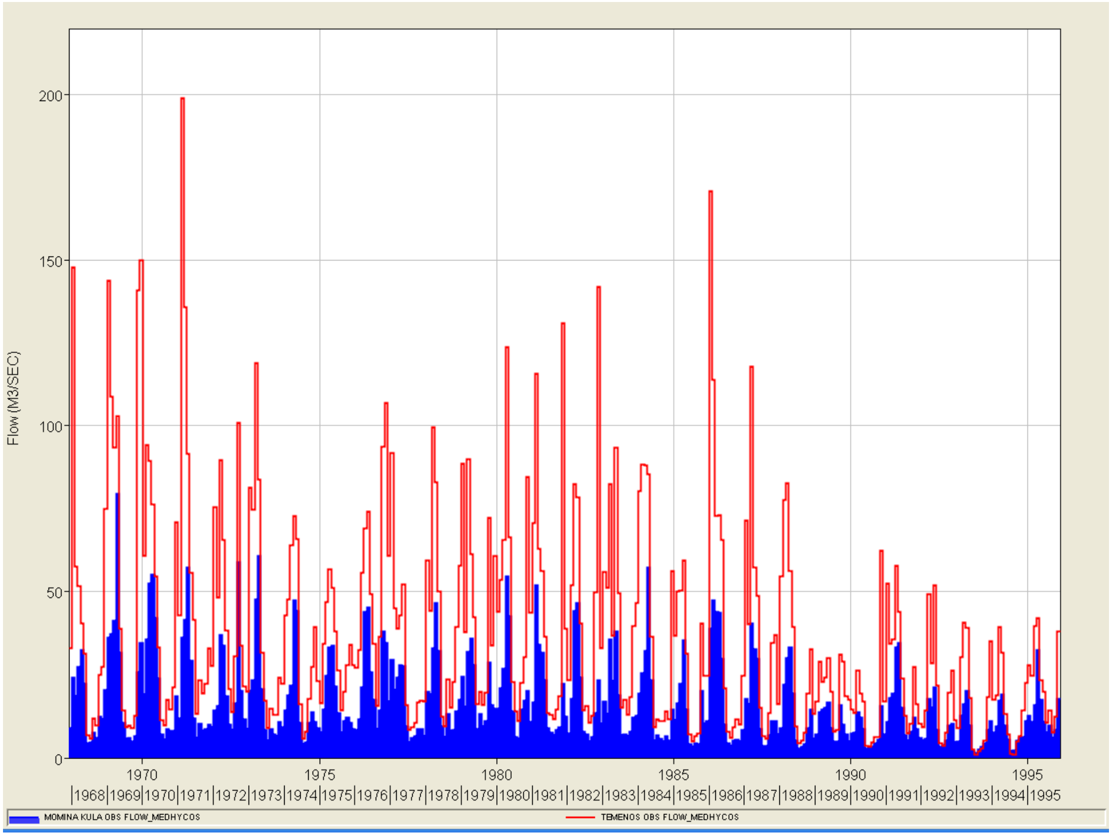


Figure 69 - Flow measured at the stations of Momina-Kula (Mesta-Bulgaria) and Temenos (Nestos-Greece) from 1968 until 1995 (27 years)

Unfortunately the results obtained by the MODSUR-NEIGE model for these sub-watershed flows are limited to the calibrating period ranging from 1 Aug 1991 until 31 Dec 1995. In order to extend these results to the to the entire 1968-1995 period it was decided to use a simplified linear regression between the measured main river flow at Temenos and each of sub-watershed flows needed to be fed into HEC-ResSim, namely: Thissavros, Platanovryssi, Temenos and Toxotes (see, Section III-6-1). Each linear regression parameters were determined using the MODSUR-NEIGE model results for the calibrating period (Fig 70)

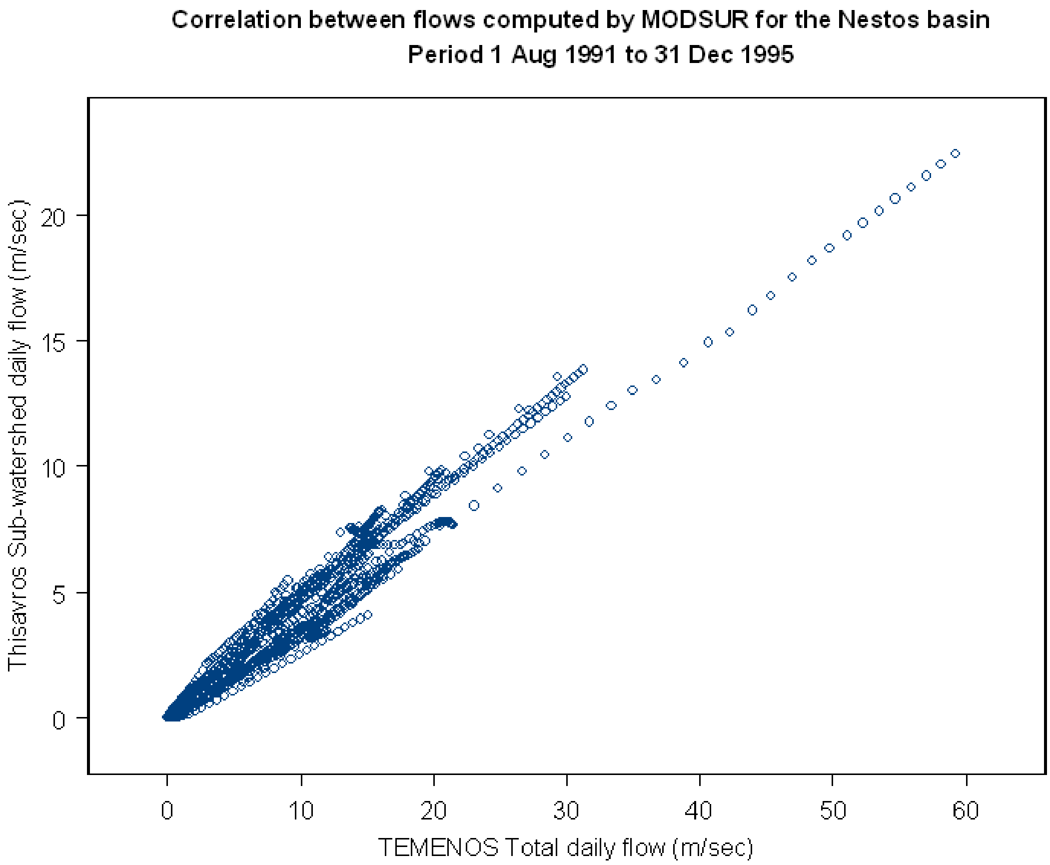


Figure 70 - Linear correlation between the MODSUR-NEIGE Thissavros watershed computed flow and the measured flow at Temenos

The regression coefficients which are determined (Table 20) also give an idea of the relative flow contribution provided by each of the sub-watershed drained by the dams.

Sub-watershed	**Regression coefficient from observed flow at Temenos station**
THISAVROS_D	0.66
PLATANOVRISI_D	0.25
TEMENOS_D	0.185
TOXOTES_D	0.56

Table 20 - Coefficients used in order to reconstruct the sub-watershed flows from the flow measured at the Temenos station on the Nestos

For the Border inflow into HEC-ResSim a similar regression has been established with the flow measured at Momina-Kula.

B - Construction of a sequence of 50 years past climate flow by duplication (PCSM)

As the time period necessary to evaluate the economics of the Temenos dam project must extend over 50 years (namely, 2010-2065), the past climate HEC-ResSim inflow series labeled PCSM have been constructed from the simple duplication of the Momina Kuala and Temenos flow measurements dating from the latest 25 years period extending from 1 Jan 1970 until 31 Dec 1995.

It is worth looking at the outputs of HEC-ResSim running under such flow conditions (Fig. 71). It is worth noting that during a period of about 5 years, the power plant is nearly inoperative because the level of the water in the lake drops below the “Plant intake level”. This 5 years period is actually duplicated but this is an artifact due to how the flow series were duplicated from an initial 25 years measurement period.

These periods when no power is produced are due to the fact, the rain being too low, most of the water is released to maintain the irrigation demand and the environment flow. This is due to presence of a dry period in the available data measurements which lasted from 1990 until 1995. It illustrates the extreme dynamic sensivity of the Nestos dam complex to periods of drought, their repetitivity and their time span.

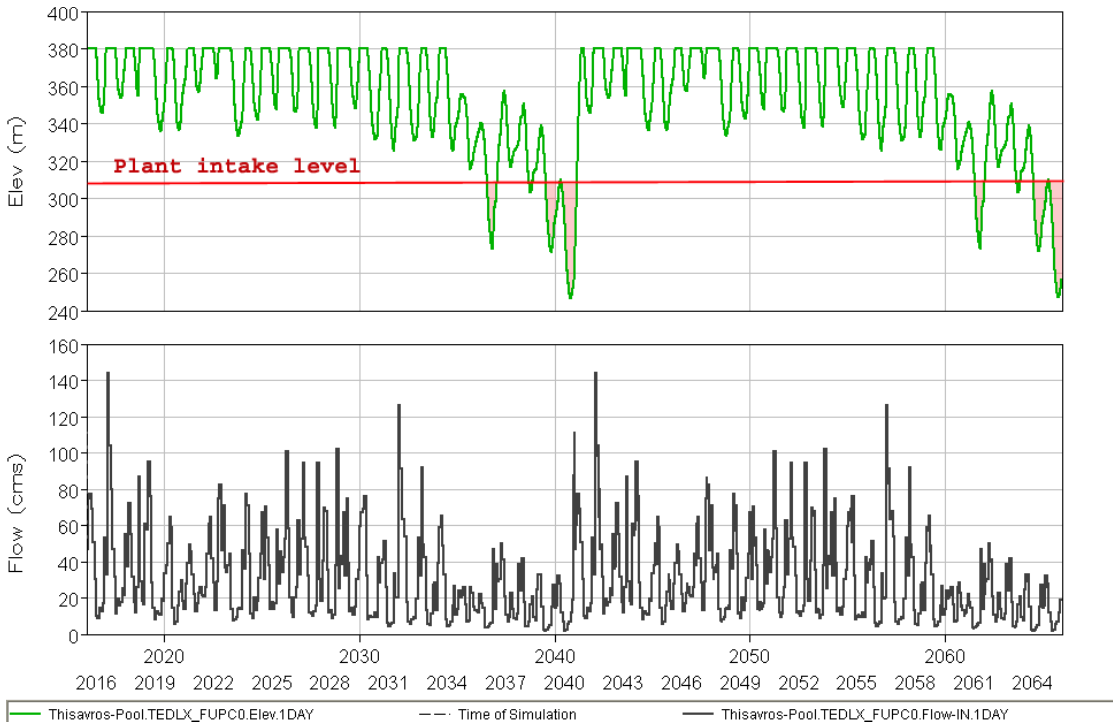


Figure 71 - Display of the 50 year past climate (PCSM) HEC-ResSim results for the pool level (m) and inflow (cms) entering the Thissavros lake

C – Building a "reference" flow sequence for average conditions for contemporary climate conditions (RFSM)

Before the last ten years since the climate change paradigm was accepted, it was common engineering practice to dimension hydropower equipments and evaluate their economic feasibility on the basis of "average" rain and flow conditions. No attempt was made to study the dynamic climate response of the systems and certainly not to introduce such a concept in the risks of investments attached to such projects. The management of climate risks (Marteau D. et al., 2004) was not routinely addressed.

As the purpose of my work is to explore the benefits of using models for a better decision analysis of water projects under the constraints of climate change, I thought that it was appropriate to find a way of reproducing the traditional criteria of decision. Therefore it was decided to create a "reference" flow regime which would be representative of the average conditions of flow during the contemporary period and form a "best case" of rain-flow conditions. A series of statistical tests have been conducted using the S-PLUS package in order to extract a sequence of contiguous year flow series which would have a statistical distribution as close as possible to the mean and standard deviation of the 27 years available data. This process selected an interval of 9 years (Fig. 72) from 1 Jan 1976 until 31 Dec 1984. This base sequence was duplicated in order to form the 50 years "reference" flows labeled RFSM.

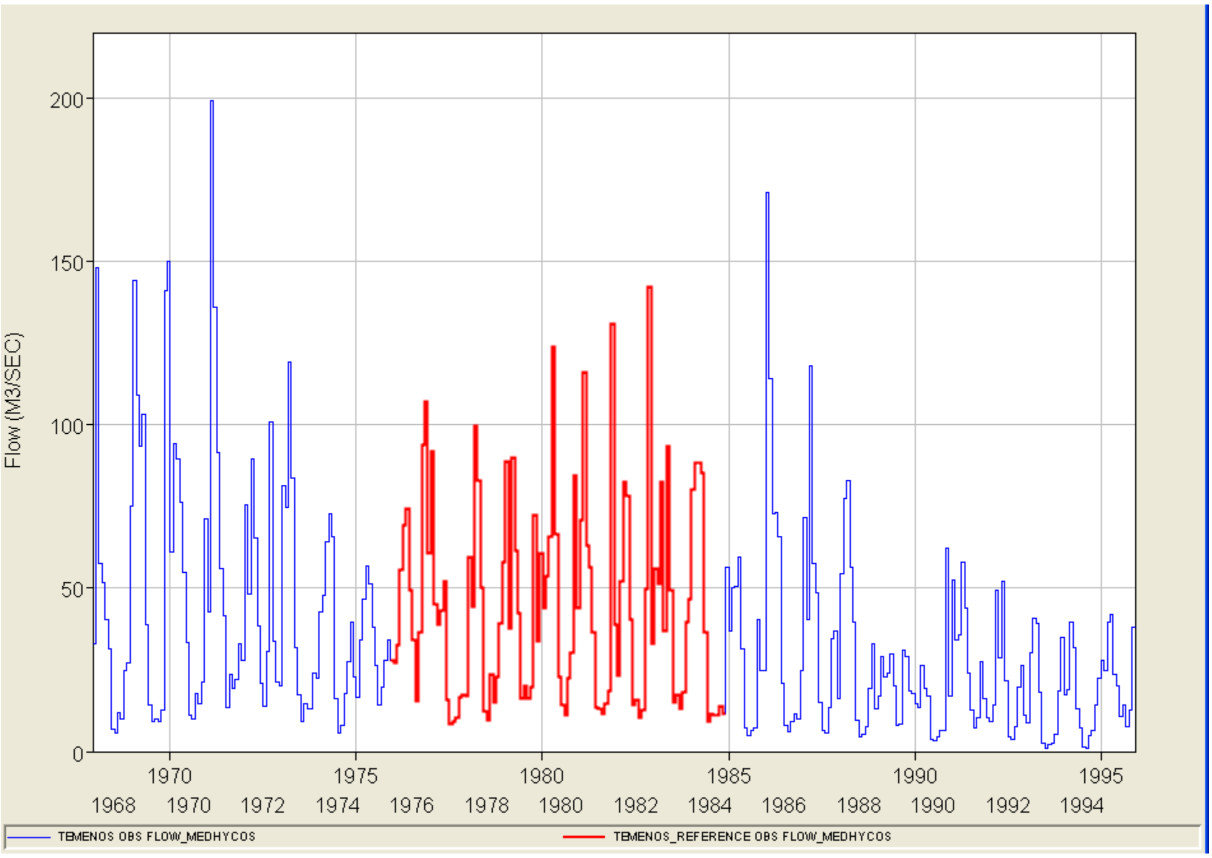


Figure 72 - Reference flow regime measured at Temenos for the 1976-1984 period (in red) compared with entire contemporary sequence available (1968-1995)

When the “reference” flows are run with HEC-ResSim (Fig. 73) the production parameters of the Thissavros dam are much more satisfactory. They clearly illustrate average “best” conditions of exploitation, also sometimes called “nominal” conditions in engineering practices. They will form the base level against which all other climate conditions will be judged in the evaluation of the sustainability of the Temenos project.

It is to note that even if the PCSM and RFSM flow series do have by construction similar statistical distribution, the final effect on the dams is strikingly different. It is worth mentioning that dams are rather “asymmetric” systems, as they can only store a limited amount of water when the rain is abundant, water is quickly missing in the case of multiyear droughts. Thus they tend to “over react” during dry conditions.

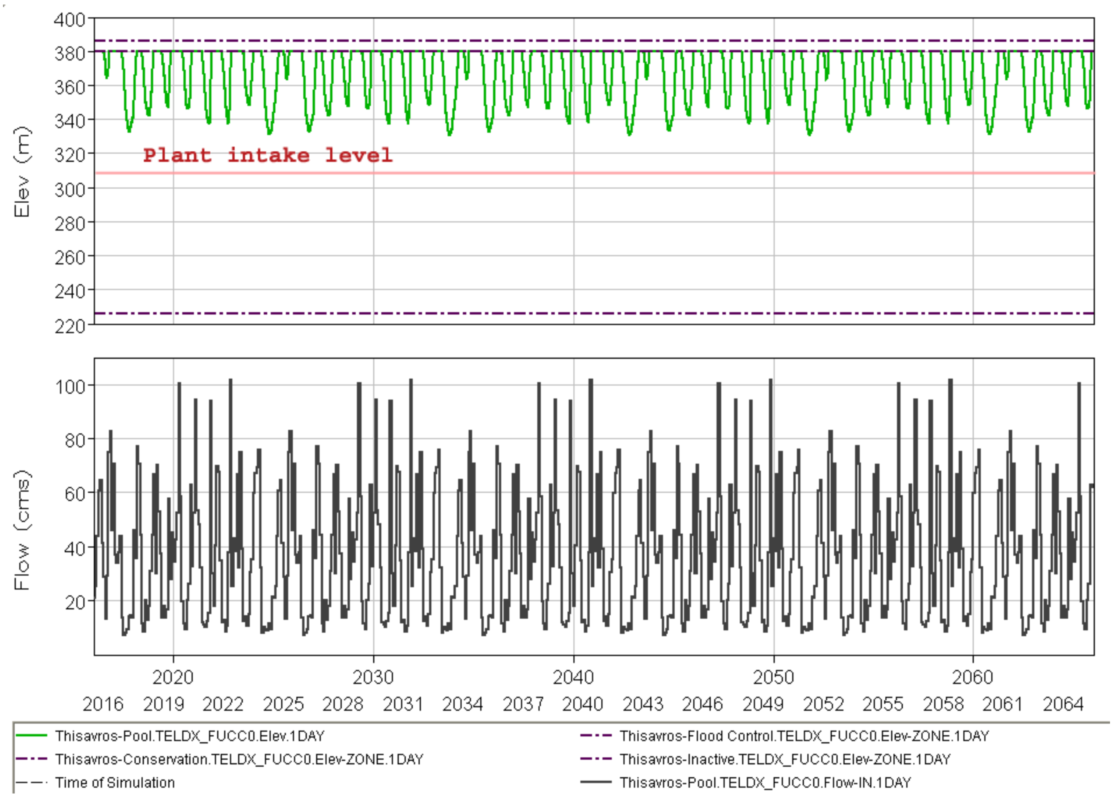


Figure 73 - Display of the 50 year “reference” climate (RFSM) HEC-ResSim results for the pool level (m) and inflow (cms) entering the Thissavros lake

III-7-2 – Using CLM-MODSUR coupling for future scenarios

Simulation data for monthly precipitation intensity, air temperature and potential evapotranspiration (PET) from the European regional climate model CLM from Max Plank Institute have been retrieved from the Climate and Environmental Retrieving and Archiving (CERA) database from the World Data Center for Climate (WDCC) which is maintained by Model and Data (M&D) and hosted at the Max-Planck-Institute for Meteorology, in cooperation with the German Climate Computing Centre (DKRZ).

The data sets retrieved concern the B1 and A1B IPPC-SRES scenarios for period 2000-2100 and the CL20_1 20th century realization run for the period 1960-2000. All CLM experiments are started from model states obtained in a 505–year long integration of the coupled global model with pre-industrial conditions called CTL. In that control experiment (CTL), the concentrations of well-mixed greenhouse gases have been specified at the observed levels of 1860 and sulphate aerosols are not included. This reconstruction of a non-drifting climate is representative of the middle of the 19th century and provides the initial fields for the 20th century global ensemble simulations. Fields from different years of CTL have been used to initialize the three different realizations among which the first has been selected for the Mesta-Nestos project, namely CL20_1.

The state of the CL20_1 run at the end of year 2000 is used to initialize the IPCC climate projections. Although the CL20 runs of the CLM are not meant to be exact duplicates of the present climate conditions in the period 1960-2000, they are supposed to be statistically representative of the past climate. They are used in my project to detect possible systematic biases as compared with the real climate conditions which have been used to calibrate the MODSUR-NEIGE hydrology model for the period 1Aug1991-31Dec1995.

A – Grid transfer from CLM climate model to MODSUR hydrology model

The output data format of the CLM regional model is provided in netCDF (network Common Data Form) format. This data structure was initially created by the University Corporation for Atmospheric Research (UCAR) as a means of exchanging array-oriented scientific data within the meteorology and climatology research community (Rew R. K.et al., 1990). An important point is that is allows a systematic transfer and manipulation of the geographic coordinates and time stamps.

Numerous software tools and libraries have been developed for handling this data format[10]. I have used the NcBrowse program both for displaying and extracting the data series from the CLM runs[11]. In particular, as the selected CLM data series are mapped on what is called a D3 (data stream 3) on a regular geographical grid with 0.2° spatial resolution, the NcBrowse was used to identify the grid elements which overlie the Mesta-Nestos region. Overall, a rectangle of 6 latitude levels by 9 longitude levels (54 grid cells) was extracted (Fig. 74).

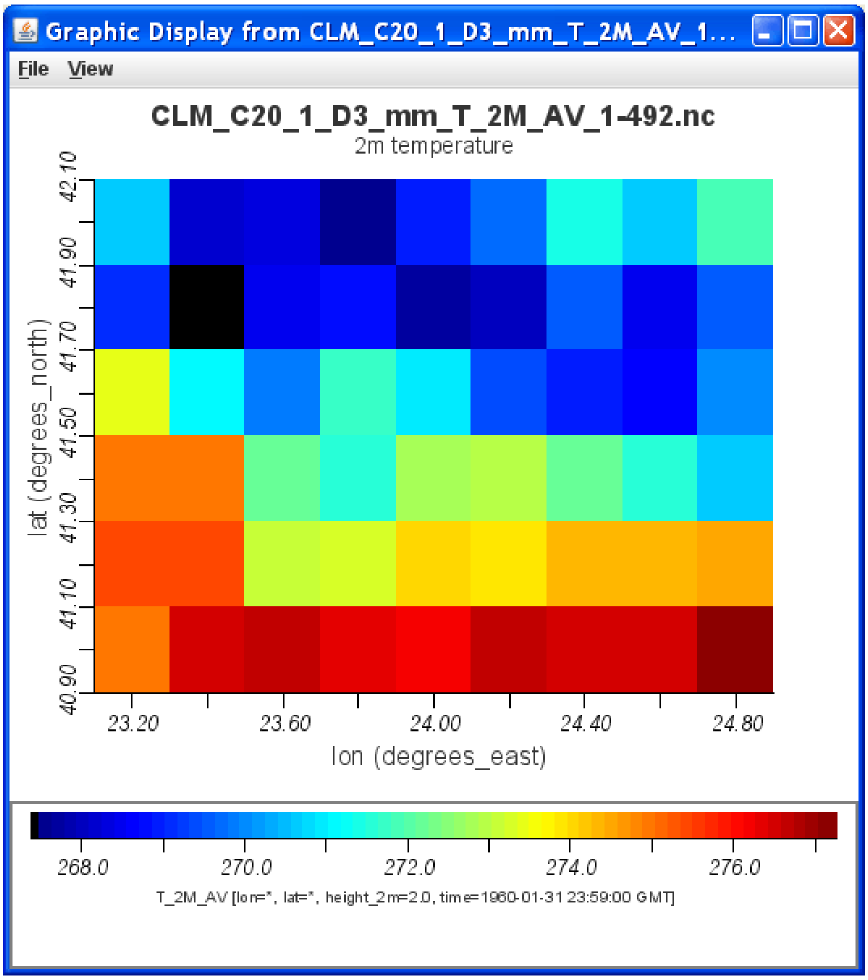


Figure 74 - NcBrowe display of CLM_C20 temperatures of January 1960 for the 54 grid cells covering the Mesta-Nestos area

[10] Software for Manipulating or Displaying NetCDF Data (http://www.unidata.ucar.edu/software/netcdf/software.html)
[11] ncBrowse - A Graphical netCDF File Browser (http://www.epic.noaa.gov/java/ncBrowse/)

Finally, the monthly data series extracted from the CLM runs needed to be formatted in order to be used as input to the MODSUR-NEIGE hydrology program. As in this model, all meteorology related information is organized by reference to the Thiessen polygons attached to each of the ground stations, The ArcGIS program was used in order to determine the percentage of coverage of each CLM grid cell over the Thiessen polygons of the MODSUR model (Fig. 75). These coefficients were used to build rain, temperature and PET data series which were fed into the hydrology model.

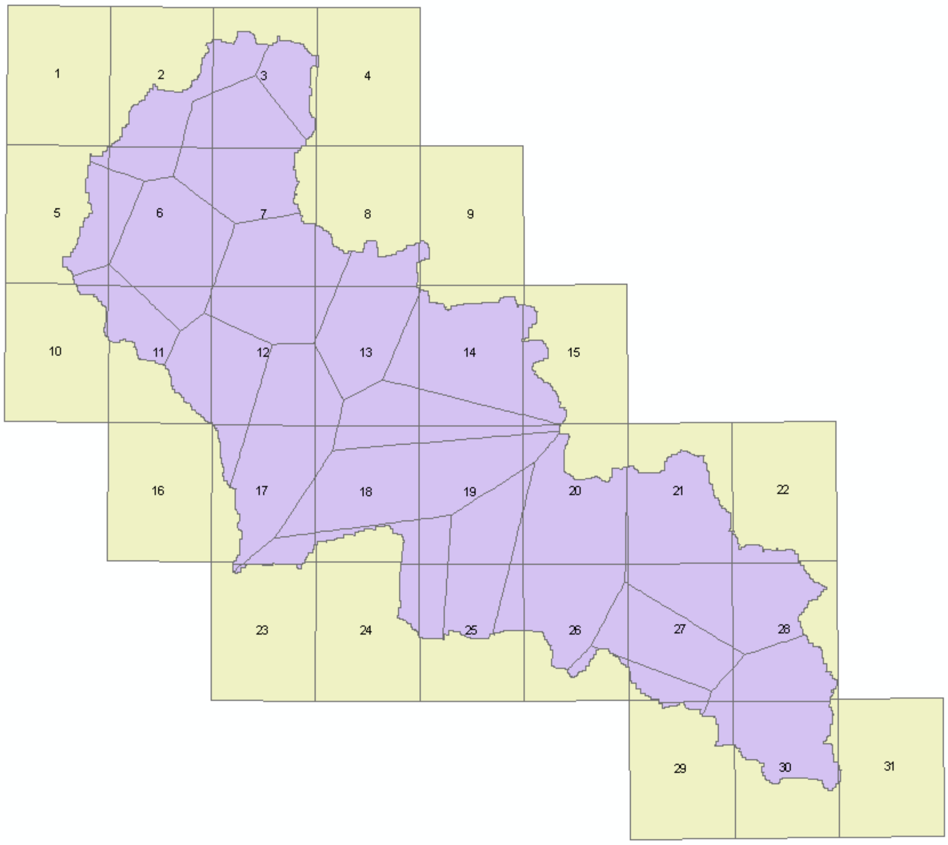


Figure 75 - Geometric coverage relationship between the CLM model regular grid and the Thiessen polygons corresponding to the 20 ground stations used in MODSUR-NEIGE

B - Calibration using the present climate CLM-C20 results

Even if CLM the computation grid is rather refined (0.2° spatial resolution or about 25 km at European latitudes) and despite the fact it is called “Local Model”, CLM is only meant to be a Regional Climate Model (RCM) which is based on a rather scarce spatial density of ground measurements, typically the WMO ground stations.

In my area of investigation, this means that CLM is only constrained by the meteorological measurements made in Thessaloniki, Greece and Sofia, Bulgaria.

Climate models constrained to a denser network of local measurements do exist. It is for example the case of the ARPEGE model of Météorologie Nationale in France (Gomez E. et al., 2002). But in my area of interest no such results have yet been made available to the public. It is expected that some biases might exist for my area of study between CLM results and actual measurements made at a more refined scale. These biases need to be identified and corrected for before running MODSUR-NEIGE. This done using CLM-CL20_1 results for the period 1Aug1991-31Dec1995

Temperature

The CLM model determines the monthly average of the daily mean of air temperature 2 m above ground. In the Mesta-Nestos MODSUR-NEIGE model, temperatures are used for the snow cover computation of both 19-Vihren and 20-Mussala Thiessen polygons. Comparison between CLM results and ground measurements (Fig. 76) show an excellent level of agreement and no correction was deemed necessary.

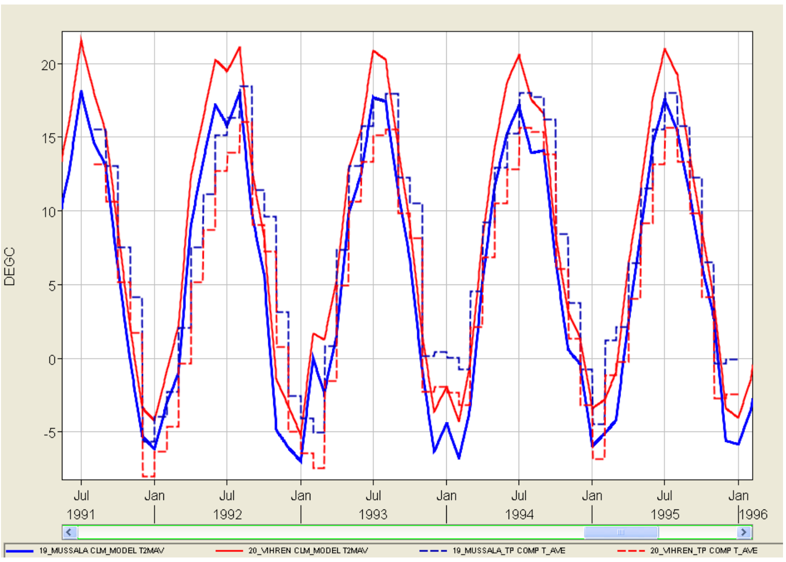


Figure 76 - Comparison between CLM (solid lines) and ground monthly temperatures (dotted lines) for zones 19-Vihren (red) and 20-Mussala (blue)

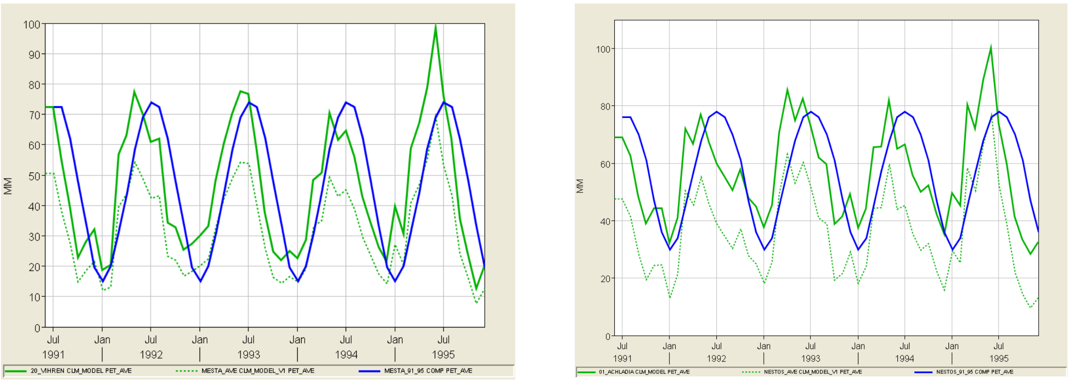
Potential Evapotranspiration (PET)

In CLM, evapotranspiration is calculated under the simplifying assumption that energy advection and storage in a canopy are negligible. In this case, ET (here, PET) expressed in kg/m2 can be directly computed from the latent heat in as:

$$ET = ALHFL\_S \times 10800 / (2.501 * 106)$$

where ALHFL_S is the latent heat computed by CLM

A regression was thus determined between these values and the average monthly PET used in MODSUR-NEIGE and expressed in mm/month. This has been done for the CLM values averaged over the Mesta (idem, Bulgaria) and Nestos (idem, Greece) parts of the basin (Fig. 77). The regression coefficients are applied to the CLM-A1B and CLM-B1 IPCC scenario outputs before processing them through MODSUR-NEIGE.

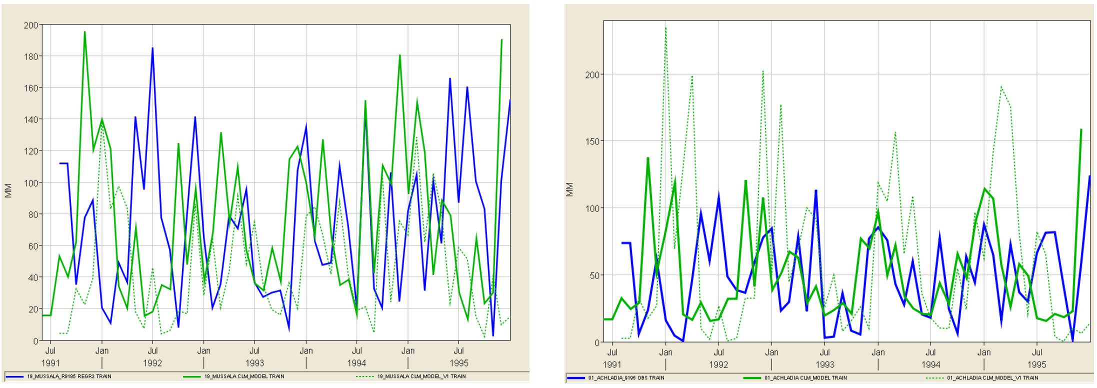


a) Calibration of Mesta area PET *b) Calibration of Nestos area PET*

Figure 77 - Calibration results of monthly CLM PET values (before: dotted green; after: solid green) with average PET ground measurements (solid blue)

Precipitation

In CLM, the monthly total precipitation is the sum of rain and snow precipitation converted to mm/month. Overall, the CLM precipitation results averaged over each of the 20 Thiessen polygons show the same order of magnitude as the measured data. This is a great progress compared with the previous generation of global model results for which large shifts could be observed over several years. However agreement needed to be improved and a regression was determined for each of the 20 stations based on average shifting and standard deviation ratioing between the statistical distributions of CLM results and measured precipitation values (Fig. 78). The regression coefficients are applied to the CLM-A1B and CLM-B1 IPCC scenario outputs before processing them through MODSUR-NEIGE.



a) Calibration of Mussala, Bulgaria station

b) Calibration of Achladia, Greece station

Figure 78 – Example of calibration results of monthly CLM monthly precipitation values (before: dotted green; after: solid green) with ground measurements (solid blue)

C – Running the MODSUR-HEC ResSim models cascade for A1B and B1 IPCC scenarios

After applying the previously mentioned transformations and corrections to the CLM outputs, these are run through the MODSUR-NEIGE hydrology model and the produced flows are cascaded through the HEC-ResSim system. The corresponding results for the Thissavros dam (Fig. 79) in the case where the full flow of the Mesta waters is transferred to Greece demonstrate the long term effect of CO2 emissions. Apparently, the rain would gradually decrease over the years thus threatening the production of electric power. Evidently, the lack of water would be worse in the case of the SRES A1B scenario than in the case of SRES B1.

Figure 79 - Comparison between CLM_B1 (blue) and CLM_A1B (green) 50 years HEC-ResSim results for the pool level (m) and inflow (cms) entering the Thissavros lake.

IV – SUSTAINABILITY EVALUATION OF THE TEMENOS HYDROPOWER PROJECT

IV-1 – The financing of dam projects

IV-1-1 - Dam projects analysis and financing

A – Hydropower in the world

One of the main uses of dams is the exploitation of hydropower. Hydropower or hydraulic power is the energy of moving water, which may be captured for further usage. Prior to the widespread availability of electric power, hydropower was considered to be a type of mechanical power used in order to facilitate arduous human labor. Nowadays, hydropower energy is considered to have several beneficial characteristics such as (Kaldellis J.K., 2006):

- Its resources are widely spread around the world with more than 150 countries involved in hydropower exploitation.
- It is a proven well advanced technology, with more than a century of experience with power plants routinely providing an efficient energy conversion process (around 70%).
- The production of peak load energy from hydropower plants allows the best use of base load electric power available from thermal and nuclear sources.
- It has the lowest operating costs and the longest plant life (typically 50 years or more), compared with other large scale power generating sources
- The fuel (water) is renewable and until now has not been subjected to market fluctuations (typically hydropower water is free for the time being).
- The hydropower plants are environmentally friendly power sources with regard to their greenhouse gases (CO_2) emissions (however, large dam reservoirs can be a significant source of methane). They do not have indirect health effects although they are a potential threat to the populations in case of dam breakdown.

Hydroelectricity: a renewable energy

Hydroelectricity or hydroelectric power is the most widely used form of renewable energy. Hydroelectricity supplies about 20% of world electricity (16% in 2003) and accounted in 2005 for over 85% of the total electricity produced from renewable resources. But these proportions are bound to decrease as the current world economic growth is driving the consumption of energy to records levels. World electricity generation has more than doubled since the last thirty years (Fig. 80) with 68% of the total being generated from conventional thermal resources. On the other hand, recent environmental protection policies such as the Kyoto protocol are defining limits and directives trending toward a more sustainable energy world demand. Similarly, by 2020, the European Union Energy policy has set a target of 20% renewable energy with a reduction of 20% in greenhouse gas emissions.

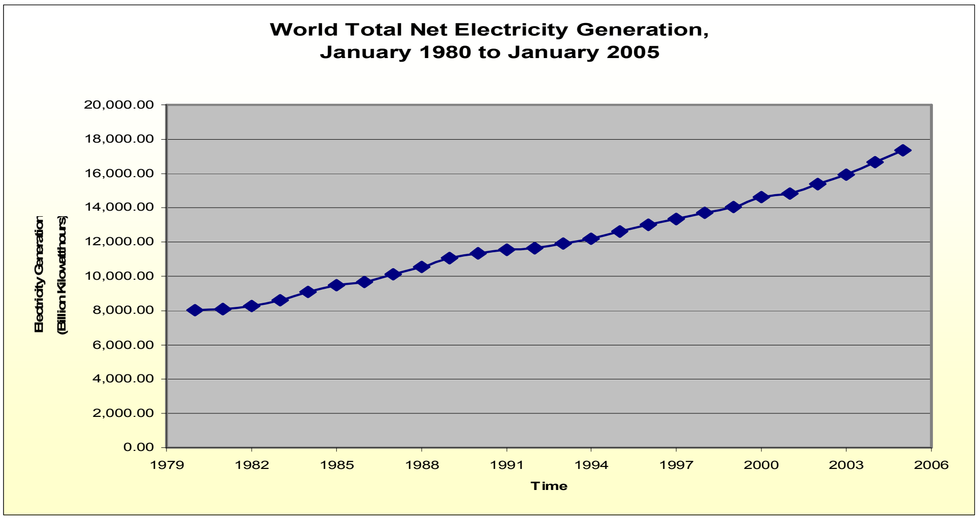


Figure 80 - World total electricity generation in the last 3 decades.
(Source: Energy Information Administration[12])

The countries with the most hydroelectric capacity are presented in Table 21. The hydroelectric capacity ranking is based either on annual energy production or on the installed capacity power rating known as the load factor. The load factor is the ratio between annual

[12] Source : http://www.eia.doe.gov/

average power and installed capacity as hydroelectric plants rarely operate at their full power over a full year.

Country	Annual Hydroelectric Energy Production(TWh)	Installed Capacity (GW)	Load factor
Canada	350.3	88.97	0.59
USA	291.2	79.51	0.42
Brazil	349.9	69.08	0.56
Russia	157.1	45.00	0.42
India	112.4	33.60	0.43
Norway	119.8	27.53	0.49
Japan	95.0	27.23	0.37
France	61.5	25.33	0.25
China (PRC)	486.7	145.26	0.37

Table 21 - Countries with the most hydroelectric capacity[13]

B – The economics of hydroelectric power operation

The cost of operating a hydroelectric plant is very low compared to other power producing systems. It is also nearly immune to increases in the cost of fossil fuels. Apart from the construction phase, the labor costs are also usually low since plants are automated and have few personnel on site during operation. Beyond hydroelectricity production itself the benefits of a dam operation extend to the flow regulation provided by the dam reservoir

[13] Source: BP Statistical Review of World Energy, June 2007

which often enable to serve downstream irrigation projects and contributes to agricultural and regional economic development.

It has been estimated that 30-40% of irrigated agriculture in the World is irrigated by water drawn from dams (Report of the World Commission on Dams, 2000). Finally, the dam reservoirs often provide facilities for recreation and become tourist attractions in themselves.

The proper scheduling of electricity generation by hydropower plants is of particular economic importance and offers the potential for significant. Linear programming techniques have been implemented in order to optimize this type of schedule (Delson, J.K. et al., 1992). In particular, the start-up phases of power production need to be minimized because they often bring an unnecessary loss of water and various deteriorations of equipment such an alteration of the turbine windings due to temperature changes (Nilsson O. et al., 1997).

In order to better schedule the start-ups of a unit or more generally of a power plant, short-run forecasting of electricity prices can be used for profit maximization (García-Martos C. et al., 2007). In Europe, just a few years ago, the evolution of demand over time was the only factor considered for power scheduling as prices were fixed at national level by the operator themselves. Nowadays, the increase in interconnections between national power networks and the privatization of operators are encouraging the formation of European wide electricity trading. On this trading market, the forecasting of the price of electricity for the next few hours or the next days guides hydropower station managers on their plant operation scheduling. An example of hourly electricity price statistics for the Spanish market (Fig. 81) displays such variations. It clearly illustrates the fact that pumped storage hydroelectricity during night periods is profitable when the stored water is released during the peak periods of the day. It is to remember that this principle is applied to the Nestos dams both for the present Thissavros-Platanovryssi and future Platanovryssi-Temenos couplings.

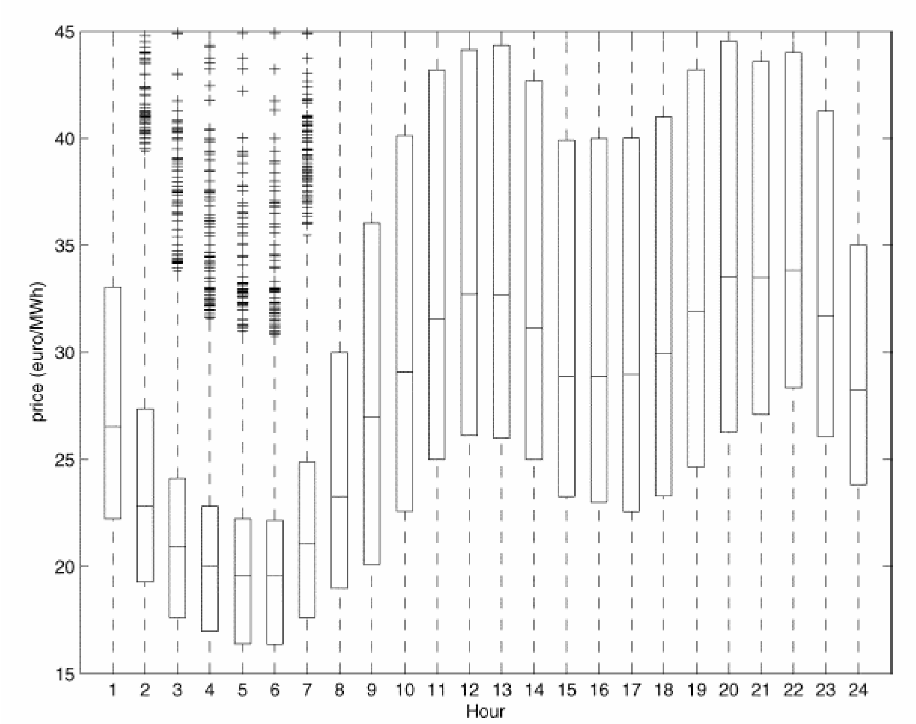


Figure 81 – Box plots of hourly fluctuation statistics on Spanish electricity prices market for the period 1998-2003

But often, plant scheduling and operation planning need to mediate several conflicting objectives such as: demand growth, price on the electricity market, behavior of other energy and financial markets, cost and availability of technologies, reliability of generating turbines, inflation rates, interest rates, economic growth, environmental regulation and public opinion (Linares P., 2002). Decisions in such a complex environment can benefit from multicriteria decision analysis (MCDA) methods. MCDA methods are widely used for comparing alternatives when there are multiple objectives (Hobbs, B.F. et al., 1994).

C– Financing dam projects

The construction of a big dam is a project of important economic and social consequences and this is the reason why it should be preceded by a careful socio-economic and operational study. On one hand, the operational investigation should take into account the dam's dimensions and purpose, the location of its watershed and its hydrology characteristics as well as the environmental constraints according to the international and national legislation. On the other hand, the socio-economic study should take into account all the variables which ensure the sustainability of the project. However, since the fuel of a hydropower plant is water, its operation interferes with water resources management of the river basin where it is situated. Thus the plant's operation efficiency must be compatible with the water demands of other actors in the basin (Rux L.M., 1993).

Until a few years ago, the vast majority of dams were funded and consequently owned by the public sector, thus project profitability was not of highest priority in the decision of their construction. Nowadays, the liberalization of the electricity market in the developed world has led to the privatization of energy infrastructures and has set new economic standards in the funding and management of dam projects. Investment decision is conditioned to an evaluated viability and profitability over the full life cycle of the project, typically 50 years, on the basis of quantitative criteria such as the Net Present Value (NPV).

In the private industry, investments decisions benefit from the art and practices of capital budgeting. Capital budgeting is concerned with the way firms evaluate project returns, project risks and make investment decisions (Pollio, G. 1999). A number of factors influence capital budgeting such as the cost and expected profitability of the project investment, the determination of the investment's appropriate returns, project risk management and mitigation, the project's optimal capital structure, the timing of the investment and the conditions under which it is economically rational to suspend or abandon rather than continue with project operations. One of the most important concepts behind project financing is that decisions taken today have effects which are not immediately realized but rather are spread out over the full project life. Since financial resources have alternative uses, it is necessary to discount over time the annual pay-offs with a return rate which needs to be high enough to be attractive to investors. Quantitative criteria have been defined in order to summarize the overall discounted project profitability. One of the most commonly used is the project Net Present Value (NPV)

In order for dams projects to be financed by the private sector they should ideally be dams for multipurpose use, mainly for electricity generation, irrigation and water supply. The other uses of a dam, such as for recreation and inland navigation, tend to be secondary uses, since they fall within the "non-commercial" category which are usually based on public rather then private investment. Additionally, flood control is difficult to justify as the sole reason for building a large dam. That is to say that it is relatively unusual for a dam to be promoted primarily for flood control, recreation or inland navigation; although these uses may increase the total socio-economic benefits of a dam whose primary function is hydropower or irrigation (Head C.R., 1999). However, as the price of energy is expected to stay at high levels for a long time, hydropower plants projects tend to be justified on the sole profitability of the generated electricity which covers the investment capital cost.

On the other hand, there are some external factors that may make it difficult for dam projects to attract financing from the private sector. Potential water management conflicts at river basin level and the exercise of the regulatory controls to achieve a sensible balance between the interests of different water users are complicated and difficult to achieve. They may generate levels of risks incompatible with private investors' interests. The uncertainties on the long term supply of water as a consequence of climate change have also brought a new category of concerns.

In the case of multipurpose dams the main source of income usually considered for project evaluation is the amount of generated electricity, even though an important part of the stored water is used for irrigation. This is because in most countries irrigation water is seldom priced at its full supply cost. However, in Europe, the implementation of the economics guidelines of the EU Water Framework Directive (WFD) should lead to a systematic valuation of water usage and facilitate the inclusion of their costs and benefits in dam projects NPV evaluation.

IV-1-2 - The concept of Net Present Value (NPV)

Cost-benefit analysis of a project is the quantitative method that estimates the equivalent monetary value of all benefits and costs of a potential project over its full lifecycle. The idea of this economic accounting is dated back to 1848 and originates from Jules Dupuit, a French engineer from Ecole Polytechnique who developed his ideas from the civil engineering projects which he supervised (Ekelund R. and R. F. Hébert, 1999). The main two principles of the cost-benefit analysis are: first, there must be a common unit of measurements, and second, the present values have to be transposed in time.

In order to apply the Dupuit's method, all the aspects related to the project, either positive or negative, need to be expressed quantitatively in terms of a common unit. On one hand, it is evident that in projects such as a hydropower station, there are quantities that undoubtedly can be expressed with monetary units such as the cost of construction or the income generated from selling electricity. However, there are other aspects of projects such as the environmental cost of the alteration or destruction of wetlands rich in flora and fauna, which cannot be measured directly by economic means. Indirect methods of valuation of the environment or other social cost and benefits need to be applied.

The so-called time shift of present values is based on the concept that a certain amount of money can be invested today and will earn a later interest for the time of the investment. If an investment is realized today at a known rate of interest, the prospective return in one year is given by the following expression:

$$FV = PV \times (1 + r)$$

where, FV is the future value, PV is the present value and r is the interest rate. The general formula for any number of years is:

$$FV = PV \times (1 + r)^n$$

where, n is the number of investment years.

In the case of capital budgeting the crucial question is how much money should be invested today (*PV*) in order to have a pay-off equal to *FV* in n year's time. From the previous equation it is deduced that:

$$PV = FV / (1 + r)^n$$

which means that a sum *FV* payable in n years and discounted (idem, compounded) an annual rate of r % is worth *PV* today. In project financing the aim is to evaluate the present value of expected cash-flow over the full cycle of the project lasting n years. It is called the Net Present Value (NPV) of the project and is the sum of the series of discounted cash flows:

$$NPV = I_0 - C_0 + \frac{(I_1 - C_1)}{(1+r)} + \frac{(I_2 - C_2)}{(1+r)^2} + \ldots + \frac{(I_n - C_n)}{(1+r)^n}$$

or

$$NPV = \sum_{n=0}^{N} \frac{I_n - C_n}{(1+r)^n}$$

where I are the incomes, C are the costs, r is the discount rate of return and n is the number of years from final return payment, i.e. the project's life time.

If the NPV of a project is higher than zero (NPV > 0) it means that the investment expected pay-off covers the investment expenditures. The higher the NPV value the higher the profits. On the other hand, a zero or negative NPV value (NPV ≤ 0) indicates that the investments expenditures are only just, or not covered, by the expected revenues, and thus the project is not considered to be profitable. Furthermore, from the NPV formula it follows that higher values of the discount rate on the basis of the same cash-flow will decrease. However, in project financing analysis it is common to increase the discount rate value in order to secure unexpected risks which could increase the project's expenditures. In general, projects with a short lifetime (for example, 10 years) have higher discount rates than those of extended lifetime (ex: 50 years).

In the practice of economic evaluation of investment projects, the evaluation of a series of NPVs depending on the variation of sensitive parameters is substituted for a one-off evaluation. In this case, the project decision will be made on the basis of the statistical distribution of possible NPVs. Statistical methods such as the Monte Carlo simulation or the Bar and Jenkins (B&J) approaches are often used to generate the project parameters' variations. For example, this is the approach used in the economic analysis of a wind power plant in Brazil (Salles, A.C.N. et al., 2004) where plausible wind speed sequences where generated statistically.

Cost-benefit analysis based on the NPV tool is universally considered as a robust decision approach for ranking and selecting investment projects. Moreover, the NPV approach takes into account the main parameters of all microeconomic models: the resources, i.e. the investment capital, the activity, i.e. the cash flow, and the timing, i.e. the life cycle of the project. The economic evaluation of Temenos dam project has been based on this concept.

IV-1-3 - Risks evaluation attached to project financing – The classical approach

Project financing is ultimately concerned with ensuring that sufficient cash flow will repay the project expenditures at the appropriate time. The a priori identification and evaluation of the impacts that specific project risks can have on individual cash flow items is a matter of great importance for the project economic sustainability. In general, project risks fall into one of five principal categories: intrinsic, production and technical, operational, political and management.

Intrinsic risk is related to unforeseen problems that emerge after the completion of the construction works and the starting of the production. Generally, intrinsic risk corresponds to an overestimation of the natural resources under exploitation. Oil reserves that are lower than originally assessed or a river natural flow that delivers insufficient water in the case of a dam project, are two representative examples of this type of risk. Thus, the decrease of revenues due to the natural resources insufficiency jeopardizes the project viability.

Production risks are related to the technical nature of a project. Construction delays, infrastructure problems, supply and quality of either production inputs or outputs, lack of expertise in the labor force are the most common risks in the construction phase of the project. Furthermore, transport risks can also be included in the production risks category. For example, even though the construction of a power plant may be completed, the generation and selling of electricity depends on the plant integration to the grid, a procedure which is controlled by another player, the transmission authority.

An additional production risk is the "force majeure", i.e. a risk which is caused from unknown and unpredictable events. An earthquake in an area where no such event was previously recorded would be a good example of this case.

Operational risk is concerned with the types of difficulties that projects may encounter over their life cycle. It includes such problems as energy or equipments costs, transportation bottlenecks, operating problems that derive from poor engineering or design work and high maintenance costs. The failure of mitigating the operational risks has serious effect on the augmentation of the operating costs. In the case that a project is not able to produce the quantity of output which was foreseen in the project feasibility report, purchasers of the project output have the right either to refuse delivery or to accept the output at a discounted price.

Market risk refers to the possibility that the project's output may not be able to be sold at a price that covers the operating costs and the required rate of return. Main factors are currency value, interest rate exposure and inflation. Projects which cash flows are fixed in terms of a currency other than the one used in the financing package are exposed to foreign exchange risk. For a multipurpose hydropower-irrigation dam, the long term evolution of energy prices might be predicted, but the price of irrigated water is a much more contentious issue, and is less predictable.

Political risks are related to any actions that might be taken by host governments that influence the project economics. These would include the imposition of new taxes, the withdrawal of previously agreed subsidies, delay on subsidies payment, implementation of extra regulations, and expropriation. Political risks may exist at both national and regional scale. The construction of a dam project, for example, may ensure the national political support both at economic and legislative level, but reactions at regional scale not only can delay the project development with consequences to the economic feasibility, but also alter the initial national agreement. In the case of the Temenos project, the main political risk is related to the enforcement of the bilateral agreement between Bulgaria and Greece.

Finally, management risks are concerned with the managerial ability. The management of a project is considered as important as its construction phase, since even the best designed project will not produce the desirable financial results if it is poorly organized and managed. Specialized managers with knowledge of the market rules, the project potential, and financial matters, are usually preferred.

IV-1-4 - Climate change risks to hydropower or irrigation projects

Even though the climate change concept is widely accepted since the early 1990s, its systematic inclusion in the risk evaluation of project financing is nowadays in its infancy. It is still treated as an intractable parameter by the investors who are not yet familiar with the opportunities offered by climate models.

This lack of knowledge and practice is even felt as a limiting factor for the development of renewable energy sources financing. On one hand, the aim to reduce greenhouse gas emissions and stabilize the emissions at the 1990s level fosters the use of clean generation sources such as renewable energy technologies. Furthermore, the rising demand for electricity coupled with an increase in fossil fuels prices is an additional factor to the use of alternative sources, including hydropower. However, on the other hand, the reliance of these renewable energy technologies on a wide range of climate variables has proven to be a limiting factor. Since the majority of investments in power generation is realized by the private sector, the lack of knowledge and practice in the evaluation of the impact of climate change on project feasibility acts as a deterrent for investors, especially in the case of hydropower projects.

Although global climate change models tend to predict an augmentation of global precipitation in the future there are regions, such as the Mediterranean region, where the opposite predictions are made. A study conducted on a basin in central Greece (Mimikou, M. et al., 1991) found that while the application of a climate change scenario resulted in a 35% reduction in annual runoff, the decrease in summer flows was almost twice as large. Furthermore, research conclusions on the operational reliability of a reservoir located also in central Greece (Mimikou, M. et al., 1997) identified increased electricity generation risks due to the diminution of the stored water volumes because of climate change impacts. In the case of hydropower projects which are coupled with irrigation projects, such as the Temenos dam project, where farmers could be entitled to compensation in case of a lack of water, climate change predictions related to dryer summers jeopardize the project viability. Additionally, research conclusions of the coupling of GCM with hydrology models over Southern Bulgaria have shown that even in cases when the mean annual runoff remains stable through time **(**Chang H. et al., 2002), the maximum runoff may change with time, for example, occurring in the early spring rather then late spring. This time shift might also affect the hydropower project viability and produce augmented risks since the liberalized energy markets provide time-dependent electricity prices. It is more profitable to produce and sell electricity in late spring and in summer, for example, than in early spring where the demand in electricity is lower. Thus, a proportionally greater effect could be seen where variations in output coincide with high-price periods (Harrison, G.P. et al., 2003). Consequently, the uncertainty derived from the effects of climate change tends to increase the investment risks.

On the other hand, private investors generally have a preference for low capital-cost options with faster payback. This concept does not favor hydropower projects since hydro capital costs are relatively high and payback periods are quite long (Harrison, G.P. et al., 2002). By adding the potential effect of climate change, hydropower investments seem to become less competitive.

However, innovative methodologies are being developed in order to assess the threat that climate change poses to future hydropower investments and could improve their attractiveness. The traditional design method of the hydropower installations, i.e. reservoir amplitude, turbines capacity etc, based on historical flow data as a predictor of future flow variations is now considered inadequate. The climate change impacts need to be evaluated by a sequence of independent but intercorrelated modeling procedures based on the outputs of climate models. This approach has been for example used for the feasibility study of the Atoka Gorge project on the Zambezi river at the boarder between Zambia and Zimbabwe (Harrison, G.P. et al., 2001). It is also the method followed in my work about the appraisal of climate change impacts on the Temenos project.

IV-2 – **The sustainability factors of the Temenos project**

IV-2-1 - The concept of sustainability

The idea of sustainable development grew initially from numerous environmental movements and was defined in 1987 by the World Commission on Environment and Development, also known as the Brundtland Commission, as:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* (UN Report of the World Commission on Environment and Development, 1987)

Furthermore, the concept reached a political reality in the Rio de Janeiro, United Nations Conference on Environment and Development (UNCED), was held in 1992.

Sustainable development focuses on improving the quality of human life without increasing the use of natural resources beyond the capacity of the environment to supply them indefinitely. Sustainable development does not focus solely on environmental issues nor is it valued exclusively on the basis of economic parameters such as gross domestic product per capita growth, as development used to be evaluated in the past. The United Nations 2005 World Summit Outcome Document refers to the "interdependent and mutually reinforcing pillars" of sustainable development as economic development, social development and environmental protection.

The integration of the sustainable development concept into water resources management practices is considered indispensable for succeeding in the protection of the water resources while fulfilling the water demands of economic development (Mylopoulos Y., 2002).

The financing of the Temenos project by the private sector demands a cost-benefit analysis and a comprehensive risk evaluation study. But this project is multipurpose in nature as it is willing to serve both the regional electricity market and the irrigation needs of the local agriculture. The latest activity demands a high level of social acceptance as it is bound to interfere with the fabric of the local economy. Matters related to the impact of the environment need also to be considered in order to fulfill the regulatory constraints set by the EU WFD. Overall it has been felt that in order reach a sufficient level of acceptance it was preferable to evaluate the sustainability of the project rather to limit the evaluation to a strict profitability.

In order to evaluate the socio-economic sustainability of the Temenos project it proposed in this work to take into account the cost of its possible "externalities" both in terms of social and environmental impacts. Externalities (Coase, R. H., 1960) are defined by the economists as whatever loss of value the project might cause outside of its basic activities. These externalities classically evaluate the cost of cleaning and remediation when an industrial activity pollutes the environment.

In the present analysis, the externalities which have been considered are: the cost of environment repair if the minimum environmental flow of 6 m^3/s cannot be delivered to the main Nestos stream and the compensation to the farmers for the value of their lost crops in the case where the amount of irrigation water is not sufficient. On the other end, the activities bringing revenues to the project are the direct selling of produced electricity or the equivalent power value of the water back-pumped in the Platanovryssi pool as well as the revenues generated by the selling of irrigation water to the farmers.

Thus, before performing this sustainability evaluation it is necessary to assess the various factors influencing key parameters such as the price of electricity, the value and nature of the crops produced in the irrigated fields as well as the environmental constraints which need to be met along the Nestos river channel.

IV-2-2 - The regional conditions in electricity production and pricing

A - The market of energy in the European Union

Based on the principle of free movement of people, goods and capital among the EU members, the liberalization of energy and the creation of a competitive internal market for electricity and gas have been progressively implemented across the EU since 1996. The formation of an Internal Electricity Market (IEM) is enforced by the Directive 2003/54/EC which can be summarized along three major implementation aspects: the opening of the market, third party access, and the principle of separation between the network system operator and the power generators (Meeus, L., et al., 2005).

The opening of the market principle is focused on the opening of the national electricity markets so that an increasing number of power generators and consumers may freely negotiate the purchase and sale of electricity over the whole EU territory. The liberalization of electricity transactions has led to improvements in energy supply and savings to the customers (Figure 82). It is of note from this illustration that after a decrease of the average price until 2002, the electicity price price increases at a moderate rate equivalent to the inflation rate experienced in the European states during the same period.

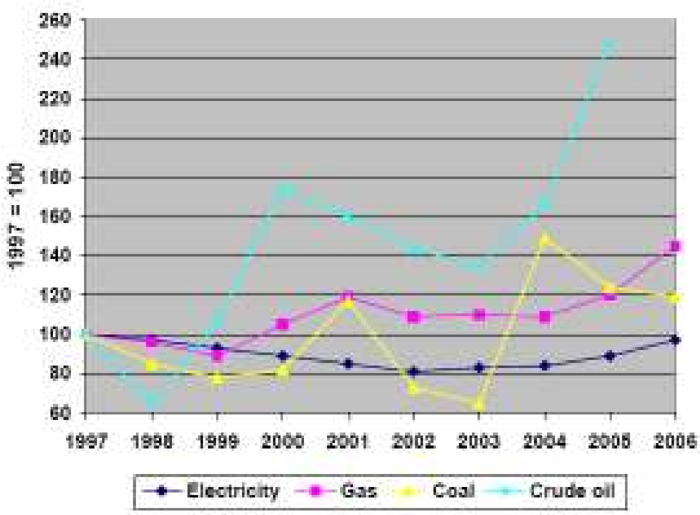


Figure 82 - Variation of average electricity and gas end customer prices from 1997 to 2006 over the whole EU relative to 1997 situation

Third party access is based on the concept that suppliers and power generators should be assured that the network system operator will grant them access to the network of national power grids. An independent national regulator is established for approving the electricity prices and controlling the management system. In practice, the generation, transmission and distribution of energy are managed by different companies. Consequently the interconnected electricity market contributes strongly to the security of electricity supply. Furthermore, the development of competition is supposed to distribute the supply of energy efficiently and eliminate undue monopoly profits (Commission of the European Communities, 2007).

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However, electricity exchange transactions occurred before the electricity Directive implementation based on national bilateral cooperation agreements. Mutual cross-border import export flows guaranteed emergency back up supplies in case of system failure and electricity supply in cases of high electricity demand on behalf of one partner (Bower, J., 2002). The first electricity market, also known as "electricity spot market" was the Nordpool. It was established in 1993 (Geman, H., 2002) in the Scandinavian countries. It is essentially a commodity market where the price is based on supply and demand for immediate requirements, i.e. the spot price is the price of electricity at one point in time on that market. Currently, there are six spot markets in the Western part of the EU (Fig. 83). The approach of interconnected spot markets is supported by the EU and considered as an efficient architecture. Nevertheless, the lack of connectivity among the already established regional spot markets has impacts on the final electricity prices. The electricity prices of the Italian market, for example, are comparatively higher due to inadequate connections with other regions.

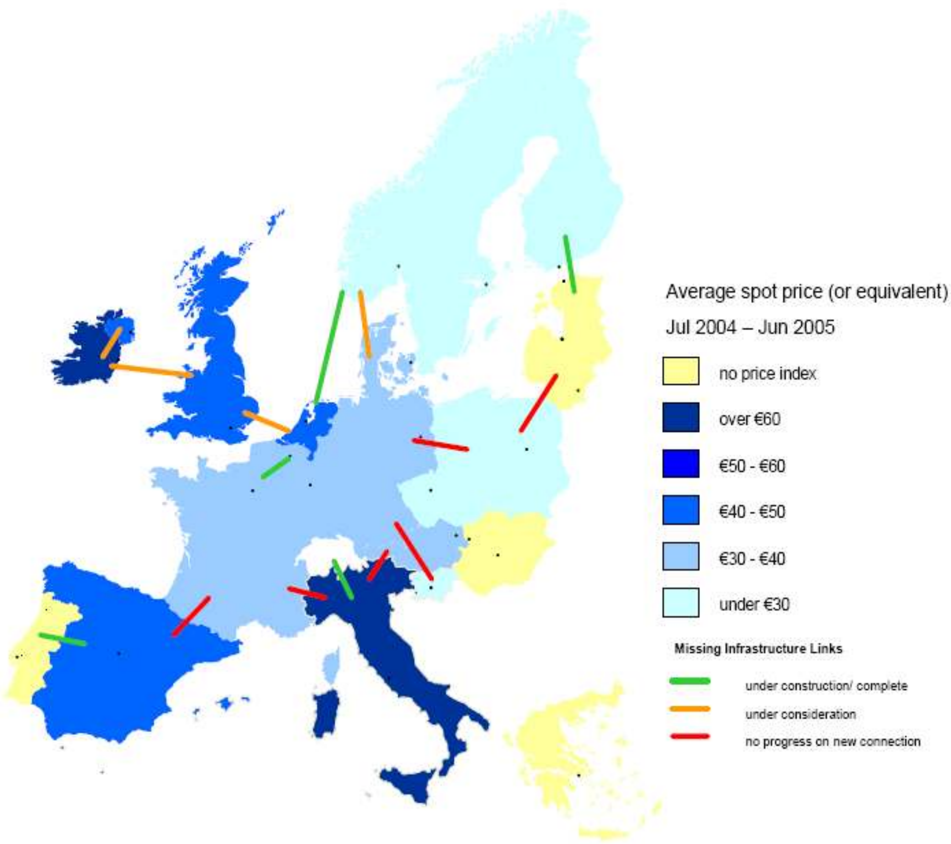


Figure 83 - Spot markets and average spot prices of electricity in Euro/KWh from July 2004 until June 2005[14]

B - The electricity market situation in the South East Europe region

It can be observed from Figure 83 that an electricity market is not yet established in the South East Europe (SEE) region. However, as energy sufficiency is an important factor for economic development, the creation of a regional electricity market (REM) was launched in 2002 by the so-called "Athens Memorandum". The initial partners of the agreement are Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, F.Y.R. of Macedonia, Romania, Serbia and Montenegro, and Turkey. They are committed to adopt the European Union legislation, create modern and efficient energy infrastructure networks (for electricity, oil and gas) and ensure that the energy system of the region can meet the energy demands of each country.

[14] Source: Commission of the European Communities, 2005

The initial timetable implied the opening of the electricity markets by 2005. However, a number of difficulties have appeared due to the insufficient size of some markets and the political uncertainty, instability in the region and bottlenecks in the transmission systems (Hristozov, M., et al., 2005).

Despite the number of difficulties, a regional approach to energy supply offers significant advantages both in terms of improved utilization of existing supply and production capacities as well as optimizing future investments. Furthermore, an analysis of the potential benefits of the Energy Community of South East Europe (ECSEE) shows that regional electricity markets provide significant benefits and cost savings compared to the operation of individual utility systems (Koritanov, V.S., 2003). Moreover, the gradually enhancing operation of the ECSEE will facilitate investments in power generation since the produced energy can be sold everywhere inside the IEM. In the case of the Mesta/Nestos River basin, the construction of the Temenos dam project could attract investors in the future, since the produced energy might either be used in the national market, or absorbed by the Balkans' regional market or eventually distributed in any other European electricity market when the full EU market connection will be established.

C - Hydroelectricity status and electricity price in Greece

Greece's energy production is based on conventional technological methods, i.e. thermal technology, such as oil and coal. In 2005 (Sakellari I.S. et al., 2006), those two energy sources represented 69.85% of the yearly electricity production, whereas hydroelectric stations and other renewable sources together represented only 12.06%. However, Greece as a state member of the EU has to adopt European legislation and produce 21% of its electric energy from renewable energy sources by the end of 2010. It is obvious that Greece is quite a way from the specific target, thus funding for new investments in renewable resources should be given priority. Hydroelectric power is one of the alternative technologies that could be employed to meet the European requirements.

In Greece there are currently fifteen large hydropower stations with a total capacity of 3,017.8 MW, (Greek Ministry of Development, 2005) and almost fifty small hydropower stations, with total power of 70.0 MW. All large hydropower stations belong to the state controlled PPC. There was a particular increase in hydropower construction from 1980 until 1999 when the Platanovryssi station started operation. Recently, a hydroelectric station was constructed in 2001 at Messochora, Thessaly, but it has not been made operational because of the possible environmental impacts on the region (PPC Press Office, 2007[15]).

The typical load factors of Greek power plants are in the range 10%-25% which is considerably lower that the corresponding European and world-wide values, i.e. 16% to 40-44% respectively. Furthermore the exploitation strategy is essentially aimed at smoothing peak load demand (Kaldellis J.K., 2006). Moreover, although most reservoirs were initially designed only for power production, important volumes of water are devoted to irrigational purposes.

As of 2007, in the wholesale market of electricity in Greece, the incumbent network utility operator, PPC S.A., retained an approximate 95% market share both in terms of installed capacity and electricity generated (Regulatory Authority for Energy - RAE, 2007). Even though PPC is now a private company, it still exerts *de facto* control over the entire market. However, it should be noted that interest for the wholesale electricity market by private investors looks promising. Three private industrial groups have announced their intention to install gas turbine GTCC units of total capacity in the order of 1200 MW by the end of the decade and furthermore, interest by private investors for developing coal plants is reaching 1600 MW of total capacity. Private construction companies have also expressed an interest for smaller hydropower projects like Temenos.

During July 2007, a period of several days of sustained high temperatures within the country resulted in new record of peak demand for the interconnected system, reaching 10.600 MW, about 600 MW higher than the previous record in August 2006.

[15] *Public Power Corporation (PPC) of Greece Press Office, August 2007.
http://www.dei.gr/Default.aspx?id=3565&nt=18&lang=1

The System Marginal Price (SMP) of electricity is the real time price equilibrium between bids and offers on a particular electricity market. For Greece, the average yearly value of SMP in 2006-2007 was at 64.13 €/MWh, with its average price during the low demand hours (02:00 – 07:00) at 51.89 €/MWh and during the high demand hours (12:00 – 24:00) at 69.01 €/MWh. The last quarter of 2006 (Fig. 84) along with the first quarter of 2007 was characterized by high prices, mainly due to the observed low reservoir levels of the hydro units.

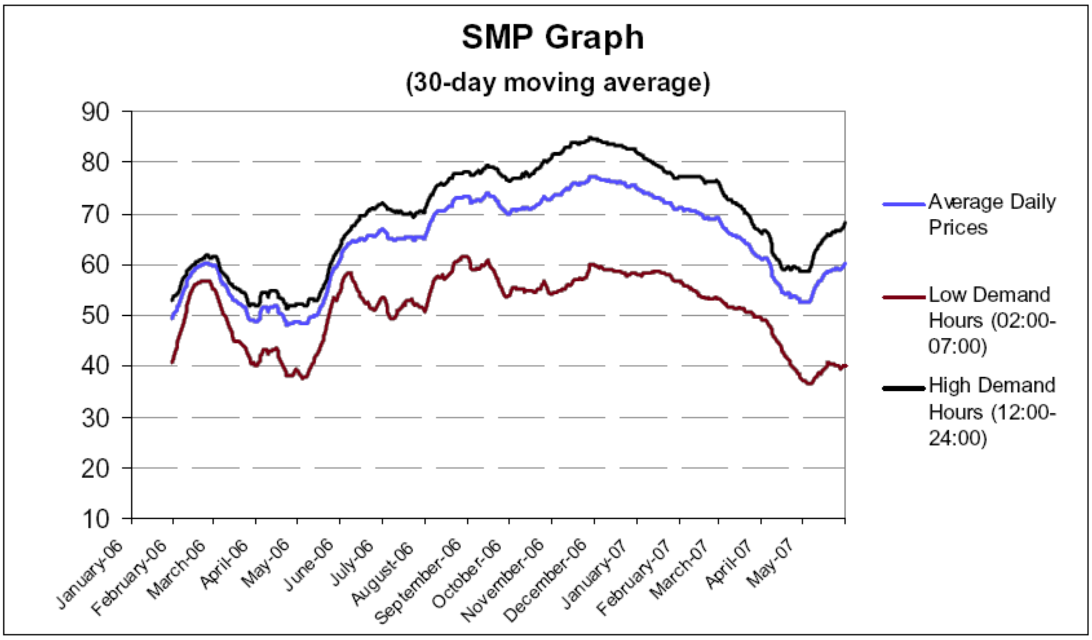


Figure 84 - Evolution of the System Marginal Price of electricity on the Greek market for the period 2006-2007

The present profile of electricity production in Greece (70% - oil and coal, 18% gas and 12% hydro-electric) is rather troublesome in matters of a possible evolution for the electricity prices. Fortunately, the Greek power network is already connected to some of its neighbors such as Bulgaria (Fig. 85) which enables PPC to buy nuclear produced electricity at peak load. With the full implementation of the Balkan electricity market it is expected that Greece will have access to the average European power mix and that in the long run prices could be maintained at a reasonable level. For the purpose of my study, I will make the hypothesis that the price increase of electricity in Greece will follow the average European inflation rate.

Figure 85 - Interconnections of the electricity power network in Northern Greece with linkage to Bulgaria

IV-2-3 – The local agriculture economics parameters

A – Agriculture economy in Europe

Europe's agricultural sector is well developed and according to agricultural statistical data gathered in 2005 (Eurostat, 2007[16]), 12.7 million people out of EU's 460 million citizens work full-time on agricultural holdings which cover 45% of the total land area. The high number of farmers in the EU indicates that farming is a corner stone for the economic sustainability and development both for the EU as an entity and for the national and regional economies. The role of the EU farming sector is not only to produce agricultural products, but also to serve the rural communities, i.e. to guarantee the survival of the countryside as a place to live, work and visit.

[16] *Eurostat, (2007). Agricultural Statistics - Main results - 2006-2007. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-ED-08-001/EN/KS-ED-08-001-EN.PDF

The EU is the world largest exporter of agricultural products (European Commission, Directorate-General for Agriculture and Rural Development, 2007), since its exports in 2005 were $79 billion, accounting for around 20% of world exports. It owns this position to the so-called Common Agricultural Policy (CAP) system which was introduced in the late 1950s. But this success should not hide the fact that agriculture economics are highly contrasted from the most productive cereal farms of the Beauce in France to the rural areas of some of the former socialist countries of Eastern Europe It is particularly the case of Bulgaria, where primitive agricultural structures subsist which were based largely on traditional forms of management and resulted in low efficiency (Margaris N.S., et al., 2001). In these countries the potential for change in agriculture practices is considerable.

A – The Common Agricultural Policy (CAP)

Agriculture was one of the first sectors of the economy to receive the attention of European policymakers. More particular, when the Treaty of Rome was signed in 1957 the founding members of the European Community (EC) set out the objectives for the first Common Agricultural Policy (CAP) in order to be secure their economies from the severe food shortages which appeared shortly after the Second World War.

These were focused on increasing the agricultural productivity as a way to ensure a fair standard of living for the agricultural community, on stabilizing food markets and on ensuring a security of supply at affordable prices to the consumers. The CAP system offered subsidies and a guarantee of fixed prices to farmers, providing incentives for them to produce more. Financial assistance was also provided for the restructuring of farming.

By the beginning of the 1980s the goal of self sufficiency in agricultural products within the EC was accomplished. However, due to the economic benefits of the CAP, the farmers augmented their production, thus producing large surpluses that needed to be exported. But in order to maintain their income, the EC subsidized these exports in order to compete on the world market. These measures had a high budget cost and distorted some world markets, as well as, resulted in raising environmental concerns about the environmental sustainability of agriculture.

Thus, the necessity to reform the initial CAP imposed itself. However such a revision is a painful and long process because it has to receive the unanimous approval of all the 27 EU member states. It started in 1992 when important reforms were agreed which involved reducing support prices and compensating farmers by paying them direct aid. Several rural development measures were introduced, notably to encourage environmentally sound farming. Production limits helped reduce surpluses. Farmers had to look more to the market place, while receiving direct income aid, and to respond to the public's changing priorities. This was finally formalized as the so-called “Agenda 2000”.

On 26 June 2003, EU farm ministers adopted a more fundamental reform of the Common Agricultural Policy (CAP) also known as the “Luxemburg Agreement 2003” or MTR 2003. It introduced a decoupling of direct aid payments from production to a standard amount of compensation on a per-hectare basis. This means that in the past the more farmers produced the more they were subsidized, but under MTR 2003, the aid to farmers is paid independently of how much they produce and induces them to be more market-oriented, i.e. they have the freedom to produce whatever they consider to be the most profitable for them, to produce commodities that will be highly demanded by the markets, while retaining their compensation level. Additionally, the action promotes of diversified activities such as rural crafts, food processing facilities on farms, tourism etc (European Commission, Directorate-General for Agriculture and Rural Development, 2007). As of 2005, the CAP was at €43 billion which represented about 44% of the EU's budget.

B - Modeling the CAPs’ impacts

The implementation of a new policy and its future targets are generally based on the analysis of historical data. In the case of common agricultural policy (CAP), the “Agenda 2000” and “Luxemburg Agreement 2003” (MTR 2003) measures were determined on the basis of a large amount of agricultural records which were collected over the whole EU following a uniform procedure. The main data sets are the Eurostat Farm Structure Survey (FSS) and the Farm Accountancy Data Network (FADN). Both surveys are regularly updated on a year by year basis with the help of digital cartographic methods and systematic remote sensing programs.

The Eurostat FSS agricultural survey is conducted in cooperation with the statistical authorities of Member States. It is general survey which gathers information about the farmers, i.e. population, gender, age distribution, educational level, number of employees, labor force etc. the production, i.e. type of products, produced quantities, production distribution, number of holdings, agricultural techniques, used technologies etc. and finally accountancy information about the prices of the products per country, the exported quantities, the revenues to farmers etc..

On the other hand, FADN is a data analysis tool designed to evaluate the income of agricultural holdings or farms. It is based on a balanced sampling extracted from a set of 82,000 commercial farms (EU Directorate-General for Agriculture and Rural Development). A commercial farm is defined as a farm which is large enough to cover the main farmer's income at a level sufficient to support his or her family. The annually collected accountancy data is processed in order to provide a set of the FADN indices mainly focused on economics aspects such as the income, the costs and inputs, the costs and external factors, the subsidies, the balance between subsidies and taxes, the production, etc.

The two main agricultural surveys are interconnected so that it is possible to attribute to each farm in the FADN sample a weight according to the occurrence of similar farms/types in the FSS survey. Additionally, both FADN and FSS use the Standard Gross Margin (SGM) criteria in order to classify the economic size of the farms. The standard Gross Margin (SGM) of a crop or livestock item is defined as the value of output from one hectare or from one animal less the cost of variable inputs required to produce that output.

Several research projects have been financed by the EU in order to develop economic modeling systems able to analyze the regional impacts of the CAP and provide decision tools suitable to the needs of the European Commission in Brussels. An example is the Common Agricultural Policy for Regional Impact (CAPRI) project and associated tools (Heckelei T., et al., 1999).

Under the CAPRI project, a region-oriented agricultural database was constructed from the FSS and FADN data sets in order to feed the farming economics model. Regions of Europe are the first administrative level under each nation level of responsibility. The key concept of this database was the disaggregating of the agricultural production process following a classification of the farm population by farm types per regions of Europe, also called “templates”. This classification is based on the FADN nomenclature (Britz W., 2005

The CAPRI economic model is split into two major modules. The *supply module* consists of independent aggregate non-linear programming models representing activities of all farmers at regional level captured by the FADN. The models simulates in high detail the premiums paid under CAP, include NPK (idem, Nitrogen-Phosphate-Potassium nutrients) balances and a module with feeding activities covering nutrient requirements of animals. The complex sugar quota regime is captured by a component maximizing expected utility from stochastic revenues. Prices are exogenous in the supply module and provided by the market module. The *market module* allows for marketable agricultural outputs over a spatial network of 40 world countries organized in 18 trading blocks. Post-model analysis includes the calculation of different income indicators such as variable costs, revenues, gross margins, yield of production, price, etc., both for individual production activities as well as for regions, according to the methodology of the FADN.

The CAPRI tool is available interactively on the Internet as both a simulator and a mapping tool. The mapping tool (Fig. 86) allows the interactive drawing of maps from the results of current runs of the CAPRI modeling system which is:

- A three year average around 2001 (base year expost simulation)
- The reference run, continuation of the Agenda 2000, results for 2009
- A simulation of a "probable" implementation of the Luxembourg MTR 2003 for the year 2009

CAPRI has been used for the Temenos project in order to evaluate the revenues of the farmers of the irrigated regions of the Nestos Delta and Xanthi. These evaluations have been based on the CAPRI outputs determined for the region of East Macedonia and Thrace in Greece under various CAP development hypotheses.

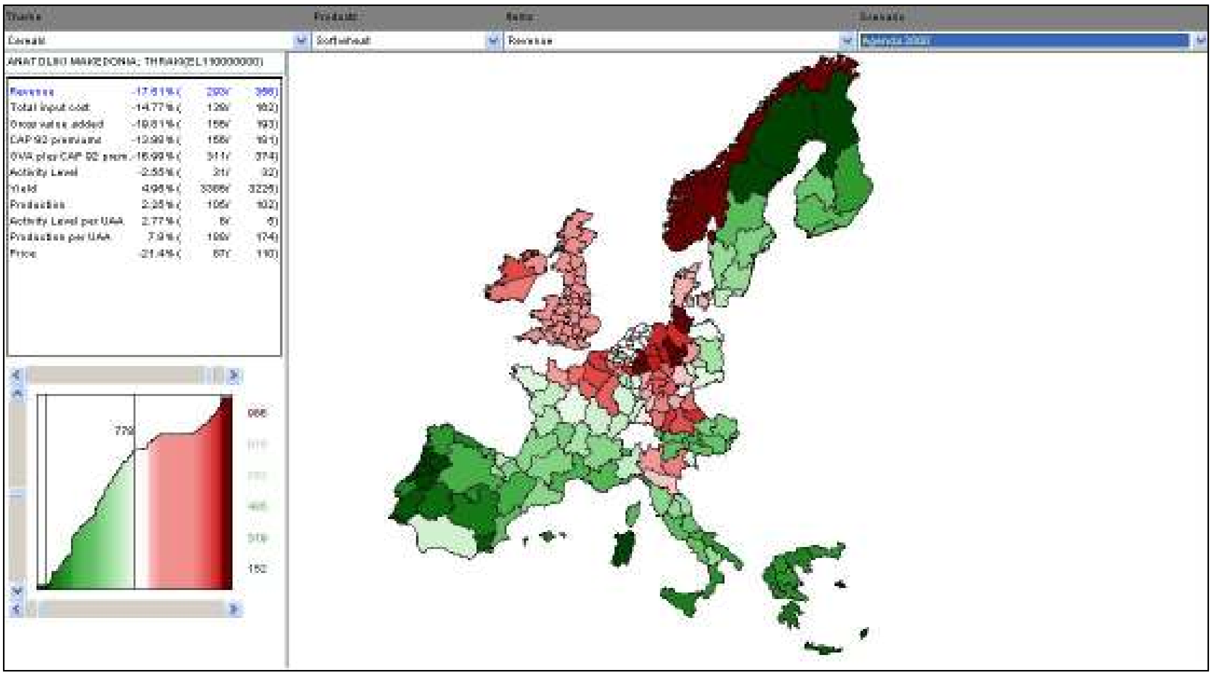


Figure 86 – Typical display of the CAPRI agro-economics mapping tool

D - The agriculture in the Nestos delta

As already mentioned in Chapter I, the Nestos delta is a highly agricultural region with great importance to the regional and national economy. Administratively it is shared between the Prefecture of Kavala on the west side of the main stream and the Prefecture of Xanthi on the east side (Figure 87).

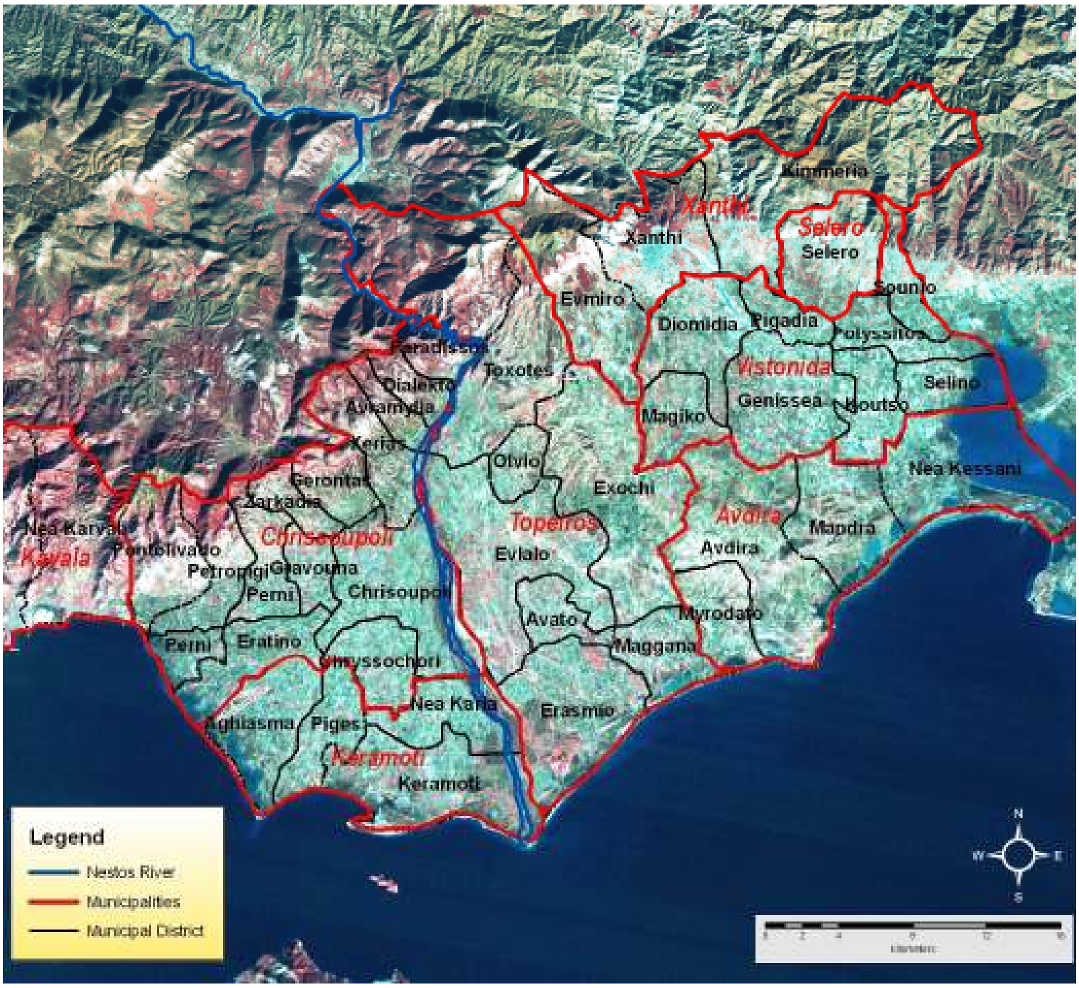
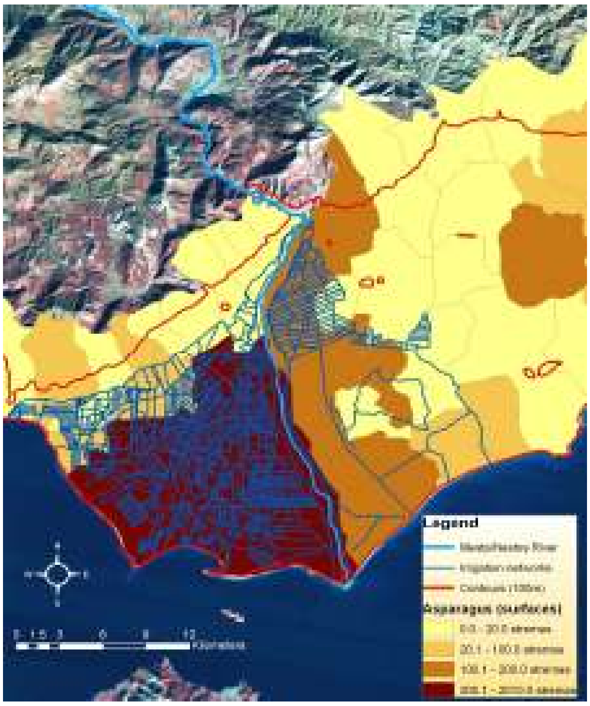
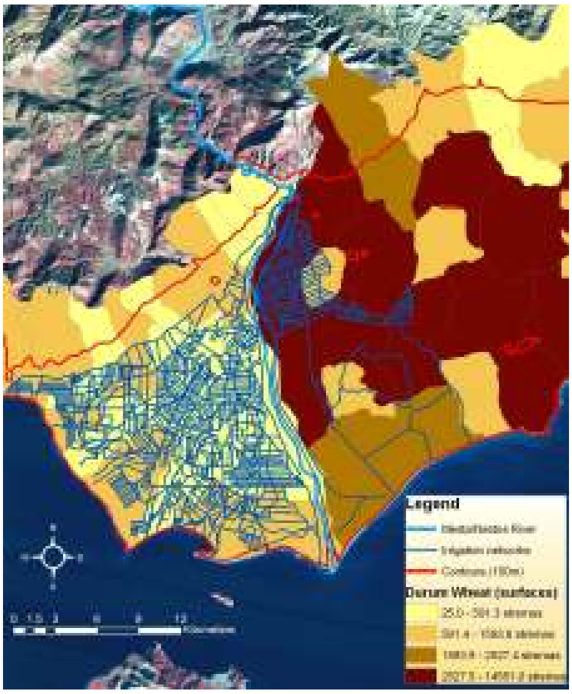


Figure 87 – Boundaries of municipalities (in black) and municipal communities (in red) for the Nestos delta and Xanthi region overlaid on a Landsat TM false color infrared composite (TM bands 4,3,2 as RGB).

In order to have a complete view of the current agricultural production in the Nestos delta region, agricultural survey data aggregated by municipality were obtained from the National Statistic Service of Greece for the years 1999 until 2003. The collected data have been stored in the ArcGIS project database in order to be represented and contains the aggregated field areas for the main ten products of the region which are listed as: soft wheat, durum (idem, hard) wheat, sugar beet, cotton, rice, barley, maize, asparagus, alfalfa and tobacco. They show a distinct contrast in some of the crops between irrigated areas on the right bank of the Nestos (idem, West) and the non-irrigated areas on the left bank around the town of Xanthi (Fig. 88).



a) Areas planted in Durum (hard) wheat, a rain fed crop (not irrigated)



b) Areas planted in asparagus, a crop typically irrigated

Figure 88 - Differences in production between the irrigated part of the delta (left) and the non irrigated part (right) in year 2001.

Typically, traditional lower yield crops grown using dry agriculture (idem, rain fed) such as the Durum wheat (idem, hard wheat) are more abundant on the non irrigated fields of Xanthi area than more technical crops with high water demands. It is expected that after the Xanthi area is irrigated by the Temenos project, farmers will change to higher yield crops. In order to evaluate the income increase which would result, I have determined from the available data an average crop profile for the existing farms on both sides of the Nestos (Table 22).

Type of crops	Nestos Delta farms (Percent cover)	Xanthi farms (Percent cover)
Soft wheat	6	15
Durum wheat	6	21
Sugar beats	3	2
Cotton	13	19
Rice	5	0
Barley	3	2
Maize	55	31
Tobacco	1	3
Alfalfa	2	7
Asparagus	6	0

Table 22 - Average crop area profile for the irrigated (Nestos Delta) and non-irrigated (Xanthi) farms in 2001

The CAPRI system was used in order to determine the average income from the two types of farms (Table 23) for three CAP scenarios: the reference conditions of 2001, the Agenda 2000 measures and the MTR 2003 measures

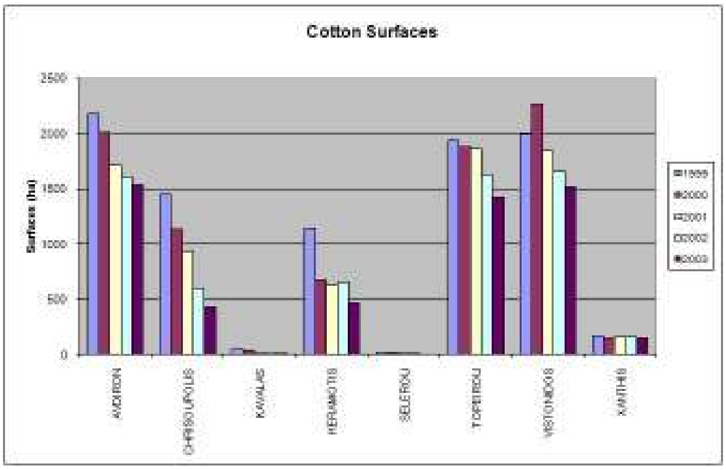
Agregated revenue terms	Reference 2001 (in Euros/ha)	Agenda 2000 (in Euros/ha)	MTR 2003 (in Euros/ha)
Irrigated	1899	1755	1822
Non-irrigated	908	818	864
Income differential	991	937	958

Table 23 - Farm average income of irrigated and non-irrigated using the CAPRI system under various EU CAP policy scenarios

It is noteworthy from the CAPRI evaluations that the change of CAP policy has a minimal effect on the differential of income between irrigated to non-irrigated farms. The benefits of the Temenos project will be evaluated using an expected average income increase (idem, marginal benefit) of 950 Euros/hectare (in Euro value of year 2001) when farms will be irrigated.

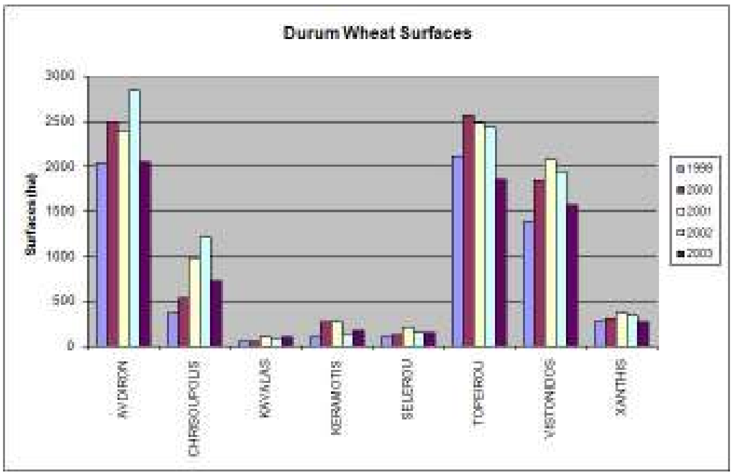
Although the approach CAPRI in matters of farm income evaluation is fairly advanced there exist other tools based on the direct simulation of the agronomy of crop growth such as the ACCESS model used in the Integrated Model to Predict European Land Use (IMPEL) project (Rounsevell M.D.A., 1999) or the STICS agro-pedology model (Ledoux E. et al., 2007). The problem is that they need detailed information on the phenology of crops, conditions of farming, soil composition, crop calendar which are not readily available for the agriculture of the Nestos Delta.

Another limitation of CAPRI lies in the fact that the software has no potential for simulation of changes in crop production based on response to changing market conditions. Figure 89 and Figure 90 illustrate these type of modifications for the period 1999-2003 during which cotton production decreased everywhere while Durum wheat production experienced fluctuations.



Cultivated surfaces in hectares per municipal communities

Figure 89 – Evolution of cotton production from 1999 to 2003 in the Nestos delta region



Cultivated surfaces in hectares per municipal communities

Figure 90 – Evolution of Durum wheat production from 1999 to 2003
in the Nestos delta region

New research tools in agro-economics are under development in the area of farmer's behavior simulation such as the AROPAj tool from the Institut National Agronomique in France (Chakir et al., 2005). Preliminary results tend to show that farmers will always tend to change crops in order to maintain their level of revenue. In my study I will make the hypothesis that the farmers of the area will tend to maintain the same income discounted by a regular inflation rate.

E – Present and future water demands

As it has already been mentioned in Section I-5, the Temenos dam project should service the extension of the existing irrigation system to the Xanthi plain. The Prefecture of Xanthi with the cooperation of the Democritus University of Thrace (DUTH) has conducted a preliminary study of a system of underground pipelines of 2.5 m in diameter which would both serve the irrigation demand and recharge the aquifers (Pliakas F. et al., 2003) in order push back the underground salty seawater front (Fig.91).

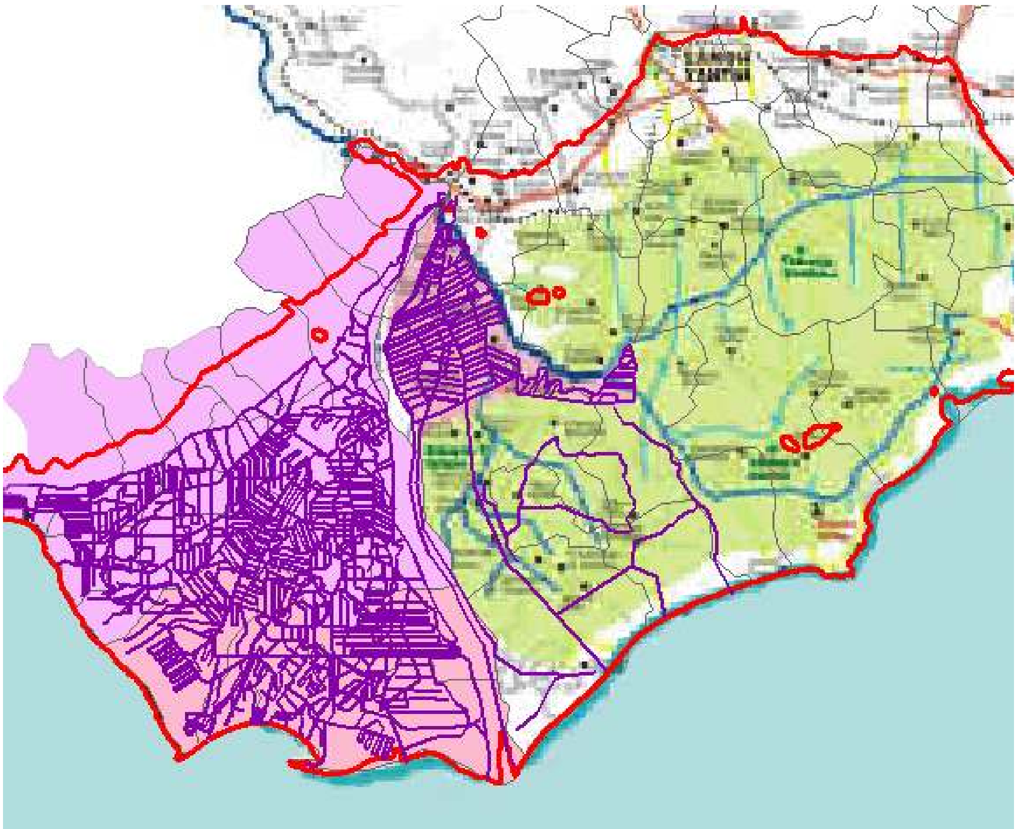


Figure 91 - Present irrigation system in the Nestos delta (in pink-magenta) and future extension to the Xanthi plain (in green-blue) in liaison with the Temenos dam project

The administration in charge of the management of the existing irrigation system is the Local Organization for Land Reclamation (TOEV) of Thalassias-Krematis. In one of its technical reports dated of 17 March 2000, it evaluated the total irrigated land at 18 900 hectares. It corresponds to the area colored in pink in Figure 91. This number is subject to some uncertainty, and may be as high as 27 000 hectares (Kampragou E et al., 2004).

As for the future extension to Xanthi plain (area colored in green in Figure 91, I have considered that limiting conditions due to local relief and soil types would probably lead to an area of new irrigation which is half the size of the existing area, thus about 10 000 hectares. Thus the total irrigated land after the Temenos dam is put in operation is estimated at 28900 hectares. It is noteworthy that in the original evaluation report of the Toxotes regulation dam, Knappen-Tippetts-Abbett-McCarthy Engineers placed the maximum possible extent of irrigated land at 15 000 hectares (YDE, 1954). The construction of the Nestos dams' complex including the Temenos project would practically double this number illustrating the effective development these dams have brought to the local agriculture.

From information acquired from the Prefectural Authority of Drama-Kavala-Xanthi and the Ministry of Agriculture in Athens, it is likely that this project will be financed jointly by the Government of Greece and the European Regional Development Fund (ERDF).

The existing Toxotes regulation dam diverts water through two irrigation ditches with a maximum flow of 11 m3/sec to the Kavala (West) side and 9 m3/sec to the Xanthi (East) side. The TOEV agency of Thalassias-Krematis publishes on a yearly basis the amount of water which has been provided by the Toxotes regulation dam. The water demands for the year 2000 are estimated at a total of 255 million m3. Values are also provided on a monthly basis and converted as a required average flow expressed in m3/sec (Table 24). Similar values have also been used in other studies on the irrigation water consumption in the delta (Kampragou E et al., 2004). Along with the existing water consumption, Table 24 presents the estimation of the future extra water consumption on the basis of its relative area (about 50%). These values have already been cited in Section III-6-2 and used in the definition of operational constraints of the dams simulated with HEC-ResSim.

Months	April	May	June	July	August	September
Existing water volumes (m^3/s)	11.5	15.7	18.5	20.9	20	13.0
Future extra water volumes (m^3/s)	5.7	7.8	9.2	10.4	10	6.5

Table 24 - Required volume of water for the irrigation demand of the existing irrigation network and those of Xanthi plain.

D – Irrigation water pricing

In the Mediterranean region both surface and underground fresh water resources are gradually becoming scarcer and more polluted. Overexploitation of groundwater resources in coastal areas, augmented water demand for irrigation purposes, and disposal of untreated waste waters back to river networks are some of the reasons which lead to this status. The use of water resources in Greece, for example, is distributed rather paradoxically since 87% of the water resources are used for agriculture, 10% for water supply and 3% for industry and energy demands. Furthermore, the irrigation systems and techniques used have tremendous associated water losses.

As of today, the farmers of the Nestos who are the major water consumers are charged by TOEV for a negligibly low price of 7 € per hectare and per year regardless the total amount of used water (Kampragou E et al., 2004).

The recently adopted EU Water Framework Directive (WFD) includes water pricing as a possible instrument to address these problems. It requires Member States to ensure that water pricing policies provide adequate incentives for users to use water more efficiently and it requires that the environmental objectives of the Directive are supported (Roth E., 2001). In the case of agriculture, pricing water policy should encourage farmers to adopt more efficient agriculture techniques which are less water-demanding.

On the other hand, the water distribution authorities will have to ameliorate the existing irrigation infrastructure in order to be able to control water consumption. This means that due to the construction method and materials of the networks in use, e.g. earthen networks with great leaks, open networks which have losses because of the evaporation etc., water losses affect the consumed water volume by the farmers.

Following this type of approach, I have decided that for the Temenos project financing scenario adopted in my work the farmers would pay for their irrigated water on the basis of a water pricing calculated per consumed cubic meter. It is quite a change for Greece and I will address the means of increasing the acceptance by the farmers of such of a cost strategy.

IV-2-4 – Protecting and valuing the lower Nestos river environment

A – Environmental protection areas

Downstream from the Temenos dam location, several sections of the Nestos watershed are designated as protected areas under various national and international conventions (Fig. 92): the Nestos Gorges aesthetic forest, the upper delta fresh water lakes, the riparian forest of the delta mouth and the coastal lagoons near Keramoti.

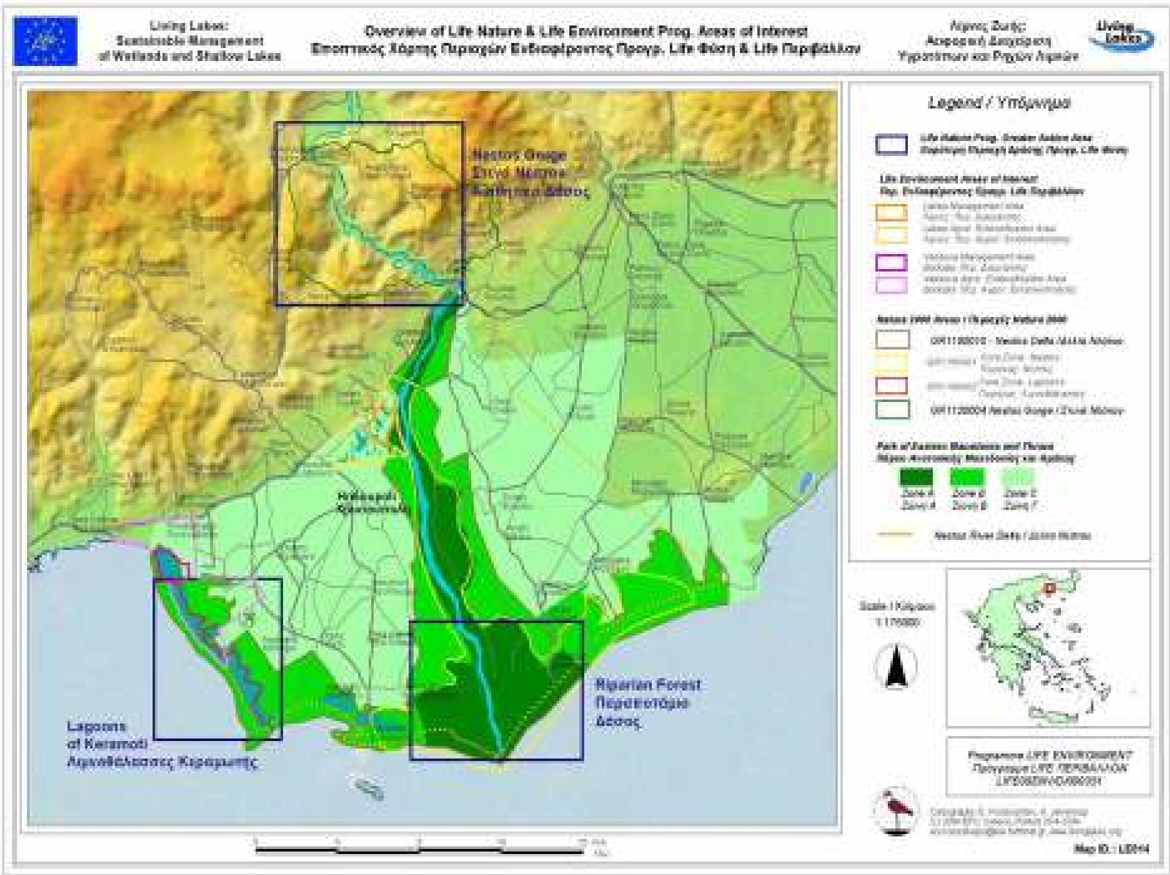


Figure 92 - The protected areas of the lower Nestos river
(Source: EPO Living Lakes)

The Nestos Gorges Aesthetic Forest is a riparian forest which covers an area of 238 hectares bordering the section of the Nestos river which cuts through the marble Lekani mountains. It is also a refuge for rare birds of prey and mammals such as the otter (Adamakopoulos P. et al., 1991) and has been protected since 11/7/1977, (State Law: 283/1977, Nestos Aesthetic Forest).

North of the town of Chryssoupoli in the upper part of the delta small freshwater lakes provide a refuge to rare species of mammals and birds. They are managed by the Society for Protection of Nature and Ecodevelopment (EPO), which is a private NGO participating in the Living Lakes International Network[17].

Near the mouth of the delta, the Nestos Delta Riparian Forest or Kotza Orman (meaning "large or legendary forest" in Turkish) is located on the banks of the Nestos, between the village of Toxotes and the Aegean Sea., the. The forest is 27 km long and 3-7 km wide, and covers an area of about 7,200 hectares, making it the largest forest of its kind in the southern Balkans. It is protected under the NATURA 2000 EU program[18].

The wetlands of the delta region, administratively belonging to the Prefectures of Kavala and Xanthi, are one of the country's most important wetlands, because of the large area they encompass and because of their diverse habitats. The protected wetlands consist of 18 fresh waters lakes and 7 lagoons, as well as the Nestos Riparian Forest (Figure 92).

In the eastern part of the delta area, along the length of delta shores, there are several salt water coastal lagoons the largest of which covers an area of 1,750 hectares. Where the Nestos meets the sea, the water flow is abruptly slowed and the river sand and silt carried by the river settle and accumulate, forming oblong ridges called sand spits. These spits act as natural dams, separating the waters and over time forming the lagoons. Usually the lagoons are connected to the sea by a channel. They are protected under the Specially Protected Areas of Wild Birds of the EU and the international RAMSAR Convention in Wetlands[19].

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[17] Living Lakes - Nestos Lakes, Greece : http://www.globalnature.org/docs/02_vorlage.asp?id=12682&domid=1011&sp=E&addlastid=&m1=11089&m2=28219&m3=11178&m4=12682

[18] NATURA 2000 Networking Programme : http://www.natura.org/

[19] RAMSAR : http://www.ramsar.org/

B – Minimum ecological flow

Human withdrawals from rivers and pollution inputs do alter the capacity of rivers to sustain natural life and processes. A tradeoff between human and ecological demands needs to be defined in order to sustain the ecological status of available water. The minimum ecological flow concept is such a tradeoff in order to ensure not only the protection of public health, but also the natural character of the environment and the water ecosystem (Ministry of Environment, Physical Planning and Public Works, 2006), something that is also stated in the EU Water Framework Directive 2000/60/EC. Thus, rivers must not dry-up, nor have their physical regimes significantly altered by human interventions in order to conserve the hydrological and ecological functions of their drainage networks.

Usually, the minimum ecological flow is expressed as a percentage of a water stream's normal flow. Both the normal flow and the percentage that corresponds to the minimum ecological flow depend on water sufficiency, minimum natural flow, economic potential, water uses etc. Therefore, a rational estimation needs to be made on a case by case basis. There exist different approaches for the estimation of the value of minimum environmental flow. Spanish River Authorities, for example, have decided that ecological use is the next highest priority after water supply to cities and towns (Estrela T. et al., 1997) and before agriculture irrigation and hydropower. In other cases, the minimum environmental flow is determined by laws imposed by governments, which are based mainly on economics criteria seeking prosperity in the region close to the river based on tourism and leisure activities rather than environmental sustainability per se. Additionally, since the water allocation involves many different stakeholders, multicriteria techniques have been developed for estimating the environmental flow in dammed river basins (Alberti M. et al., 2004).

In the case of the Nestos basin, a minimum environmental flow of 6 m^3 per second has been mentioned in the environmental impact studies which were associated with the construction of the Thissavros and Platanovryssi dams. This value has become a de facto standard in all impact studies which followed in the area. It is the value that has been retained in my investigation of the Temenos project sustainability and interpreted as the minimum value which should be maintained for the outflow of the Toxotes irrigation dam into the last natural portion between Toxotes and the mouth of the delta.

C – Environmental impact of dams

The impacts of hydroelectric projects mainly concern the water compartment of ecosystems and can be disruptive of their surroundings both upstream and downstream of the plant site. Upstream of the dam the main environmental impacts are: erosion and landslides from the slopes of the reservoir (Anastassopoulos K., 2006) causing an increase of sediment load, water losses due to evaporation, degradation of water quality because of stationary waters and production of greenhouse gases. The latter contradicts the accepted fact that hydroelectricity is a clean energy source. Nevertheless, the production of methane comes from the reservoir itself and not from the power plant. This phenomenon has mainly been observed in reservoirs in tropical zones, where the organic content of inflowing water is exceptionally high (Greenhouse Gas Emissions from Dams, 2007). A direct solution to this problem is the prior deforestation of the reservoir area. But it may also appear in deep reservoirs such as that of the Thissavros dam

As for the downstream environmental impacts, effects are diverse. Water exiting the turbine are usually very low in sediments, consequently the volume of sediments that come from the downstream part of the basin is inadequate, and thus scouring of river beds and coastal erosion occurs. This is what as been claimed for the Nestos river where coastal erosion has increased since the start of operation of the hydro power dams.

Other downstream factors are the irregularity of flow which might disrupt the aquatic fauna as well as a usually lowered water temperature from previous natural flow conditions. When water exits reservoirs where the water intakes are deep the water can be too cold and disrupt fish spawning, trigger fish species modifications and disrupt irrigated agriculture practices. This type of disruption has been observed downstream of the Thissavros and Platanovryssi dams where water temperature can be as low as 15°C below average air temperature during the summer (Psilovikos Ar. et al., 2006).

D - Valuing the environment

We can define environmental economic valuation as the attempt to assign quantitative values to the goods and services provided by environmental resources. As an environmental resource simply exists and provides us with products and services at no cost, its "value" is not related to an explicit payment of any sort to enjoy its benefits but rather a "willingness to pay" in order to restore them to their previous status if they were to disappear.

In the case of the Nestos, we shall not be interested in valuing all the benefits provided by good water status but rather limit ourselves to the benefits of maintaining a sufficient value for the environmental flow. The minimum ecological flow requirements are constraints which have been included into the dams' operation management simulated by the HEC-ResSim program. It is beyond the scope of my study to evaluate the effects other good water status parameters such as a sufficient sediment load to maintain the delta coastline geometry or a minimum water temperature necessary to maintain endemic fish populations.

My evaluation is based on the hypothesis of a complete loss of water in the main stream during a year. The predicted effects on the natural environment would probably be: loss of fish and mammal species, drastic reduction of bird migrations, loss of riparian forests including the Nestos Gorge and Kotza Orman remains, drastic increase in costal erosion of the delta mouth and loss of sea fish spawning grounds due to over salinization. On the side effects on human activities linked to the environment it could be: drastic impact on coastal fisheries and reduction of tourist activities along shore by loss of sand beaches and inland by loss of interest for the Nestos Gorges, loss of recreation activities such as rafting and closing of park and educational activities in the delta.

Environmental economists have classified values by the type of human usage of the environment (Barbier E.B., 1994). I shall illustrate these types by reference to the Nestos case. The first type is called "Direct Use Value" and corresponds to economic activities which can be quantified monetarily, such as fishing, tourism, and rafting. The second type is the "Indirect Use Value" which comes from the indirect benefits such as: nutrient source for species, shallow groundwater recharge to sustain the riparian vegetation, shoreline stabilization. The third is the "Option value" which relates to the future benefits of the today usage such as: education activities in wetlands or future park developments.

Finally, the "existence value" is non usage value which anyone, being a local resident or not, is willing to attach to the very existence of the Nestos river as an historic symbol or as an archetype of one of the few natural wetlands left in the Balkans.

If the evaluation in monetary terms of the "Direct Use Value" and the "Indirect Value" is relatively feasible, it is not the case of the two other terms. A way of estimating these two terms is by surveying a population by questionnaires. In my area of interest, a study of this type was recently conducted (Pavlikakis G. et al., 2006) and surveyed 1600 inhabitants of the Thrace region who expressed a "willingness to pay" an average of 36.15 Euros per person in order to maintain the natural environmental status (idem, "the existence value") of an area including the Nestos Delta. It is expected that they meant that this existence would be maintained over their expected lifetime. Which for an average lifetime of 80 years would give a "willingness to pay" of 0.45 Euros per year. This value is used in my project on the basis of a total of 1,000,000 persons in the World willing to pay for the existence of the Nestos.

Any exercise of evaluation environmental is bound to be subjective but I have done this exercise (Table 25) and proposed to value the environmental benefits of the maintained natural flow in the Nestos in Euros on the basis of one year of usage. It is based on published economic values of commercial activities in the area. The "Total Environmental Value", the sum of all environmental values, is estimated at 12 million Euros per year. This value will be used in the Temenos project accounting in order to evaluate (idem, monetize) the ecological impact when the main stream flow cannot be maintained at the minimum value of 6 m3 per second.

Direct Use Value		Indirect Use Value		Option Value		Non Use Value	
Fishing	2	Birds and mammals	1	Education	0.5	Existence	0.45
Tourism	4	Coastline	2	Parks	0.5		
Rafting	0.5	Forest	2				

Table 25 - Proposed repartition of ecological values for a year of maintained environmental flow in the Nestos (Values in million Euros)

The amount of my estimation is of similar magnitude to that obtained in a previous study which evaluated the expected damages (idem, externalities) caused to the close environment of the Thissavros and Platanovryssi dams due to the flooding of their reservoirs and their operation nuisance (Kollas I.G. et al., 2002). The authors estimated the "Total Environmental Value" loss at 3.7 million Euros per year for an impact of lesser geographic extension and environmental interest.

IV-3 – **Outcomes of the Temenos project evaluation**

IV-3-1 – A possible multi-purpose financing structure

A – Project financing structures and the "project company» concept

In contemporary times, the tradition of project financing takes its origins from the construction of the Suez Canal which was promoted by the Frenchman, Ferdinand de Lesseps. Its principle is that of the "non recourse" funding of a project company. It is now the de facto standard in the matter of project investment.

The idea is that the promoters of the project (actually called "sponsors"), either persons or companies, have the technical expertise to evaluate with a sufficient degree of realism the potentials of a particular resource which can be an oil field, an ore deposit, a hydropower potential, a road infrastructure potential… etc.

The promoters generally do not possess enough assets on their own to finance the construction and operation related to that resource. Instead, they develop a proposal (idem, a tender) for the creation of a "project company" which will be endowed by the value of the resource and for which a well documented life cycle balance sheet is published. The balance sheet contains details related to costs of construction and operation as well as the incomes related to the marketable resource produced. A group of investors (also called "lenders") are solicited on the basis of "non recourse" loans (Pollio G., 1999). "Non recourse" (coming from the French: "non recours") meaning that the lenders cannot be served any form of guarantee but the balance sheets of the "project company". It is obvious that before engaging in lending the investors will conduct comprehensive risk studies on all the aspects of the "project company" operation. They will ultimately form their decision on the choice of a particular rate of return (idem, discount rate) for which the Net Present Value (NPV) of the accumulated balance sheets is computed over the expected life of the "project company". Lenders will also propose a repayment schedule on the basis of the expected cash flow time table.

Ounce the lenders have given their approval and deposited their funds, the "project company" will start operating by appointing contractors during the construction phase. The production phase follows and the product is sold to "buyers" (Fig. 93), repayment of loans starts until the tipping point when the company will operate on its own funds.

In practice, project structures and lending partners do evolve over time. For example, the improvements to the existing irrigation system of the Nestos Delta were funded in 1974 by the IBRD/IDA branch of the World Bank[20]. The World Bank has low lending rates equivalent to US Treasury Bonds which for long return periods of 15 to 20 years were around 4% in 2008. The Thissavros-Platanovryssi complex was funded for a large part by European Community (now, EU) Structural Funds and as the operation of the project was guaranteed by the Greek Government, the Public Power Corporation (PPC) was named as the operator without the creation of a "project company".

For the Temenos project, as it was initially conceived as a part of the initial Nestos dams complex it is most probable that EC Structural Funds would have been granted. Nowadays, EU Structural Funds have been replaced by the European Investment Bank[21] (EIB) which is devoted to finance the former Eastern Block countries and concentrates on small businesses, innovation and environmental protection. The only option left today for financing the Temenos project is through private funding following the traditional constraints of its practices. Recently, a private company, the MICHANIKI S.A. group, one of the leading construction companies in Greece, has publicly expressed an interest in promoting (idem, sponsoring) the Temenos project and published an evaluation dossier.

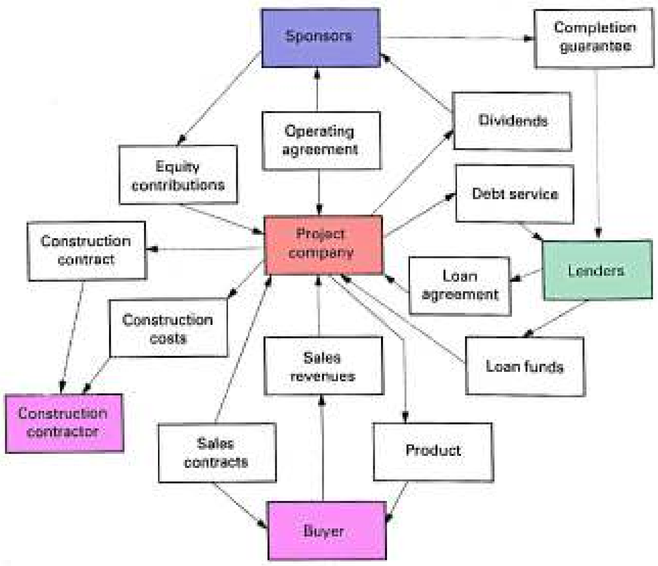

Figure 93 - Typical structure of operation of a "project company"

[20] Nestos and Yannitsa Irrigation Project: http://web.worldbank.org/external/projects/main?pagePK=64283627&piPK=73230&theSitePK=40941&menuPK=228424&Projectid=P008424

[21] European Investment Bank: http://www.eib.org/?lang=en#

B – Example of project tender for the Temenos HEP

During the HYDRO2006 Conference[22] which was held in Porto Carras, Greece on 26-28 September 2006, the MICHANIKI Construction Company handed out a flyer[23] detailing their project financing of the Temenos project. Quoting the main elements of this publication:

> *"Although the initial tendered power production was evaluated for three power units of 6.3 MW each it was later decreased at 5.0 MW per unit due to the revaluation of hydrological data. In addition, this change in the power production opened to a possible partial financing from the 4th European Community Support Program.*
>
> *The initial production energy level was based on a study made by PPC, in which the mean annual discharge of the Nestos River at Temenos (based on 21 years of data from 1965 until 1986) was estimated to be equal to 43.00m^3/sec with an annual mean discharge of 1,356 10^{6}m^3/year (PPC's Feasibility Report, 2nd Edition, March 2001). Thus, the production from the Temenos HEP was initially estimated to be of 71GWh per year.*
>
> *Because of the extended period of drought experienced between 1985 and 2000, the expected production of energy from the Nestos complex was perceived to be uncertain. After a new computation of the last 30 years of hydrological data (1970-2000), the mean annual discharge of the Nestos River at Temenos was estimated to be equal to 33.5m3/sec with an annual mean discharge of 1,061 10^{6}m^3/year (PPC's Feasibility Report, 3rd Edition, September 2001). Thus, with this new hypothesis* ***the production from Temenos HEP is now estimated to be 62GWh per year, and valued at 4.2 million Euros at a selling price of 73€/MWh****.*
>
> *Furthermore, according to PPC's Feasibility Report of March 2001, the construction of the Temenos HEP should bring a fair return in the operation of the upstream Platanovryssi's HEP. According to Scenario 1 of the document, the return should be equal to 1,672,500 € annually for mean annual discharge of 1,356 106m3/year. Scenario 2 also cites a respective return of 2,245,000 € and 3,213,500 € annually. These amounts are evaluated using the electricity sale price of 2001. According to these numbers,* ***the returns on the operation of the upstream Platanovryssi's HEP could be estimated at 1,881,000 € per year.***
>
> *In the present financial evaluation, all the necessary costs and returns have been integrated, namely: the initial expenditures (CAPEX), the incomes from the downstream utilization of the water (mainly incomes from the irrigation), and the running costs of the operation of this project (OPEX).*

[22] HYDRO2006: http://www.hydropower-dams.com/hd_67_0.htm
[23] The MICHANIKI flyer was originally printed in Greek and translated for the texto f this thesis

<u>*Hypothesis 1*</u>

For the evaluation of the economic output and the feasibility of the construction of the Temenos HEP, a commercial viability model has been using a scenario which includes:

- a total investment cost (CAPEX) equal to 63,615,000 €
- an annual energy production of 62 GWh, valued at a **market price of 73 €/MWh.**
- additional charging of irrigation users equal to 0 €/KWh.
- financing by the 4th European Community Support Program is evaluated at 22,723,300€.
- income from the enhanced operation of the upstream Platanovryssi's HEP is evaluated at 1,881,000 € per year.

In this initial scenario, the commercial viability of the project is estimated at an NPV of 24,701,200 € with an IRR of 11.73 % and an ROE of 9.66 %.

<u>*Hypothesis 2*</u>

Furthermore, a second hypothesis has been made ***without the financing by the 4th Community Support Program*** *in which case the NPV is equal to 3,755,400 €,* ***the IRR to 7.85 %*** *and the ROE to 7.19 %. These results can be considered satisfactory for this type of investment project.*

The project incomes could be significantly influenced by the utilization of the downstream water for irrigation uses. ***A potential extra return of 0.009 €/KWh for irrigation use could make the investment much more feasible. This is equivalent to an extra charge of 0.000985 €/m3 of the irrigation or potable water uses.*** *It must be noted that the Ministry of Development is presently preparing the legislation frame in order to adapt the European Framework in the Greek legislation which should bring a fair market price for electricity rate and a better charging policies for the utilization of water."*

It is of note that the tender mentions some concern about the uncertainties due climate variations and their influences on the overall profitability of the project. However, these risks are evaluated from past flow measurements but do not mention the possibility of a definitive modification of the river regime due to climate change. It is also striking to note that no mention is made of a possibility of resource decline which could come from Bulgaria enforcing the flow treaty.

As a means of demonstrating the use of my mathematical model cascade for the evaluation of the impact of these risks on the project, it was decided to retain the basic economics parameters of the proposal. Considering the fact that it is unlikely that any EU funds would be devoted to the funding of the Temenos dam, “Hypothesis 2” has been retained. On the other hand, considering that the application of the EU Water Framework Directive (WFD) is bound to institute a system of water pricing, the hypothesis of an income from irrigation water has also been retained.

In summary, the project financing risks investigation will be conducted using the two following parameters:

- **A market price of electricity of 73 €/MWh**
- **A rate of return of 7.85 %** for the NPV computation
- **An income of 0.000985 €/m3** from the **irrigation water** sold to the farmers

C – A possible multi-purpose Temenos project company

In the classical case of financing hydropower projects, the “project company” would be formed on the sole basis of the balance sheets of the electricity production. But in the case of the Temenos project, the multipurpose nature of the dam operation leads to a more holistic view where all costs and benefits would be exposed.

It is particularly the case of the benefits to the agriculture of the Xanthi plain balanced by the new cost induced to the farmer’s revenues due to the application of a water pricing calculated on the basis of the actual cubic meters of irrigated water consumed. Even if this would be a new practice in Greece, there other parts of the world where the management of irrigation system projects is associated with the direct participation of farmers both to capital and operation expenditures (idem, CAPEX and OPEX). In other words, farmers are both shareholders and managers of their irrigation systems. It is particularly the case of the Victoria irrigation system in Australia (Langford K. J., 1999). Similar cases of direct involvement of farmers in the economics of irrigation water are also found in Europe like the “water trading markets” organized between agricultural cooperatives in Spain (Garrido A., 2000). In any case, it has been observed that irrigation systems were more efficiently managed with less impact on the environment when farmers were directly involved (Briscoe J., 1999)[24].

Thus for the present evaluation exercise I have proposed that the “Temenos project company” would cover both hydropower and agriculture activities. The alliance of energy and agriculture would probably have sounded inappropriate in the past but the recent evolution of the World economy facing shortages in oil energy have amply proven that connections do exist. This might actually be the case in the Xanthi plain where a large sugar producing plant which used to operate from the highly subsidized sugar beet production by the local farmers is now pursuing a possible conversion to ethanol production.

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[24] Briscoe, John. 1999. “The Changing Face of Water Infrastructure Financing Developing Countries,” International Journal of Water Resources http://lnweb18.worldbank.org/essd/essd.nsf/a95275735facede4852569970057eeb2/bee47c61be53f8e285256998005cc8e0/$FILE/ijwrdfinal1.doc.

On the resources side of the balance sheet of the “Temenos project company” both electricity and crop values will be aggregated. On the cost sides, apart from the classical CAPEX and OPEX costs of the Temenos plant it will hypothesize that the irrigation water revenues will cover the operation (OPEX) costs of the Xanthi plain irrigation system as this system construction cost should be covered by Government-EU funding.

However, in order to have a more realistic view of the socio-economic sustainability of the project and increase its acceptability by the public and the various governing bodies, it is my opinion that “external” costs should be included in the balance sheet. I will essentially consider the negative returns of the project in terms of conflicts in cases of shortage of water. In particular, the value of crop lost in the case when the required levels of irrigation water are not met as well the cost of impact on the water environment when the minimum ecological flow cannot be maintained. The latter will be evaluated on the basis of the “total value of the environment” presented in Section IV-2-2.

IV-3-2 - Evaluation of the Temenos project sustainability

A – The discounted cumulative cash flow

The discounted cumulative cash flow (DCCF) over the life cycle of a project is one of the most commonly used tools for project financing evaluation and decision (Bénichou I. et al., 1996). It can be represented graphically and offer a clear view of when the project NPV reaches its minimum following the money draw-down during the construction phase, when the NPV starts to be positive reaching what is known as the “break-even point” and at what level the NPV will hopefully culminate at the end of the project. These three phases are illustrated in the following diagram illustrating the use of the discounted cumulative cash flow in the evaluation of project in biopharmacy (Fig. 94)[25]. For a particular project, the discounted cumulative cash flow depends upon the targeted rate of return. Another popular concept is the Internal Rate of Return (IRR) which is the rate of return for which the project would commercially break even (idem, NPV = 0) at the very end of its life.

[25] EPA - Biotechnology Program Under Toxic Substances Control Act (TSCA) http://www.epa.gov/biotech_rule/pubs/ria/ria055.htm

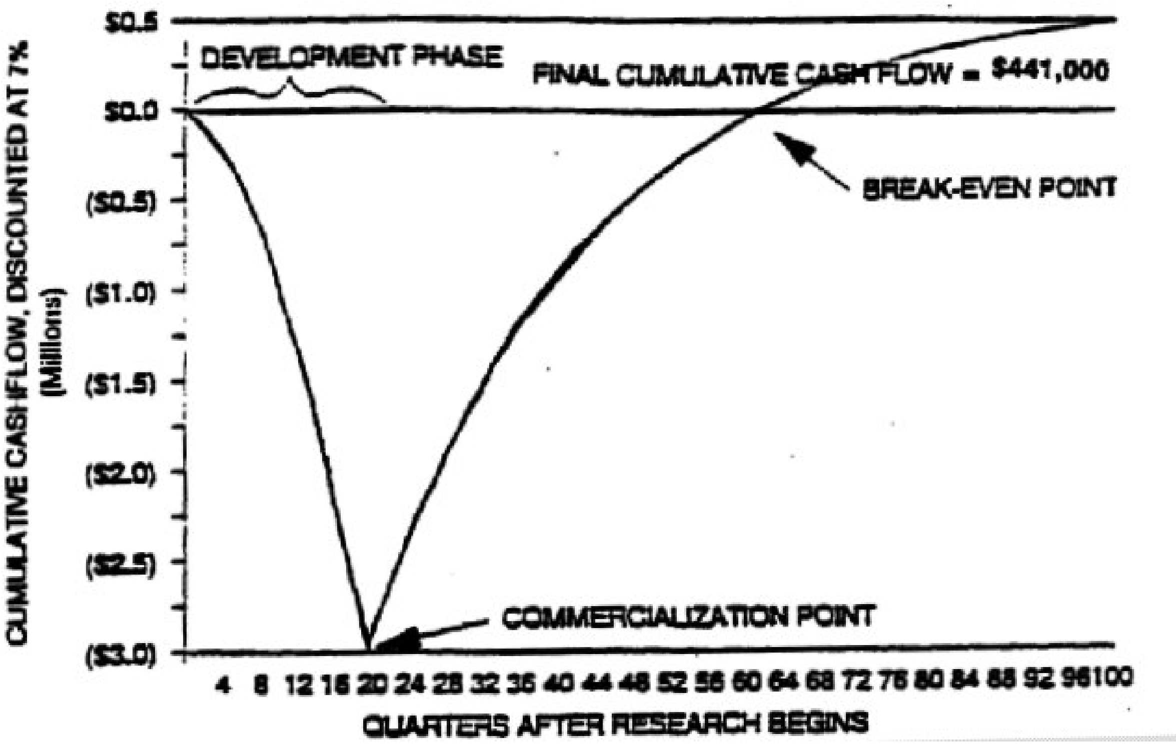


Figure 94 - Example of discounted project cumulative cash flow in the biopharmacy industry

B - The Temenos project evaluation tool

For the economics evaluation of the "Temenos project company" sustainability I have devised a discounted cumulative cash flow (DCCF) tool which facilitates computation of the NPV of the project over its full life cycle which has been fixed at 50 years with a start of construction in 2016 and a decommissioning in 2065. This tool is based on the Microsoft Excel spreadsheet program (Fig. 95).

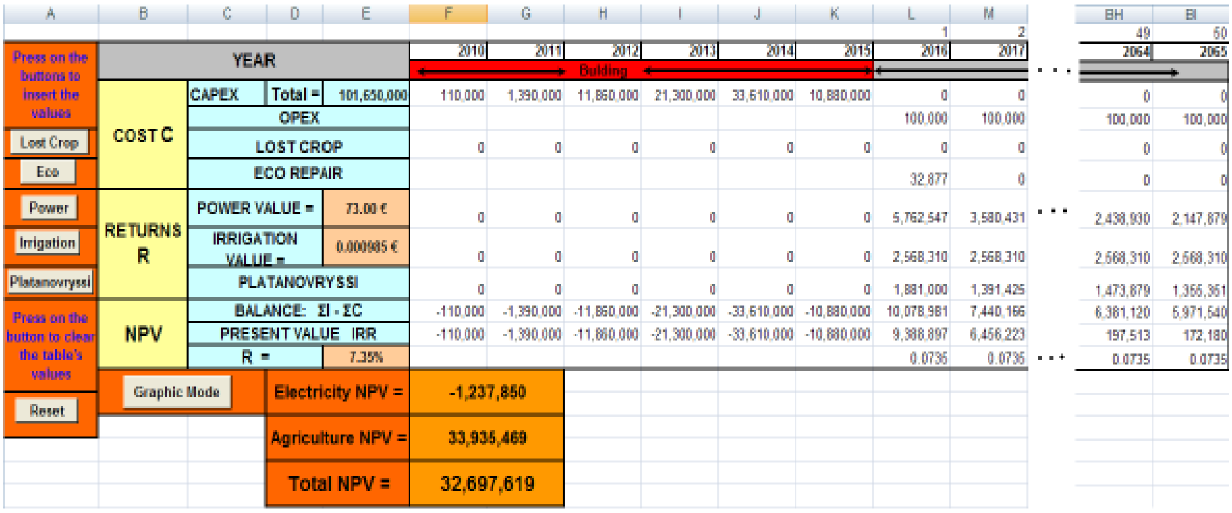


Figure 95 – DCCF economics tool for the evaluation of the Temenos project sustainability

The variable parameters of the DCCF tool are:

- the **market price of electricity** expressed in €/MWh year 2001
- the **price of irrigation** water expressed in €/m3
- a target **rate of return** expressed in %

The DCCF Excel spreadsheet is fed by the cascade of programs used in my processing protocol under various climate and bilateral flow treaty enforcement hypotheses (Fig. 96).

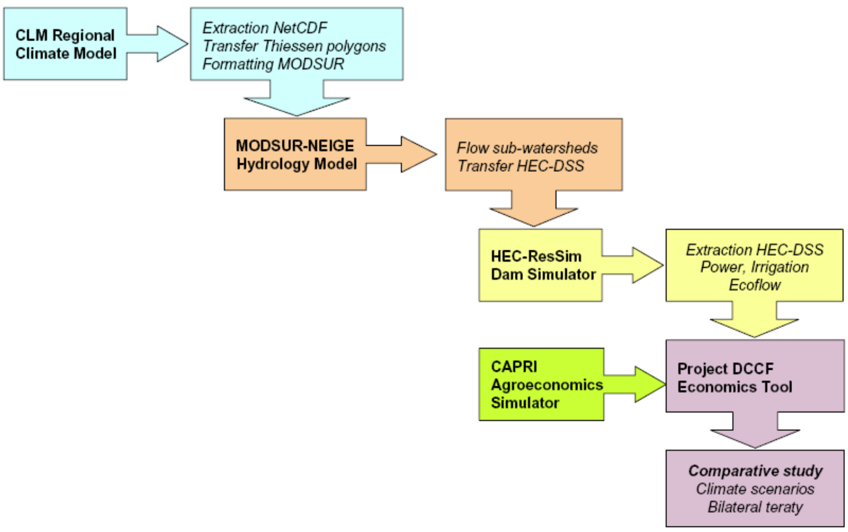


Figure 96 - The processing protocol used in order to evaluate the Temenos project

The income terms of the DCCF tool

The project income is composed of three terms:

- the "Power Value" comes from the electricity produced by the Temenos during a year and sold on the market,
- the "Irrigation Value" comes from the marginal revenues accumulated over by the farmers of the Xanthi plain in comparison to the past situation when they were not benefiting from irrigation,
- the "Platanovryssi" term corresponds to the revenue made from the Temenos plant from its reselling of water to the upstream power plant of Platanovryssi during the pump storage procedure.

The computation of the "Power Value" is based on the year production of the Temenos power plant extracted from HEC-ResSim and expressed in MWh. The production is then multiplied by the parameter "**market price of electricity"** expressed in €/MWh

The water volumes released from the Toxotes regulatory dam for agricultural irrigation are extracted from the results of HEC-ResSim and expressed in m3/sec. They are transformed into the "Irrigation Value" using a factor called "value agri/m^3" expressed in Euros/m3. The "value agri/m^3" in based on the **marginal benefit per hectare** which has been determined in Section IV-2-3 as **950 Euros/hectare** using the CAPRI tool and an estimated extent of the project in the Xanthi plain at 10000 hectares. The "Irrigation Value" is also augmented by the amount of irrigation water sold to the farmers of the existing Nestos Delta.

Finally, the computation of the revenue parameter "Platanovryssi" is based on the number of days when the level of the Temenos dam pool is sufficient for the back pumping to the Platanovryssi plant at night. This number of days is extracted from HEC-ResSim and monetized on the basis of **full year of pump storage procedure to Platanovryssi estimated at 1,881,000 €** by the MICHANIKI company in its tender (see above).

The costs terms of the DCCF tool

The project cost is composed of several terms:

- The capital expenditure (CAPEX) is spent for the construction of the Temenos dam and plant. It includes an equipment renewal after 25 years. It does not include the investment cost of the irrigation system in the Xanthi plain.

- The operational expenditure (OPEX) is spent on maintaining the Temenos plant and the irrigation system of the Xanthi plain.

- The "Lost Crop" term is the value of the crop which could be lost if irrigation demands are not met

- The "Eco Repair" term is the amount of damage done to the environment in case the minimal ecological flow could not be maintained

The CAPEX and OPEX terms for the Temenos plant are derived from the corresponding terms as published by PPC in the original tender for the Nestos dam complex in the 1990s (Table 26). The only alteration from the original numbers is the conversion from drachmas to Euros Year 2001. Furthermore, a cost of replacement for the mechanical equipment (because of wear) in half of the project lifetime has been evaluated at 22.5 million Euros.

As for the operational expenditures (OPEX), the amount of 100,000 Euros per year is estimated to cover the operational needs and salaries. The OPEX part related to the maintenance of the Xanthi irrigation network is covered by the water sold to the farmers of the Xanthi plain.

The "Lost Crop" term is evaluated from the water deficit if it exists between the demands for irrigation and the actual flow sent to irrigation from the Toxotes dam. This last term is extracted from the results of HEC-ResSim. This term is monetized using a factor called "value agri/m^3" expressed in Euros/m3. The "value agri/m^3" in based on the **total revenue per irrigated hectare** which has been determined in Section IV-2-3 as **1850 Euros/hectare** using the CAPRI tool and an estimated total extent of irrigated fields of 28900 hectares.

“Eco Repair” computation is based on the concept that the annual total environmental value of the delta ecosystem is **12 million Euros** (see, Section IV-2-3). The HEC-ResSim model simulates the daily water volume which is discharged from the Toxotes dam towards the river outlet. The sequence of data is extracted in order to define the number of days where water deficiency occurred, i.e. the discharged water volume is less than the environmental flow of 6 m^3/sec. The “Eco Repair” cost is computed in proportion to the full year value.

Contract and description	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	Amount
Land and Land rights															0.11
TEH-1 Diversion Channel, Coffer-dams etc.															4.13
TEH-2 Dam, Spillway, Power plant and Appurtenances															31.50
TEH-3 Electromechanical Equipment															22.50
TEH-4 Steel Liners, Gates, Trashracks, Cranes etc.															7.13
TOTAL DIRECT COST	-	-	-	-	-	-	-	0.11	1.13	9.75	17.63	27.75	9.00		65.37
Omissions and Contingencies	-	-	-	-	-	-	-	-	0.11	0.98	1.73	2.78	0.90		6.50
TOTAL CONSTRUCTION COST	-	-	-	-	-	-	-	0.11	1.24	10.73	19.35	30.53	9.90		71.86
Engineering. Supervision and PPC's Overheads	-	-	-	-	-	-	-	-	0.15	1.13	1.95	3.08	0.98		7.29
TOTAL COSTS	-	-	-	-	-	-	-	0.11	1.39	11.86	21.3	33.61	10.88		79.15

Table 26 - Construction time schedule and cash flows (values in million of Euros) of the Temenos dam project (source: PPC)

DCCF economics tools output

As already cited in Section IV.1.3, according to the Net Present Value (NPV) formula the result of incomes minus outcomes is divided by the discount rate which is augmented with time. For the Temenos project, the discount rate R which is tested is the value which was adopted by the MICHANIKI tender report and is equal to R = 7.35%.

The program facilitates the extraction and display (Fig. 97) of the yearly sequence of the accumulated NPV of the whole project (idem, DCCF) along with the income from electricity production and agriculture as well as the evolution of the CAPEX. The other DCCF terms may also be extracted from the Microsoft Excel sheet.

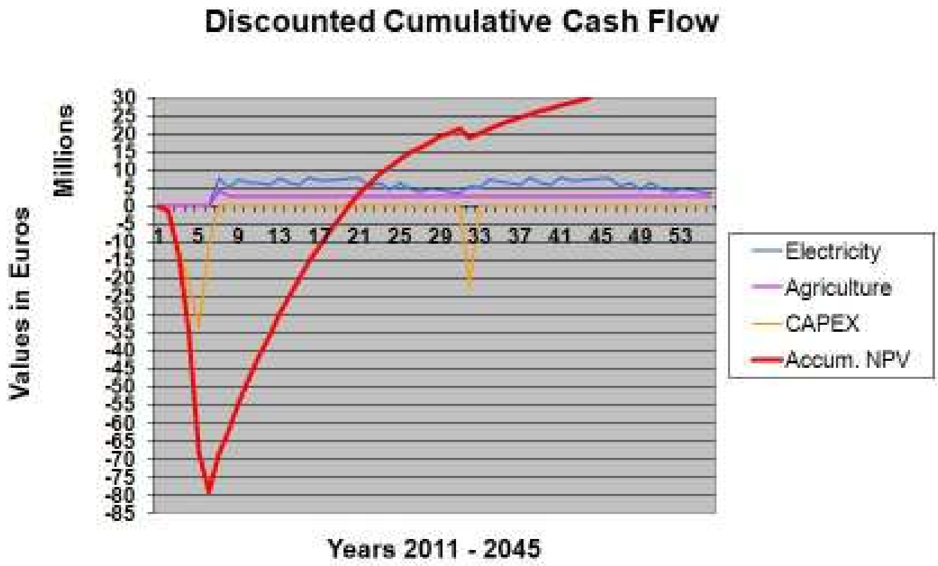


Figure 97 - Graphical representation of the economics of the Temenos project

IV-3-3 - Testing project sustainability under climate change and transboundary scenarios

A – Comparison of NPV values

The simulation of the Temenos dam project as well as the simulation of the dams' complex on the Nestos River was conducted by taking into account the past climate sequences RFSM and PCSM (Section III-7-1) and the future climate change sequences CLM_A1B and CLM_B1 (Section III-7-2) produced by the CLM Regional Climate Simulation model. In the presentation of the results, these sequences are named with a prefix "TEDLX" which is an acronym standing for the "Temenos + Delta irrigation + Xanthi irrigation" project simulation.

Besides testing different climate conditions, two alternatives have been added. Named FUCC and 29CC, they correspond respectively to a full Mesta river flow from Bulgaria and a reduction at 29% in a case of a strict enforcement of the bilateral Bulgaria-Greece flow treaty.

Thus, the economic feasibility of the Temenos project has been evaluated for a total of 8 scenarios, and the summary results presented in Table 27. For each scenario, partial NPV has been computed separately for the electricity production part and for the agriculture production part. The Total NPV result includes a combination of the two preceding terms to which have been added the "externalities" which are the "Lost Crop" compensation and the "Eco Repair" value.

NPV results for the TEMENOS project - Period of operation 2016-2065							
Full Mesta water	**Power**	**Agri.**	**Total**	**29% Mesta water**	**Power**	**Agri.**	**Total**
Past Climate Conditions							
TEDLX_RFSM_FU	2.7	31.9	34.7	TEDLX_RFSM_29	-7	33	26
TEDLX_PCSM_FU	-1	33	32	TEDLX_PCSM_29	-20	31	10
Future Climate Scenarios							
TEDLX_CLM_B1_FU	-33	32	-1.8	TEDLX_CLM_B1_29	-84	30	-56.6
TEDLX_CLM_A1B_FU	-42.8	32.5	-10.3	TEDLX_CLM_A1B_29	-118	27	-95

Table 27 - NPV results for the Temenos project (Values in million Euros)

As it can be observed at a glance, the positive Total NPV values are only related to the present climate conditions. The Agriculture NPV is always positive although decreasing with climate change conditions. This results from the fact that in the operation of the dams, the servicing of the irrigation demands has been given the highest priority. The worst results are obviously obtained for the Electric Power NPV. Another obvious feature is that a strict application of the bilateral flow treaty, should it happen, would have a strong impact on the profitability of the whole project.

The main reason behind the increased project failure to reach a positive NPV as one goes further into future climate scenarios lies essentially in the decrease in the overall amount of precipitation as it has been already illustrated in Section III-7-2. According to the results of the TEDLX_CLM_A1B scenario, for example, the predicted water quantities are inadequate to cover the agricultural demand on water or the minimum environmental flow (Fig. 98).

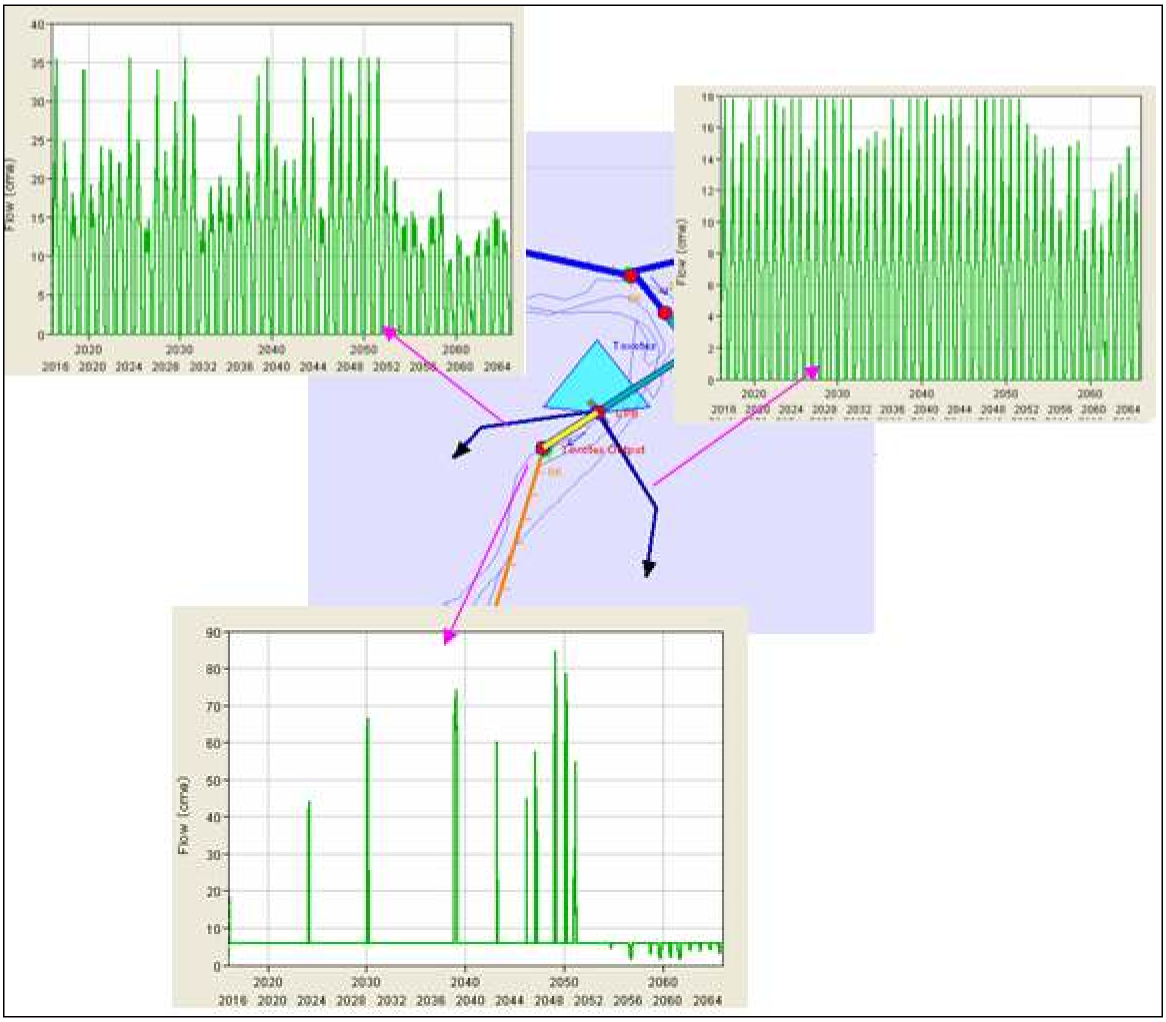


Figure 98 - Deficiencies in covering the agricultural demand on water (top left and right) and the environmental flow (lower diagram) in case of the TEDLX_CLM_A1B scenario

Furthermore, because of lack of water, the average generated energy per day from the Temenos hydroelectric plant is equal to 2.9 MWh, an amount which does not come close to the planned 20MWh per day by the MECHANIKI company in its tender (Figure 99).

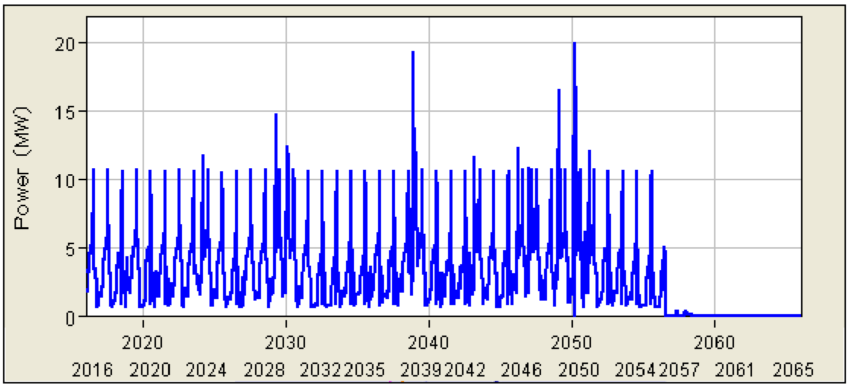


Figure 99 - Insufficient power generation of Temenos HEP for TEDLX_CLM_A1B scenario

Thus, the expenditures related to the compensations to farmers and to the rehabilitation of the environment coupled with the diminution of income from marketing electric energy not only jeopardize the project viability, but in the case of an inflow of 29 % of the total the project may be considered as being completely inappropriate for financing. In the latter case, the total losses would be approximately 95 million Euros.

A closer analysis of the Discounted Cumulative Cash Flow (DCCF) offers a detailed evolution of the NPV along the project lifecycle and provides a better understanding of the dynamic influence of climate change scenarios on the project sustainability.

B – DCCF curves for Past Climate conditions

As can be seen from Figure 100, the project has a positive NPV whatever the past climate simulated sequences and the conditions of flow from Bulgaria although it could be as low as 20 million Euros for the worst case. Results are better for the ideal "average" Reference Climate (RF) sequence and slightly worse for the Past Climate (PC) sequence which contains two period of drought. In conditions of full flow received from Bulgaria the Total NPVs are similar with a tipping point situated after about 10 years of operation following the construction phase. These are appropriate conditions for a financing plan.

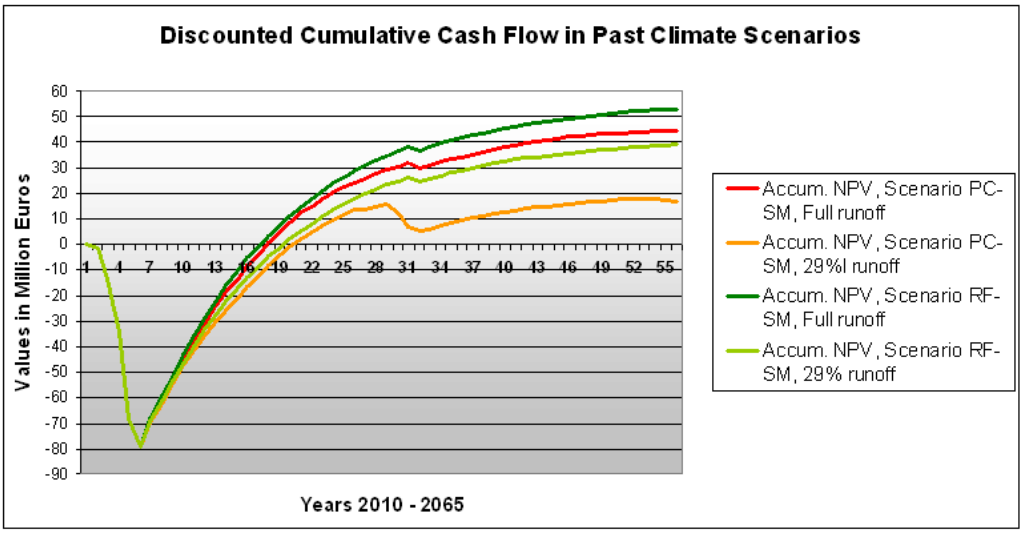


Figure 100 - Discounted cumulative cash flow in past climate change scenarios

C – DCCF curves for IPCC-SRES future climate scenario B1

In the case of IPPC-SRES B1 climate change scenario (Fig. 101), conditions are strikingly worse with the project never reaching profitability. For a Mesta flow limited at 29% from Bulgaria, conditions are disastrous due to the continuous lack of water for irrigation which accumulates the compensations for “Lost Crop”. In the case of full flow from Bulgaria, the NPV reaches a plateau of about -30 million Euros and the project might be declared feasible if a lower rate of return could be accepted.

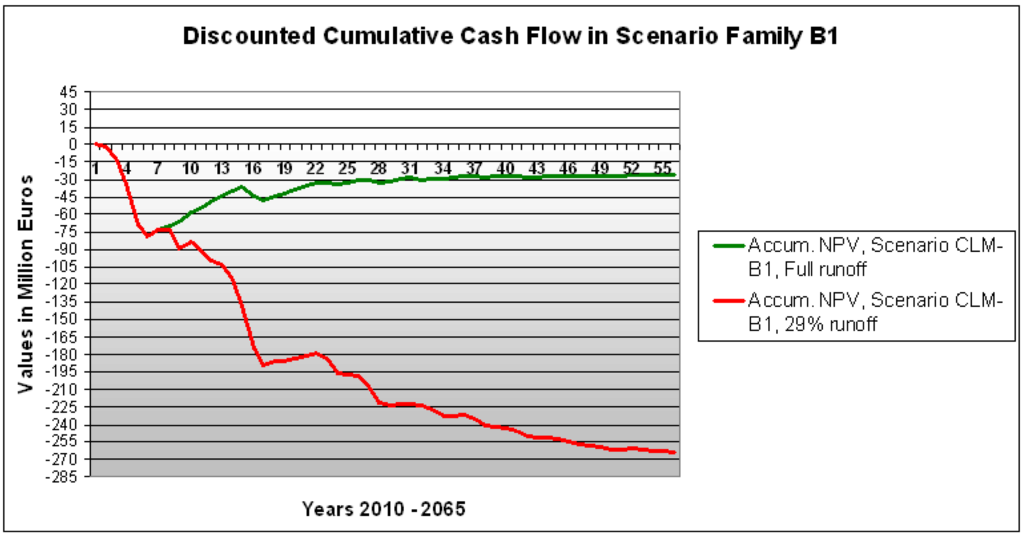


Figure 101 - Discounted cumulative cash flow in climate change scenario A1B

D - DCCF curves for IPCC-SRES future climate scenario A1B

The worst case is by far that of the IPPC-SRES A1B climate change scenario (Fig. 102). Even in the case of full flow received from Bulgaria, the NPV loses its plateau of about -75 million Euros because of a period of increased drought after year 2050. This makes the project extremely risky even if a severely lower rate of return could be accepted.

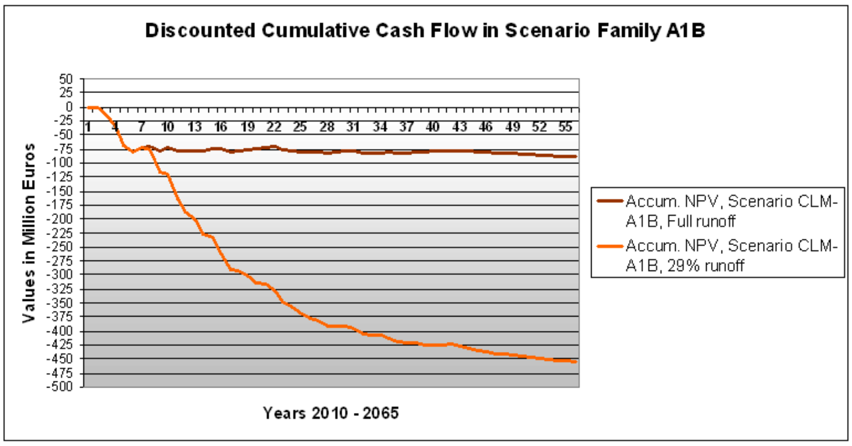
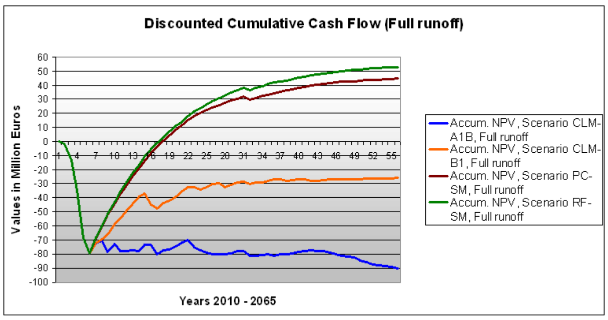


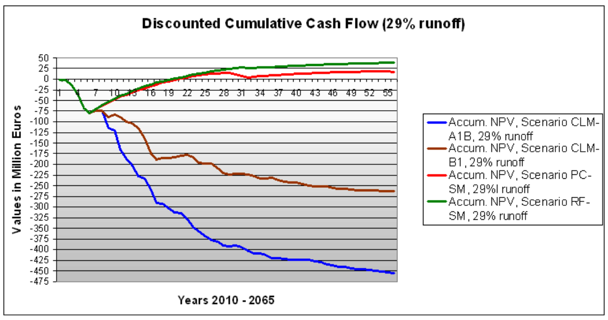
Figure 102 - Discounted cumulative cash flow in climate change scenario A1B

E –Influence of bilateral flow treaty application on the Temenos project sustainability

Overall, the comparison of DCCT curves through all climate scenarios (Fig. 103) gives an idea of the range of impacts that climate scenarios might have on the sustainability of the project under varying conditions of flow percentage received from the Mesta river.



a) NPV variations with full Mesta flow



b) NPV variations with 29% Mesta flow

Figure 103 - Comparison of the discounted cumulative cash flow in all climate scenarios under the two hypotheses of flow supply from Bulgaria

It is important to note here that the full temporal simulation all the natural and technical factors (rain, hydrology, hydropower, irrigation, agriculture, ecological flow) is the only way to produce a realistic vision of how the functioning of the “Temenos project company” would unfold through the 50 years of project life. It gives a much better understanding of the sustainability of the project then the publication of the sole Total NPV value.

Using the simulation protocol which has been designed in my thesis work with readily available software module any potential participant in the project may realistically evaluate the influence of the many factors involved. In this test exercise I have voluntarily limited the variability study the two factors of climate change and transboundary management. But the method developed can easily be applied to the study of other factors such as the style of dams operations, the variation of prices of electricity and crop products as well as other irrigation scenarios.

IV-4 – **Deciding within the complexity of climate change**

The Temenos project NPV results presented in the previous section that the potential climate change impacts on the region's overall temperature, precipitation and evapotranspiration, which consequently affect the hydrological regime of basins, are interfering with a number of potential "conflicts" which affect the Nestos river water allocation and use.

These conflicts may be of different nature such as political, industrial, agricultural and environmental. The political conflicts are linked with the quantity of inflow water from the Bulgarian part of the basin. Industrial conflicts may come from the operation style of the dams which need to mediate between the amount of electricity produced and the assurance of a sufficient quantity of irrigation water. Socio-economic conflicts could consequently emerge if in case of water scarcity the farmers' income would be in jeopardy. Finally, as the good status of the Nestos waters must be maintained in accordance with the EU WFD, environmental goals would also necessarily conflict with others in case of drought. Within this complex context, it is worth investigating ways of mediating those conflicts in order to reach acceptable decisions.

IV-4-1 - The impact of transboundary management hypotheses

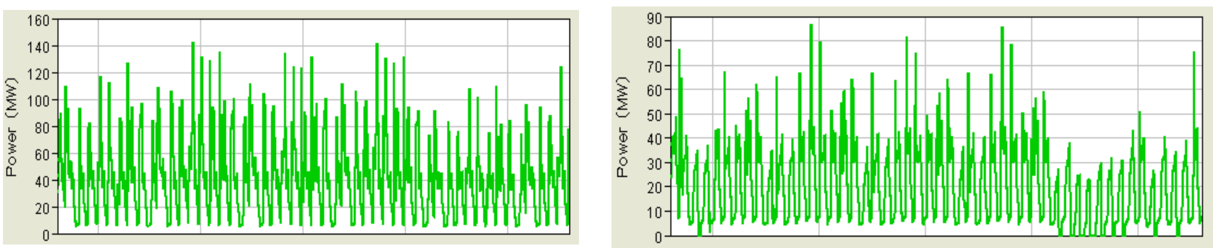
The bilateral agreement between Bulgaria and Greece states that Greece should receive up to 29 % of the Mesta/Nestos river mean annual water flow. The duration of the agreement is for 35 years, from 1995 until 2030. Let us note that this time interval overlaps with the proposed Temenos project life which should extend from 2011 until 2045. This adds an element of uncertainty to the sustainability of the project because the two countries have not yet addressed the issues related to the agreement termination.

Currently, according to estimations, the water inflow from the Mesta River into Greece is estimated at approximately 85 to 90 % of its mean annual water flow (excluding Dospat river). This indicates that today the water abstraction in the Bulgarian part is limited to a modest irrigation system and water supply installations serving medium sized towns. This situation has been stable since the 1970s and this has encouraged the Greek side to construct large development projects. The Temenos project is a further increase in this development.

In this situation, a marked reduction in the inflow into Greece from Bulgaria would have a serious effect on the hydropower dams and the socio-economic well being of the local population in the Nestos Delta and Xanthi areas. In case of diminution of the inflows quantities neither the electricity production nor the irrigated agriculture could be covered successfully. This is the reason why the inflow percentage is considered as a potential political conflict issue. This is what will be illustrated through various results obtained with HEC-ResSim under the most optimistic climate instance which is the "Reference Past Climate" rain sequence.

Examples of the inflow water quantities impacts

The impacts of the two inflows alternatives on power generation of the Thissavros dam are presented in Figure 104. For 100% of water inflow (Fig. 104a) the average generated power is 41.6 MW, the maximum is equal to 141.5 MW and the minimum generated power is 5.1 MW. On the other hand, in case of 29% of water inflow (Figure 104b) the average generated power is equal to 21.0 MW, the maximum is equal to 86.1 MW and there are cases, e.g. from 2054 to 2057, when the power plant is stopped. With the reduction of water inflow all instances of reduced rain fall are exacerbated.

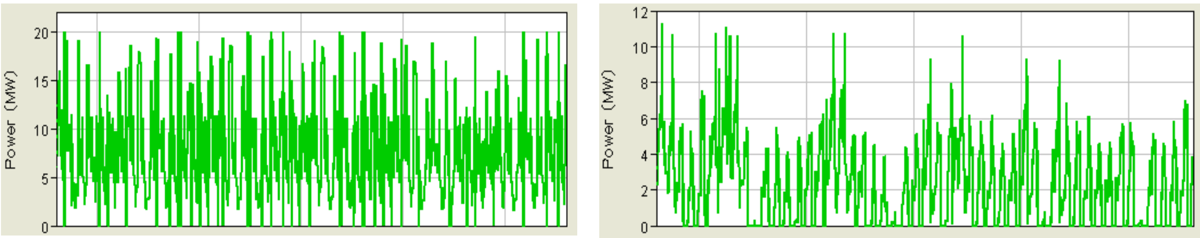


a) The case of 100 % of water inflow from Bulgaria

b) The case of 29 % of water inflow from Bulgaria

Figure 104 – Variations in Thissavros dam power generation with transboundary hypotheses

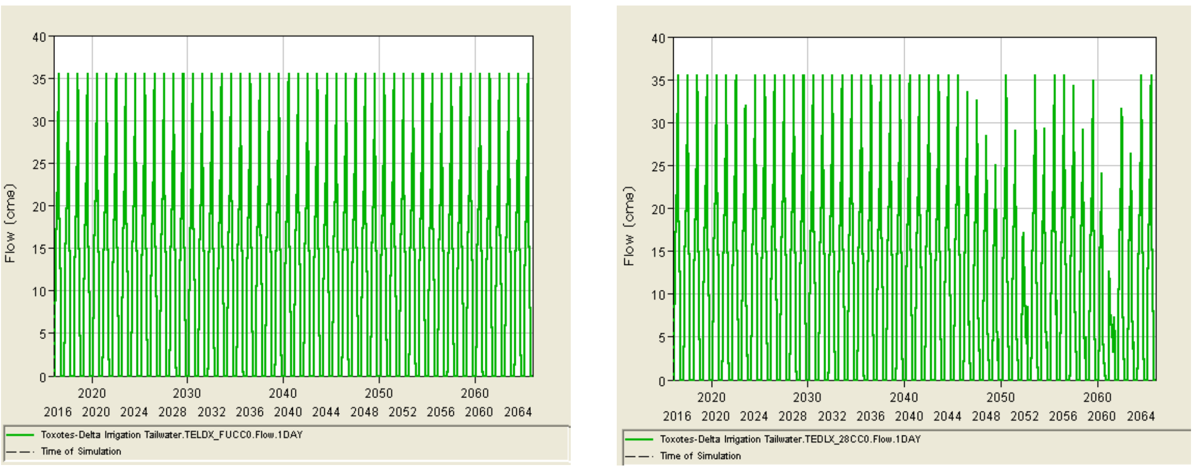
As the Temenos dam pool has a much smaller storage capacity than that of the Thissavros dam, these extreme cycles are even amplified as it can be seen on Figure 105. In the Temenos dam, in case of full water inflow (Figure 105a), the average generated power is 7.6 MW and the maximum is equal to 20.0 MW. In the case of 29% of water inflows (Fig. 105b), the average generated power is 6.0 MW, the maximum is 20.0 MW and there are many periods during which the power generated is interrupted.



a) The case of 100 % of water inflow from Bulgaria *b) The case of 29 % of water inflow from Bulgaria*

Figure 105 – Variation in Temenos dam power generation with transboundary hypotheses

The water volume released by the Toxotes dam in order to cover the water demand of the irrigation network is presented in Figure 106. In case of full water inflows (Figure 106a) the water volumes are at nominal level and adequate to cover the agricultural but in the case of 29 % of water inflow (Figure 106b) there are years when the irrigation water is deficient.



a) The case of 100 % of water inflow from Bulgaria *b) The case of 29 % of water inflow from Bulgaria*

Figure 106 – Toxotes Dam water volumes addressed to the existing irrigation networks

All these detailed outputs from the HEC-ResSim dam simulation program clearly show that even in the best climate conditions there is a risk that under modest reduction of precipitation, the reduction of flow from Bulgaria to its minimum would certainly have disturbing effects on the activities on the Greek side.

IV-4-2 - Agriculture versus electricity power capacities

Water allocation among different stakeholders in a transboundary river basin is a particularly sensitive issue due to the potential conflicts which may arise in case of water scarcity. International organizations, such as UNESCO, have foreseen this possible threat and have developed initiatives to foster co-operation between stakeholders in the management of shared water resources, while helping to ensure that potential conflicts do not turn into real ones (UNESCO, From Potential Conflict to Cooperation Potential program (PCCP)[26]). However, water allocation is also a sensitive issue at national and regional scale. The rapidly increasing demand for water which is correlated with the economic development of a region may often result in competition between different water users.

In the Nestos delta region, all stakeholders are interested in accessing larger water volumes. Among others, the farmers, for example, are seeking more water in order to increase their agriculture production. Environmentalists on the other hand aim to preserve the delta ecosystem and improve the current wetlands status. The dam complex authority wants to increase the power generation by releasing less water for agricultural purposes. Groundwater managers require more fresh water for the enrichment of the overexploited aquifers. This list of diverging objectives illustrates the difficulty of finding a balanced allocation of the water in order to avoid potential socio-economic conflicts.

In the simulation of the Nestos dams' complex done for this study, the operation of the dams has been constrained so that the highest priority is given to the service of the irrigated agriculture, the next lower priority is given to the maintenance of the minimum environmental flow and the lowest priority is given to the production of energy.

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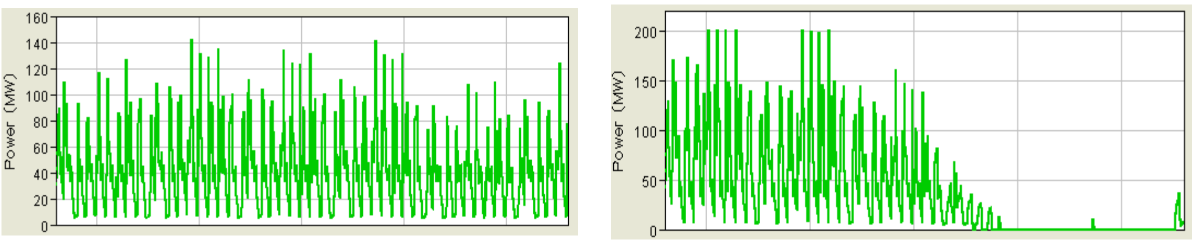
[26] http://www.unesco.org/water/wwap/pccp/

However, the top priority given to the agricultural sector has negative consequences on the power generation which de facto is not at its top level. This effect is illustrated in the various results of simulation tests with HEC-ResSim where priorities have been inverted using a climate sequence showing a contrast between a 30 years period of plentiful rain followed by a lasting multiyear dryer period.

Examples of decreased power generation due to increased water to agriculture

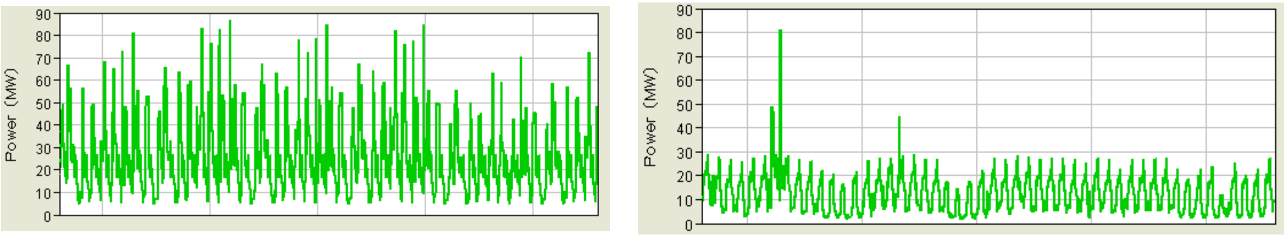
If priority is given to power production (Figure 107a) the average generated power by the Thissavros dam is equal to 43.3 MW which corresponds to produced energy equal to 1038.3 MWh and the maximum capacity is 141.5 MW or 3395.2 MWh of produced energy and the minimum capacity is 5.4 MW. On the other hand, if agriculture is set as first priority (Fig. 107b), the average power production is 36.6 MW which corresponds to 877.9 of produced energy and the Thissavros dam stops producing power from 2048 to 2063 because the pool level is below the entrance of the power plant intake.



a) in case of priority to power production *b) in case of priority to agriculture*

Figure 107 – Variations in the Thissavros dam power generation due to different operation policies

Under similar climate conditions, for the Platanovryssi dam, in case of priority given to power generation (Fig. 108a) the average power production is 25.8 MW, the maximum is equal to 86.3 MW and the minimum 4.7 MW which corresponds to produced energy equal to 620.3 MWh and the maximum power corresponds to generated energy equal to 2070.3 MWh. When priority is given to agriculture (Fig. 108b), the average power production is 12.1 MW which corresponds to an amount of produced energy equal to 290.0 MWh, the maximum is 80.3 MW or 1927.9 MWh of produced energy and the minimum power capacity is 1.8 MW.



a) in case of priority to power production

b) in case of priority to agriculture

Figure 108 – Variations in the Platanovryssi dam power generation due to different operation policies

The previous examples clearly demonstrate that in order to obtain a maximum yield in one sector, in this case in agriculture, the yield and consequently the profit of the other involved sectors, that is to say the generated energy, are sacrificed.

IV-4-3 Environmental impact scenarios

In the case of the construction of big dams, most of the disadvantages are in the area of the natural environment. In the case of the Nestos dams' complex, the sustained minimum ecological flow of 6 m^3/s is an issue of great importance for the well-being of the riparian ecosystem. It has been shown in the previous HEC-ResSim results that it is only under the most extreme weather stress conditions like the IPCC-SRES A1B scenario that the ecological flow cannot be sustained. Should the priority of this objective be lower in the operation of the dams, the consequences would even be more severe.

However, other factors can degrade the quality of water. Studies on the dams' impacts (McCartney M.P. et al., 2001) have shown that the chemical composition of water within a reservoir can be significantly different to that of the inflows. Furthermore, the size of the dam and the detention time of the water influence the way that storage modifies water quality. If the released water comes from the upper part of the stocked water then it is well-oxygenated, warm, nutrient depleted water. In contrast if the water comes from the lower part of the reservoir it is cold, oxygen-depleted and nutrient-rich water.

In the case of the Thissavros dam, which is the biggest of the dam complex, according to the correspondence with the management authority of the dam, the released water comes from the power intake duct which is found at a height of 310 m. Moreover, the bottom duct which is at a height of 226 m, has never been used for releasing water.

Thus, the stocked water between the power intake and the bottom duct is considered to be too contaminated since it has not been renewed by fresh water quantities. However, the maintenance works of the dam, e.g. removing the sediments volume from the bottom of the reservoir, which should be carried out in the projects half lifetime, require the opening of the bottom duct in order that the water volume be decreased. Thus, the threat of polluted water to be discharged from the Thissavros dam is quite possible in the near future with severe consequences to the ecosystem, the quality of the agricultural products and even human health.

IV-4-4 Multicriteria decision analysis, a possible solution to conflicts of interest

As the review of the various conflicts in the management of the Temenos project suggests, it is apparent that in such a situation the preferences of all stakeholders ideally need to be mediated in order to find solutions which are acceptable by all. Each of these stakeholders is focused on a particular set of objectives or criteria which he/her wants to see realized or maximized. None of these objectives or criteria is likely to be accepted by all the stakeholders. In such a case, finding a best solution which might satisfy all of them cannot be solved by simple ranking methods. Multicriteria Decision Analysis (MCDA) is a branch of decision theory which is devoted to find ways of constructing solutions which can be considered by all project actors as an acceptable compromise. Introduced in the 1970s, MCDA techniques are gaining in importance as potential tools for solving complex real world problems, because of their inherent ability to consider different alternative scenarios, the best of which may then be analyzed in depth before being finally implemented. (Goicoechea A.et al., 1982).

A – The nature of MCDA techniques

In order to apply MCDA techniques, it is important to formulate the project alternatives in terms of the following parameters or concepts (Ganoulis, J., 2003):

- *The attributes*, which are the characteristics, factors and indices used in order to evaluate the alternative management scenarios. The attributes may be quantitative or simply expressed in terms of preferences.

- *The constraints*, which are restrictions on attributes and decision variables that can or cannot be expressed mathematically.

- *The objectives*, which indicate the directions of state change of the system under examination and need to be maximized, minimized or maintained in the same position.

- *The criteria*, which can be expressed either as attributes or objectives.

In MCDA the aim is not to obtain an optimal solution, as it can be the case if only one objective is used, but rather to find an acceptable solution which is either "non-inferior" or "non-dominated" by the others. This is a solution that improves all objective functions, and all other solutions cannot improve a single objective without causing a degradation of at least one other objective. The multicriteria techniques that have been developed in order to find an acceptable solution can be categorized as following:

- Value or utility-type, which essentially coalesce the multiple objectives into a one-dimensional “multi-attribute” risk function.

- Distance-based techniques, which seek to find a solution as “close” as possible to an ideal point such as Compromise Programming (Ballestro, E., 2005) where the ideal solution is sought to be as “far” as possible from a “worst” solution.

- Outranking techniques, which compare pairs of alternatives pairs where alternative A(j) is preferred to alternative A(k) if a majority of the criteria C(i) are better for A(j) than for A(k) and the discomfort resulting from the aggregated evaluation of those criteria for which A(k) is preferred to A(j) is acceptable. The most common techniques are ELECTRE (Roy B. et al., 1993) and PROMETHEE-GAIA (Brans J.P. et al., 1984).

- Direction-based, interactive or dynamic techniques where a so-called progressive articulation of preferences is undertaken.

- Mixed techniques, which utilize aspects of two or more of the above four types.

The main advantage of MCDA techniques is that they facilitate the comparing of heteroclite sets of conflicting objectives such as rates versus total resource cost, environmental impacts versus financial criteria, pricing policy versus regional economic development, etc. (Hobbs B.F., et al., 1994).

Environmental planning and decision-making in water resources usage are essentially conflict analyses characterized by sociopolitical, environmental, and economic value judgments. With the use of MCDA techniques, starting from a list of attributes as basic indicators (Fig. 109) the three drivers of sustainability, i.e. the economics, the social and the environmental objectives, may be defined hierarchically and aggregated into higher level Objectives and Goals. The evaluation of the different attributes and objectives is based on a number of criteria and constraints. For example, in the case of the construction of a dam, attributes may be the economic sustainability and the revenue generated, thus they form an economic objective. However, the economic profitability depends upon operational criteria, releasing water to cover the irrigation demand, and on constraints such as the minimum environmental flow which needs to be released.

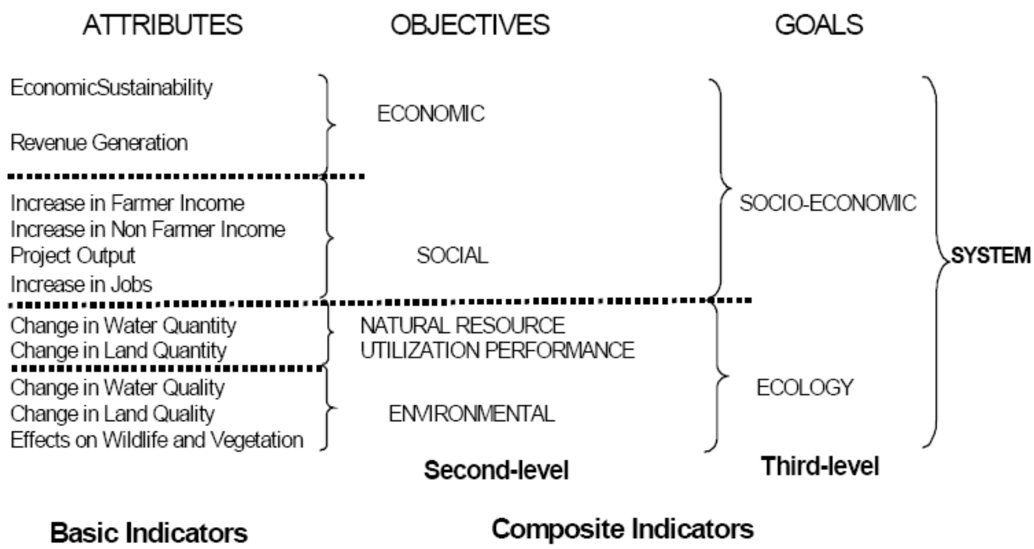


Figure 109 – Hierarchy of social, economic, and environmental attributes, objectives and goals in water resources management (source: Ganoulis J., 2003)

At this point it should be noted that the nature of the constraints of the Temenos project are economic (selling electricity and irrigation water), environmental (sustaining a minimum environmental flow) and social (compensations to farmers in case of lack of water). Thus, it is obvious that the nature of the Temenos project leads to a possible application of MCDA techniques.

A – Past applications of MCDA to management problems in the Mesta/Nestos river basin

According to the literature related to the Mesta/Nestos river basin, MCDA techniques have already been used as a decision support methodology in order to propose solutions to both the mediation of transboundary issues related to different objectives set by Bulgaria and Greece and the management of potential conflicts related to the Greek part of the basin.

As far as the transboundary nature of the Mesta/Nestos River is concerned, the distance base MCDA technique has been proposed as a means of facilitating negotiations and final decisions related to the river's water management (Ganoulis J. et al., 2003). After identifying the main problems in each part of the basin, water quality, water availability, environmental and development problems in the Greek part of the basin and water quality, development and different socio-economic conditions problems in the Bulgarian side, the formulation of the alternative scenarios was carried out. The study concluded that by examining each country preferences separately, hydropower and agriculture development project scenarios were of highest priority both for Greece and Bulgaria but that the integration of the preferences of the two countries in an MCDA run leads to an accepted mutual preference for tourism development (Ganoulis J. et al., 2003).

At a regional scale, MCDA techniques have also been used for evaluating the public opinion, preferences and perceptions about the creation of a National Park of Eastern Macedonia and Thrace which would in particular include the Nestos delta area (Pavlikakis G. et al., 2003). More specifically, the results of a survey among the local inhabitants about the management of the park where processed using MCDA tools. The study concluded that the most preferable management technique for the protection of the park area would be to encourage the reduction of fertilizers and the cultivation of less water demanding crops. The public consensus was that the short-term losses in agricultural income caused by the modifications in farming practices cultivation alterations would be offset by future well-being gains due to the improvement in water quality and quantity.

Finally, in an other instance, the MCDA PROMETHEE-GAIA method has been used in order to evaluate which of proposed irrigation projects in the area (Nestos Delta, Xanthi plain and Drama plain) would reach a majority of the criteria levels regarding the environment, the quality and quantity of fresh water and the availability of ground water (Anagnostopoulos K.P. et al., 2005).

C - MCDA and the Temenos project evaluation tools

Recent trends in the application of multicriteria techniques are leading to the concept of Multiple Criteria Decision Making (MCDM) which advocates the use of MCDA methods in the context of negotiation and decision support. Looking beyond the search of best solutions following a careful analysis of all aspects of a particular problem, MCDM proposes to use multicriteria techniques as part of the group decision dynamics formed by actors during the very process of negotiation (Araz et al., 2007). In other words it is proposed that during the negotiation, each actor (idem, stakeholder) would run its own MCDA evaluation of the outcomes of a project, a mediator being in charge to moderate the contradictory evaluations of each participants and eventually seek a group consensus on the attributes, constraints, objectives and criteria used in the MCDA program runs. This technique was used in the past with specially equipped negotiation rooms. Recently, the capabilities of the Internet enable the participants to remotely participate in this type of dialogue without being physically regrouped.

It is my belief that the full set of programs which have been used in this work in order to build the evaluation protocol (Fig. 96 – Section IV-3-2) of the Temenos project could be made available as separate modules on the Internet so that the actors of the project could dynamically evaluate the outcomes of a particular set of objectives and constraints related to climate prediction, transboundary flow restrictions, hydropower and irrigation dam operation and farming policies. Should this system be made available to all actors during negotiation phases, MCDA methods could be used in order to find acceptable compromises in the management of the project.

V - CONCLUSION AND PERSPECTIVES

One of the main intents of the thesis was to demonstrate the use of new computer based technologies and the integration of different mathematical models for the management of water resources at a basin scale. The initial review of available models in hydrology and dam simulation showed that a great variety of tools are presently available. But the sole existence of the mathematical models does ensure that useful results can be extracted from their use. In the case of the Mesta-Nestos basin as in any other water resources modeling exercises the data gathering and proper model calibration still necessitate appropriate skills.

A large amount of background information was gathered from existing maps or thematic data bases, from remote sensing sources and from previous water resources project such as TRANSCAT. Several geographical information sytems and image processing tools were used in order to integrate data sets of various natures such as: hydraulic, climatologic, meteorological, geological, land use, pedological, topographic… etc. The transboundary nature of the Mesta/Nestos basin increased the difficulties in the data gathering and the necessity of reconciling disparate sources such as building a uniform geology map legend on both sides of the Bulgaria-Greece border.

However, the use of remote sensing and satellite imagery which offered a synoptic overview of both sides of the basin did not offset the fact the use of an hydrology model such MODSUR-NEIGE necessitates the gathering of ground rain measurements and river flow gauged data. The gathering of appropriate data related to the Greek part of the basin was challenging due to the fact that in Greece a large number of authorities are engaged in the collection of meteorological and hydrology data. Precipitation data, for example, were obtained from the Ministry of Environment, of the Ministry of Agriculture, the Ministry of Development, the Power Public Company, the regional and local water authorities, the National Meteorological Service, as well as from internal records of the Aristotle and Democritus Universities. On the Bulgarian side difficulties were of another nature and essentially related to the reluctance of national authorities to release information outside the country. It is only through direct contacts within UNESCO sponsored programs such as INWEB and HELP and within European cooperation programs with research institutions in Bulgaria that enough data could be acquired.

However, valuable data sets publicly released on the Internet through the World Meteorologiacl Organization (WMO) although scarce were critical in order to anchor the local data sources from Greece and Bulgaria which are often of uncontrolled quality. Following data screening and intercalibartion, all hydrology related data sets were standardized using the HEC-DSS data management tool.

The necessary calibration of the models was regarded more as a challenge rather than a difficulty. Regarding the basin hydrology modeling simulation, the initial lack of data from the Bulgarian part of the basin resulted in the low degree of correlation between the model outputs and the gauged data during the first phase of my work. The later use of a more complete dataset on Bulgaria revealed that in order to maintain a realistic river flow during summer seasons one needed to take into account both groundwater flow and snow melting. The use of the MODSUR-NEIGE model which takes into account the snow melting was necessary in order to properly calibrate the monthly flow in the Mesta-Nestos river. As for the HEC-ResSim reservoir simulation model, the real challenge lay in the fact that there exists no documented application of this model to the processing of long multiyear daily flow sequences. Furthermore the large number of technical parameters of this model necessitated a rather long step by step approach in order to interpret them from the documents released by the Public Power Corporation. Several exchanges with the engineers in charge of the dams operation were necessary in order to check the feasability of the model outputs. Finally, the CLM climate model in one of the most recent regional climate models and was only released in late 2007. The evaluation of its results at local level is still under way at the Max Plank's Institute and my work for this matter might be seen as pioneering as it is the first time that its precipitaiton results are coupled with a hydrology model.

The huge amount of the CLM model results, since it covers the whole Europe, and the selection of those which covered the Mesta/Nestos basin area coupled with the netCDF format of the results were the two main obstacles. However, the utilization of a climate change model which has never been used in Bulgaria and Greece was conceived as an extra motivation for its utilization.

The diversity of models used and their coupling in order to form a modular data processing protocol has necessitated the building of a number of intermediate programs responsible for the translating of data formats in order to execute the bridge between the different models. These “software bridges” were based on a diversity of tools and techniques. As the hydrology simulation of the river basin was conducted using the spatially distributed MODSUR-NEIGE model, the ArcGIS program was used in order transcribe land cover and land use information in the form of quatree gridded production functions. The same GIS tool was used for the preparation of background layers used for the construction of the HEC-ResSim dam network. In terms of bridging, the input and output time series linking to the various models of the processing protocol were all starndardized with HEC-DSS data management and processing system. In particular, the macro language of HEC-DSS was used in order to automatically post-process the results of HEC-ResSim before their input in the NPV economics tool.

Up until recently, the current practice in water resources project dimensioning is to rely on historic flow records or other water parameters. I have tried to show in my work how the climate changes predicted by the IPCC Panel are drastically changing that point of view and that the necessity of studying the “dynamic” response of the water systems to these changes can be successfully met through the use of appropriate physical models. However, the results of climate scenarios produced by the numerical climate models like Global Climate Models or Regional Climate Models such as CLM are still rather at a rather coarse scale. I have demonstrated in my work how these difficulties can be solved at the local scale of the Mesta/Nestos basin. The latest results produced by the CLM model from the Max Plank’s Institute showed rather good correlation with ground data and enable us to develop appropriate downscaling approach in order to use them as input to the models.

Finally, I have shown how a hydrological model coupled with a sequence of models “en cascade” such as reservoir simulation models and economic evaluation enable a realistic assessment of the sustainability of dam construction project under various hypotheses of climate change. In order to evaluate this sustainability I have introduced a conjunction of economic rules such as those implemented in the Net Present Value of produced energy with social and environmental criteria.

Until the late 1980s the construction of water resources projects was related only to economic criteria. However, the implementation of International and European Conventions such as the Helsinki Convention and the Water Framework Directive respectively, fostered the transition to development projects which are based on the three pillars of sustainability, i.e. coupling of economic, social and environmental development. Inspired by this approach, the proposed economics tool merges market revenues of the produced energy and of the water sold to farmers for their irrigation needs, with the social and environment "externalities" of the project, such as compensations to farmers in case of lack of water and the rehabilitation costs of the environment in case of river flows lowers below a minimum environmental flow.

The simulation of the dams on the Nestos River was conducted by prioritizing the agricultural demand on water over the power production. A more rational approach should probably be based on the opinion of the local inhabitants and the results of a statistical survey among the different water users about their needs and their priorities. It is also proposed that the evident conflicts which may arise in the management of the compromises between the objectives of the power production and the social needs of the Nestos delta stakeholders may be mediated using MCDA techniques.

The dissemination of information related to water usage to the local communities is an issue of great importance, also noted by the WFD. A first attempt for publishing information about the quantity and quality of the Nestos on the internet was carried out during my work. More particularly, an extensive GIS database in ArcGIS format covering all aspects of factors involved in water problems including: DTM, aerial and satellite observations from 1945 to nowadays, geology, land-use, agriculture, irrigation, has been uploaded on a server, http://socrates.civil.auth.gr/mapserver/map_mnhu/Data/, and enables a direct access to the basic information both by institutions and the public. However, it would be useful in the future to publish a more interactive database which could include the modeling protocol so that the users could be able to evaluate on-line the results of different climate change scenarios on the hydrological regime, the power generation and the availability of water for the agriculture.

VI - REFERENCES

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VII – ACRONYMS AND ABBREVIATIONS

AGCM	Atmospheric GCMs (AGCM)
AGREE	Surface reconditioning system for DEM
AOGCM	Atmosphere-ocean coupled general circulation model (AOGCM)
ArcView	GIS Software
ArcGIS	GIS Software
ARGUS One	Grid handling software for input to mathematical models
AR4	Fourth IPCC Assessment Report
ASCE	American Society of Civil Engineers
AUTH	Aristotle University of Thessaloniki
A1	IPCC SRES Scenario
A1B	IPCC SRES Scenario
A1FI	IPCC SRES Scenario
A1T	IPCC SRES Scenario
A2	IPCC SRES Scenario
BG-GR PHARE CBC	Bulgaria-Greece cross-border cooperation (see PHARE CBC)
BNB	Bulgaria National Bank
BP	British Petroleum
B&J	Bar and Jenkins
B1	IPCC SRES Scenario
B2	IPCC SRES Scenario
CAD	Computer aided drafting
CAP	Common agricultural policy (CAP)
CAPEX	Capital expenditure (CAPEX)
CAPRI	Common Agricultural Policy for Regional Impact (CAPRI)
CCC	Canadian Climate Centre model (CCC)
CEMAGREF	Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement
CERA	Climate and Environmental Retrieving and Archiving
CIG-ENSMP	Centre d'Informatique Géologique-Ecole des Mines de Paris
CISL	Computational and Information Systems Laboratory of NCAR

CLM	CLM which stands for Climate version of the “Lokal Model”
CORINE	Coordination of information on the environment
COSMO	Consortium for Small-scale Modelling
DCCF	Discounted cumulative cash flow
DEM	Digital Elevation Model
DKRZ	German Climate Computing Centre (DKRZ)
DTM	Digital Terrain Model
DSS	Decision Support System
DUTH	Democritus University of Thrace (DUTH)
DWD	Deutscher Wetterdienst (DWD)
EC	European Community (EC)
ECHAM4	Max Planck Institute GCM model
ECHAM4-OPYC3	Max Planck Institute GCM model coupled with OPYC3 ocean model
ECHAM5	Max Planck Institute GCM model
ECHAM5-MPIOM	Planck Institute GCM model coupled with MPIOM ocean model
ECMWF	European Centre for Medium Range Weather Forecast
ECSEE	Energy Community of South East Europe (ECSEE)
EESD	Energy, Environment and Sustainable Development EU-FP6 Program
EIA	Energy Information Agency, USA
ELECTRE	ELimination Et Choix Traduisant la REalité
ENSMP	Ecole Nationale Supérieure des Mines de Paris (now, Mines ParisTech)
EPO Living Lakes	NGO operating on Nestos Delta
ESRA	European Solar Radiation Atlas (ESRA)
EU	European Union
EU-FP6	(see FP6)
EuropeAid	EU External Cooperation Programmes
FADN	Farm Accountancy Data Network (FADN).
FAR	First IPCC Assessment Report
FP6	EU Sixth Framework Programme supporting Research
FSS	Eurostat Farm Structure Survey (FSS)
GCM	Global climate model
GDP	Gross Domestic Product
GEWEX	Global Energy and Water Cycle Experiment (GEWEX
GIS	Geographic Infromation System

GISS	Goddard Institute for Space Studies (GISS)
GNP	Gross National Product
GPCP	Global Precipitation Climatology Project
GTCC	Gas Turbine Combined Cycle power plant
GUI	Graphical user interface
GTOPO30	Worldwide DTM at 30' resolution (1 km), USGS, USA
HadCM2	GCM from Hadley Centre, Bracknell, UK
HEC	Hydrologic Engineering Center of USACE
HEC-DSS	HEC Data Storage System
HEC-GEOHMS	Geospatial Hydrologic Modelling Extension
HEC-HMS	Hydrologic Modelling System
HEC-ResSim	HEC-Reservoir Simulation model
HEC-5	Simulation flood control and conservation system from HEC
HELP	Hydrology-Environment-Life UNESCO-IHP program
HEPP	Hydroelectric power plant
HGRS87	Hellenic Geodetic Reference System (HGRS 87)
HNMS	Hellenic National Meteorological Service
HydroDEM	DTM hydrography processor from CEMAGREF
IDRISI	GIS software
IEM	Internal Electricity Market (IEM) in EU
IGME	Institute of Geology and Mineral Exploration, Greece (IGME)
IHP	UNESCO International Hydrological Programme
ILO/UNDP	UNDP Joint Program on Employment and Poverty
IMPEL	Integrated Model to Predict European Land Use (IMPEL)
INTERREG	EU Inter-regional Programme
INRA	Institut National de la Recherche Agronomique, France
INWEB	International Network of Water-Environment Centres for the Balkans
IPCC	Intergovernmental Panel of Climate Change
IRR	Internal Rate of Return
ISBA	Interface Soil Biosphere Atmosphere Model (Météorologie Nationale)
ISLSCP	International Satellite Land Surface Climatology Project
IS92a	IPCC "Business as usual" climate scenario
IUCN	International Union for Conservation of Nature
LAM	Limited Area Model

LHP	Large hydropower plants
MCDA	Multicriteria Decision Analysis (MCDA)
MINAGR	Ministry of Agriculture of Greece
MINENV	Ministry of Environment (MINENV or YPEXODE)
MODCOU	Modèle couplé surface-souterrain (CIG-ENSMP)
MODCOU-ISBA	Coupling MODCOU with ISBA
MODCOU-STICS	Coupling MODCOU with STICS
MODSUR	Modélisation des Transferts des Surfaces, hydrology software (CIG)
MODSUR-NEIGE	Snow melting version of MODSUR
MOEW	Ministry of Environment and Water of BUlgaria
MPI	Max Planck Institute (MPI) for Meteorology in Hamburg.
MPIOM	Max- Planck- Institute ocean model
NAGREF	National Agricultural Research Foundation (NAGREF)
NASA	National Aeronautics and Space Administration, USA
NATURA 2000	EU Nature Protection Network Programme
NCAR	National Center for Atmospheric Research (NCAR)
NEK-EAD	Natsionalna Elektricheska Kompania (NEK) EAD
netCDF	network Common Data Form
NEWSAM	Groundwater distributed model, CIG-ENSMP, France
NGO	Non Govermental Organisation
NIMH-BAS	Meteorology and Hydrology Service, Bulgaria
NPV	Net Present Value (NPV)
NWSRFS	US National Weather Service River Forecast System (NWSRFS)
OGCM	Oceanic GCMs
OPEX	Operational expenditure (OPEX)
OPYC	Ocean and isoPYCnal co-ordinates
ORSTOM	Institute of Research for Development in Cooperation (now, IRD)
PCCP	UNESCO Potential Conflict to Cooperation Potential programme
PDs	production functions (PDs)
PET	potential evapotranspiration
PHARE CBC	EU cross-border cooperation for former Eastern Europe countries
PIREN-Seine	Programme Interdisciplinaire de Recherche sur l'Environnement de la Seine
PPC	Power Public Corporation of Greece also known as DEH
PRC	Popular Republic of China

PROMETHEE-GAIA	MCDA method
RAMSAR	International Convention on Wetlands
RCM	Regional climate model
REM	Regional electricity market (REM)
RIVERSTRAHLER	River stream software from UPMC
ROE	Return on Equity, a financing criterion
rTPA	Regulated third party access (rTPA)
SAMMIR	Groundwater model (ancestor of NEWSAM, CIG)
SAR	Second IPCC Assessment Report
SDSM	Statistical DownScaling Model
SDSS	Spatial decision support systems
SEE	South-Eastern Europe
SENEQUE	UPMC
SGM	Standard Gross Margin (SGM)
SHP	Small hydropower plants
SIGMOD	CIG-ENSMP module for building MODSUR model grids
SMP	System Marginal Price
S-PLUS	Statistical software based on S language from Bell Labs
SPANS	GIS system from Tydac Technology
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
STICS	Agronomy crop model from INRA, France
TAR	Third IPCC Assessment Report
TeraVue	Remote sensing processing software (Editions de la Boyère)
TGICA	IPCC Task Group on Scenarios for Climate and Impact Assessment
TRANSCAT	Integrated Water Management of TRANSboundary CATchments
UAA	Utilised agricultural area (UAA)
UKHI	UK Meteorological Office High Resolution model
UNCED	United Nations Conference on Environment and Development
UNDP	United Nation Development Programme
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCO-HELP	(see HELP)
UNESCO-INWEB	(see INWEB)

UNESCO-PCCP	From Potential Conflict to Cooperation Potential
UNESCO-IHP	(see IHP)
UPMC	Université Pierre et Marie Curie
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
WBUDG	Physically based hydrological model
WCRP	World Climate Research Program
WFD	EU Water Framework Directive
WMO	World Meteorological Organisation
WWTP	Waste water treatment plant

ANNEX 1 - The bilateral treaty in the Greek Official Gazette

1879

ΕΦΗΜΕΡΙΣ ΤΗΣ ΚΥΒΕΡΝΗΣΕΩΣ

ΤΗΣ ΕΛΛΗΝΙΚΗΣ ΔΗΜΟΚΡΑΤΙΑΣ

ΤΕΥΧΟΣ ΠΡΩΤΟ

Αρ. Φύλλου 98

4 Ιουνίου 1996

ΝΟΜΟΣ ΥΠ' ΑΡΙΘ. 2402

Κύρωση Συμφωνίας μεταξύ της Κυβέρνησης της Ελληνικής Δημοκρατίας και της Κυβέρνησης της Δημοκρατίας της Βουλγαρίας για τα ύδατα του ποταμού Νέστου.

Ο ΠΡΟΕΔΡΟΣ
ΤΗΣ ΕΛΛΗΝΙΚΗΣ ΔΗΜΟΚΡΑΤΙΑΣ

Εκδίδομε τον ακόλουθο νόμο που ψήφισε η Βουλή:

Άρθρο πρώτο

Κυρώνεται και έχει την ισχύ, που ορίζει το άρθρο 28 παρ. 1 του Συντάγματος, η Συμφωνία μεταξύ της Κυβέρνησης της Ελληνικής Δημοκρατίας και της Κυβέρνησης της Δημοκρατίας της Βουλγαρίας για τα ύδατα του ποταμού Νέστου, που υπογράφηκε στη Σόφια στις 22 Δεκεμβρίου 1995, της οποίας το κείμενο σε πρωτότυπο στην ελληνική γλώσσα έχει ως εξής:

ΣΥΜΦΩΝΙΑ
ΜΕΤΑΞΥ ΤΩΝ ΚΥΒΕΡΝΗΣΕΩΝ ΤΗΣ ΕΛΛΗΝΙΚΗΣ ΔΗΜΟΚΡΑΤΙΑΣ
ΚΑΙ ΤΗΣ ΔΗΜΟΚΡΑΤΙΑΣ ΤΗΣ ΒΟΥΛΓΑΡΙΑΣ
ΓΙΑ ΤΑ ΥΔΑΤΑ ΤΟΥ ΠΟΤΑΜΟΥ ΝΕΣΤΟΥ

Η Κυβέρνηση της Ελληνικής Δημοκρατίας και η Κυβέρνηση της Δημοκρατίας της Βουλγαρίας, που θα αναφέρονται εφεξής ως "Συμβαλλόμενα Μέρη", επιθυμώντας να αναπτύξουν ακόμη περισσότερο τις μεταξύ τους φιλικές σχέσεις και τις σχέσεις καλής γειτονίας, σύμφωνα προς τους κανόνες του Διεθνούς Δικαίου, τις διατάξεις των μεταξύ τους σχετικών Συμφωνιών και την Κοινή Δήλωση που υπέγραψαν οι Πρωθυπουργοί των δύο χωρών, στις 20 Ιουλίου 1995 στην Αθήνα, συμφώνησαν τα ακόλουθα:

Άρθρο 1

Το ύψος των δικαιωμάτων χρήσεως της Ελληνικής Δημοκρατίας καθορίζεται σε ποσοστιαία βάση επί των υδάτων του ποταμού Νέστου που σχηματίζονται στο Βουλγαρικό έδαφος, με βάση το σύνολο της Μέσης Φυσικής Απορροής πολλών ετών. Το ποσοστό αυτό καθορίζεται στο 29%. Η Μέση Απορροή πολλών ετών έχει καθορισθεί βάσει στοιχείων των ετών 1935-1970, σε ένα δισεκατομμύριο πεντακόσια εκατομμύρια κυβικά μέτρα (1.500.000.000 Μ3). Το μέγεθος τούτο θα επικαιροποιηθεί από την Επιτροπή Υδροοικονομίας, που προβλέπει το Άρθρο 5 της Συμφωνίας, το αργότερο εντός τριών (3) ετών από της θέσεως σε ισχύ της Συμφωνίας αυτής. Κατόπιν, το μέγεθος αυτό θα επικαιροποιείται από την ίδια Επιτροπή κάθε επτά (7) χρόνια, εκτός αν η Επιτροπή αποφασίσει διαφορετικά.

Άρθρο 2

Οι ποσότητες ύδατος που θα εισρέουν στο ελληνικό έδαφος από τον ποταμό Νέστο, πέραν του συμφωνηθέντος στο Άρθρο 1 ποσοστού, δεν θα θεμελιώνουν απαιτήσεις ή δικαιώματα αποζημιώσεως.

Άρθρο 3

Τα Συμβαλλόμενα Μέρη θα ανταλλάσσουν πληροφορίες και στοιχεία σχετικά με την κατάσταση των υδάτων του ποταμού Νέστου από άποψη ποσότητος και ποιότητος, καθώς και για τα υπάρχοντα, τα υπό εκτέλεση και τα σχεδιαζόμενα έργα που δύνανται να επηρεάσουν τη φυσική απορροή και την ποιότητα των υδάτων αυτών.

Άρθρο 4

Τα Συμβαλλόμενα Μέρη θα λάβουν όλα τα προσήκοντα μέτρα με βάση τις Διεθνείς Συμβάσεις, τα διεθνή πρότυπα και τις Οδηγίες της Ευρωπαϊκής Ένωσης για τη βελτίωση της ποιότητος των υδάτων του ποταμού Νέστου και τη διατήρηση της ισορροπίας του οικοσυστήματος του ποταμού. Τα Συμβαλλόμενα Μέρη θα ορίσουν κριτήρια για την εκτίμηση της ποιότητος των υδάτων, τις θέσεις και την μεθοδολογία της λήψεως, επεξεργασίας και αναλύσεως των δειγμάτων επί τη βάσει των υποδείξεων της Ευρωπαϊκής Ένωσης.

Άρθρο 5

Τα Συμβαλλόμενα Μέρη συμφώνησαν να συστήσουν Μόνιμη Ελληνο-Βουλγαρική Επιτροπή Υδροοικονομίας στην αρμοδιότητα της οποίας θα συμπεριληφθούν η παρακολούθηση και ο έλεγχος για την εφαρμογή επί μονίμου βάσεως της παρούσας Συμφωνίας.

Η κατανομή των εξόδων για τη βελτίωση, κατασκευή και συντήρηση του συστήματος παρακολούθησης και ελέγχου της φυσικής απορροής του Νέστου καθορίζεται από την παραπάνω Επιτροπή.

Η Μόνιμη Ελληνο-Βουλγαρική Επιτροπή Υδροοικονομίας θα υιοθετήσει τον Εσωτερικό της Κανονισμό με τις αρμοδιότητές της, κατ' εφαρμογή της παρούσας Συμφωνίας.

Άρθρο 6

Η παρούσα Συμφωνία θα τεθεί σε ισχύ από την ημερομηνία ανταλλαγής των Εγγράφων Επικυρώσεώς της μεταξύ των Συμβαλλομένων Μερών και θα παραμείνει σε ισχύ επί τριάντα πέντε (35) έτη.

Άρθρο 7

Ένα (1) έτος προ της λήξεως της ισχύος της παρούσας Συμφωνίας, τα Συμβαλλόμενα Μέρη θα διεξάγουν διαπραγματεύσεις για τη σύναψη νέας Συμφωνίας για τα ύδατα του ποταμού Νέστου, επί τη βάσει της τότε ισχύουσας πραγματικής και νομικής καταστάσεως.

Άρθρο 8

Όλες οι διαφορές σχετικά με την ερμηνεία ή την εφαρμογή της παρούσας Συμφωνίας θα επιλύονται από τη Μόνιμη Ελληνο-Βουλγαρική Επιτροπή Υδροοικονομίας που προβλέπεται στο Άρθρο 5. Αν η Επιτροπή δεν επιτύχει να επιλύσει τη διαφορά, αυτή θα επιλύεται με διαπραγματεύσεις μεταξύ των Κυβερνήσεων των δύο χωρών.

Η παρούσα Συμφωνία υπεγράφη στη Σόφια την 22α Δεκεμβρίου 1995, σε δύο πρωτότυπα, ένα στην ελληνική και ένα στη βουλγαρική γλώσσα. Τα δύο κείμενα έχουν την αυτή ισχύ.

ΓΙΑ ΤΗΝ ΚΥΒΕΡΝΗΣΗ ΤΗΣ ΕΛΛΗΝΙΚΗΣ ΔΗΜΟΚΡΑΤΙΑΣ	ΓΙΑ ΤΗΝ ΚΥΒΕΡΝΗΣΗ ΤΗΣ ΔΗΜΟΚΡΑΤΙΑΣ ΤΗΣ ΒΟΥΛΓΑΡΙΑΣ
(υπογραφή)	(υπογραφή)
ΚΑΡΟΛΟΣ ΠΑΠΟΥΛΙΑΣ	ΓΚΕΟΡΓΚΙ ΠΙΡΙΝΣΚΙ

Άρθρο δεύτερο

Τα Πρωτοκόλλα-Πρακτικά που καταρτίζονται από τη Μόνιμη Ελληνο-Βουλγαρική Επιτροπή Υδροοικονομίας σε εκτέλεση του Άρθρου 5 της Συμφωνίας, εγκρίνονται με κοινή Πράξη των αρμόδιων κατά περίπτωση υπουργών.

Άρθρο τρίτο

Η ισχύς του νόμου αυτού αρχίζει από τη δημοσίευσή του στην Εφημερίδα της Κυβερνήσεως και της Συμφωνίας που κυρώνεται από την πλήρωση των προϋποθέσεων του Άρθρου 6 αυτής.

Παραγγέλλουμε τη δημοσίευση του παρόντος στην Εφημερίδα της Κυβερνήσεως και την εκτέλεσή του ως νόμου του Κράτους.

Αθήνα, 29 Μαΐου 1996

Ο ΠΡΟΕΔΡΟΣ ΤΗΣ ΔΗΜΟΚΡΑΤΙΑΣ
ΚΩΝΣΤΑΝΤΙΝΟΣ Δ. ΣΤΕΦΑΝΟΠΟΥΛΟΣ

ΟΙ ΥΠΟΥΡΓΟΙ

ΕΞΩΤΕΡΙΚΩΝ	ΕΘΝ. ΟΙΚΟΝΟΜΙΑΣ
ΘΕΟΔ. ΠΑΓΚΑΛΟΣ	**ΓΙΑΝΝΟΣ ΠΑΠΑΝΤΩΝΙΟΥ**

ΓΕΩΡΓΙΑΣ
ΣΤΕΦ. ΤΖΟΥΜΑΚΑΣ

Θεωρήθηκε και τέθηκε η Μεγάλη Σφραγίδα του Κράτους.

Αθήνα, 30 Μαΐου 1996

Ο ΕΠΙ ΤΗΣ ΔΙΚΑΙΟΣΥΝΗΣ ΥΠΟΥΡΓΟΣ
ΕΥΑΓΓ. ΒΕΝΙΖΕΛΟΣ

ΑΠΟ ΤΟ ΕΘΝΙΚΟ ΤΥΠΟΓΡΑΦΕΙΟ