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Soulis Konstantinos

Nicholas Dercas

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AgroHydroLogos: development and testing of a spatially distributed agro-hydrological model on the basis of ArcGIS.

Soulis Konstantinos[1], Dercas Nicholas[2]
Agricultural University of Athens, Department of Natural Resources Management and
Agricultural Engineering, Sector of Water Resources Management, Athens, Greece,
([1]soco@aua.gr, [2]ndercas1@aua.gr)

Abstract: In this paper the development and testing of AgroHydroLogos is presented, which is a new spatially distributed, continuous hydrological model. The model was developed as an extension of the ESRI ArcGIS Geographical Information Systems' software package. It calculates, on a daily basis, the main hydrological balance components, and other important parameters, including plants water stress and irrigation water needs. Its conceptual scheme was based on simplified but well established methods for the simulation of the various hydrological processes. The hydrological model is being developed using object oriented programming techniques, and its Graphical User Interface is very easy to use and it follows the standard ArcGIS software extensions form. The model was tested in a Mediterranean experimental watershed in Greece. The final conclusion is that AgroHydroLogos can produce valuable information concerning agricultural water management; it can also produce important information for the assessment of climate change impacts and for the evaluation of various adaptation and mitigation strategies.

Keywords: hydrological model; climate change; water management; GIS (Geographical Information System); OOP (Object Oriented Programming).

1. INTRODUCTION

Much current research in hydrology is directed at improving the ability to predict the effect of various land-use and climate conditions on the water balance, streamflow variability and water quality of river basins. These and most other practical applications of hydrology require the use of hydrological models [Digman 2002]. Models are extremely useful as test beds for ideas, as data processing and analysis aids, and for exploring scenarios that cannot be tested in the real world. However, it is not a unique opinion that modeling is fine as long as it is not confused with the real world [Silberstein 2006]. A simulation model is a representation of a portion of the natural world, which is simpler than the prototype system and which can reproduce some but not all of the characteristics thereof [Dooge 1986]. Specific scales and specific purposes require the use of different modeling approaches. Advances in hydrological research and the abundance of computer power, facilitate the development of more efficient and more sophisticated hydrological models, as well. As a result, the hydrologic literature abounds with descriptions of models.
Hydrological models can be categorized based on their spatial representation to "Lumped" models, which represent a catchment as a single entity, or a small group of entities, and simulate state variables and fluxes into and out of the catchment as a whole, e.g. HEC-1 (US Army Corps of Engineers) and SWAT (USDA, US Department of Agriculture), and to "Distributed" models, which divide the catchment into many entities, each representing small parts of the catchment, and the state variables and fluxes between the entities are determined across the catchment, e.g. MIKE SHE [Refsgaard and Storm 1995], CASC2D [Ogden 1997] and SHETRAN [Ewen et al. 2000]. There are also semi-distributed models, in which variables are not explicitly distributed across the catchment, e.g., TOPMODEL [Beven and Kirkby 1979]. Concerning their simulation basis, models can be also

categorized to "conceptual", "empirical" or ''physical'' [Digman 2002]. The vast majority of models in the literature are ''conceptual'', using a priori relationships to simulate flows and storages [Alemaw and Chaoka 2003, Moretti and Montanari 2007, Meng et al. 2008]. The recent development of Geographical Information Systems (GIS) and the availability of large volumes of spatial data have raised a high demand for closer integration of GIS and hydrological models. Recent efforts to develop hydrological models on top of GIS are presented by Jain et al., [2004], Shena et al. [2005], Efstratiadis et al. [2008], Li and Zhang [2008], and Teng et al. [2008]. Also, advances in computer programming techniques, such us Object Oriented Programming (OOP), triggered the development of new hydrological models [e.g. Band et al. 2000, Wang et al. 2005, Leone and Chen 2007, and Martinez et al. 2008]. Current efforts are also focused on the development of integrated models involving different scientific disciplines [Pietroniro et al. 2006, Krol et al. 2006, Krysanova et al. 2007, and Krol and Bronstert 2007].

In this paper the development and testing of AgroHydroLogos is presented, which is a new spatially distributed, continuous hydrological model, aiming to produce valuable information concerning agricultural water management, assessment of climate change impacts and evaluation of various adaptation and mitigation strategies. The model was developed as an extension of the ESRI ArcGIS, a GIS software package, in order to facilitate the fully spatially distributed calculation of the hydrological balance components, and at the same time to make use of the advanced capabilities of ArcGIS in managing, editing, analyzing and visualizing geographical data. The model calculates, on a daily basis, the main hydrological balance components, such as, soil moisture, direct runoff, deep infiltration, actual evapotranspiration, and base flow. Furthermore, it can calculate other important parameters, including plants water stress and irrigation water needs in order to constitute a valuable software tool for agro-hydrological analysis. The hydrological model is being developed using OOP techniques, thus facilitating further development. The Graphical User Interface (GUI) of the model is very simple to use and it follows the standard ArcGIS software extensions form. The hydrological model is simple and flexible, as its conceptual scheme was based on simplified but well established methods for the simulation of the various hydrological processes. The model was tested in a Mediterranean experimental watershed in Greece, in order to validate the soundness of the conceptual scheme and to evaluate its efficiency.

2.   AGROHYDROLOGOS SOFTWARE DESCRIPTION

AgroHydroLogos software consists of a geographical database, a knowledge base, data pre processing and post processing tools and the core hydrological model. The model was developed on the basis of ESRI's ArcGIS 9.2 software based on ArcObjects functionality. Arc Objects are built using Microsoft's Component Object Model (COM), therefore it is possible to extend them by writing COM components using any COM compliant development language. Through Arc Objects, ArcGIS exposes all its functionality and its data structure to the modeler, allowing the development of applications dynamically linked to the geographical database. AgroHydroLogos model components were built making use of the above functionality and then were embedded to ArcGIS as an extension. It was developed based on OOP techniques, using Visual Studio .NET 2005. The model was organized in a collection of discrete objects that facilitate the efficient description of the hydrological cycle. AgroHydroLogos GUI follows the form and the operation of ArcGIS extensions. AgroHydroLogos can be activated or deactivated through the "Extensions" menu. The GUI consists of the main toolbar and the various forms activated through it. Each AgroHydroLogos project is embedded in an ArcMap project and the values of all its options and its parameters are stored in the related .mxd file. A number of tools are also added to the existing GIS functionality in order to assist the dynamic preparation of input data layers and the post-processing of results.

2.1   Geographical Database and Knowledge Base

The model works as part of the Geographical Information System in direct interaction with the Geographical database. The inputs come directly from the Geographical database and

the resulting outputs, either directly from the model or from post processing tools, are stored in it too. In this way the user has access to all the GIS functionality for data preparation, storage, visualization and analysis in a familiar and user-friendly graphical user interface. Moreover, all the advantages of a database management system are provided.

The structure of the Geographical database must follow the predefined data model and all spatial input data must be geo-referenced. The spatial outputs are also geo-referenced, allowing easy overlapping and comparing the results with data coming from other sources or sharing the results with other users. The required input data are a depressionless Digital Elevation Model (DEM), soil, land cover, geology and weather stations. Based on the above data, all the requested parameters for running the model are calculated in spatial distributed form such as: the soil water holding capacity, the soil permeability, etc. The above data layers can be calculated dynamically, making use of the knowledge base, facilitating the assessment of various scenarios.

The knowledge base contains information needed for spatial data pre-processing and for some procedures of the hydrological model like the soil group - land cover complex and Curve Number correspondence, soil hydraulic property estimation or vegetation characteristics (rooting depth, planting dates, coefficients needed for actual evapotranspiration calculation, etc). All this information is stored in the form of a separate database to promote adding or editing capabilities.

2.2 Meteorological data

In isolated areas, like mountainous regions with steep relief or small islands, the surface meteorological information available is scarce and confined to plain or coastal locations, considered to be representative at a regional or synoptic scale. Therefore, this information cannot reflect the spatial variation of the climate as influenced by topography and advective processes [Brito et al 1999].

The approach used in the presented model in order to overcome this problem is the use of interpolation techniques accompanied with adjustments depending on topography. In the methodology used, the weight of each selected weather station for each grid cell of the simulated area is calculated at the beginning of each execution of the model, using the Inverse Distance Weight or the Thiessen Polygons method. The values of the meteorological parameters are then calculated on a day by day and cell by cell basis during run time, using the calculated weights and taking also into account the geomorphologic conditions in every grid cell. With this methodology a negligible cost is required with regard to performance or storage. Similar techniques, like spatial interpolation of the meteorological data prior to the running of the model, decrease significantly the model's performance and necessitate significant storage space.

2.3 Spatial Resolution

A primary goal of developing spatially distributed hydrological models is to minimize the number of parameters which need calibration [Schumann and Geyer 2000]. Lumped models need much less computation effort and, most of the time, have comparable accuracy but always under the condition of extensive calibration. However, the results obtained with spatially distributed hydrological models are considerably dependent on their spatial resolution. In general, a small pixel size gives more accurate representation of spatial parameters such as slope, hydrographical network or water divide [Zhang and Montgomery 1994, Garbrecht and Martz 1994, Thieken 1999, and Wang et al. 2000], but increases geometrically the computing time as well as the volume of the input and output spatial data. Even so, small pixel size is not always related to more accurate results. Zhang and Montgomery [1994] suggested that a DEM spatial resolution finer than the original data accuracy can cause artefacts and subsequent wrong slope and flow direction representation. In this model the spatial resolution is set equal to the spatial resolution of the mask grid that is used to define the modelling area. By this way the pixel size can be easily adjusted to achieve the optimum relation between accuracy and performance.

2.4   Hydrological Model Structure

The hydrological model in the core of AgroHydroLogos Software, calculates in spatial distributed form and on a daily basis, the main hydrological balance components, such as, soil moisture, direct runoff, deep infiltration, actual evapotranspiration, and base flow, and other important parameters for agro-hydrological analysis, including plant water stress and irrigation water. The daily temporal discretization was chosen in order to describe with satisfactory detail the hydrological processes and at the same time to allow the simulation of long time periods and the utilization of readily available meteorological data and data concerning future climate projections. The conceptual scheme of the model was designed in order to achieve the following targets:

- to make use of simplified but well established methods for the simulation of the various hydrological processes
- to require easily available spatial data and parameters
- to adapt to semi-arid and arid regions
- to efficiently describe vegetation-water dynamics

The conceptual scheme and the involved stores and flows are presented in figure 1 and described in detail in the following paragraphs.
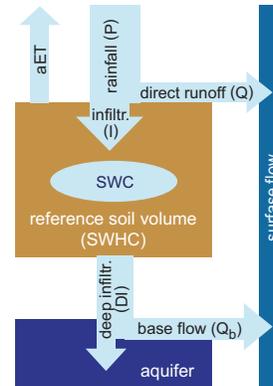
Figure 1. Schematic representation of the model conceptual scheme.

Water Balance of the reference soil volume

Soil moisture of the top soil layer is directly involved in the calculation of most water balance components such as direct runoff, infiltration, deep infiltration, and actual evapotranspiration. Thus, the principal equation of the hydrological model is equation (1) that describes the water balance of the reference soil volume:

$$SWC_{i-1} - SWC_i = P_i - Q_i - aET_i - DI_i \tag{1}$$

where SWC_{i-1} and SWC_i (mm) are the reference soil volume water contents of the day before and the actual day respectively, P_i (mm) is the total rainfall depth the actual day, Q_i (mm) is the direct runoff the actual day, aET_i (mm) is the actual evapotranspiration the actual day and DI_i (mm) is the deep infiltration the actual day. As reference soil volume is defined the top soil layer, which in deep soils is limited to the rooting depth. A schematic representation of the interactions determining the water balance of the reference soil volume is shown in figure 1.

In wet periods *SWC* can increase up to a maximum, which is equal to the water holding capacity of the reference soil volume (*SWHC*), resulting in significant decrement of the infiltration rate, increment of the actual evapotranspiration rate and increment of the deep infiltration rate. In dry periods soil becomes very dry limiting actual evapotranspiration rate and deep infiltration rate and increasing infiltration rate when rainfall occurs. *SWC* value is one of required initial conditions for the application of the model. Generally the determination of the initial *SWC* is very difficult. However, in some specific periods of the year (after a very wet winter period or a very dry summer period) we can set *SWC* equal to the *SWHC* or equal to zero, respectively.

Direct Runoff

The Soil Conservation Service Curve Number (SCS-CN) method is used to calculate direct runoff in relation to land use, soil type and antecedent moisture. This method was originally developed by the U.S. Department of Agriculture (Soil Conservation Service) and documented in detail in the National Engineering Handbook, Section 4: Hydrology (NEH-4) [SCS 1956, 1964, 1971, 1985, 1993]. Due to its simplicity, it soon became one of the most popular techniques among the engineers and the practitioners, mainly for small catchment hydrology [Mishra and Singh 2006]. The main reasons for its success is that it accounts for many of the factors affecting runoff generation including soil type, land use

and treatment, surface condition, and antecedent moisture condition, incorporating them in a single CN parameter. Furthermore, it is the only well established method that features readily grasped and reasonably well-documented environmental inputs [Ponce and Hawkins 1996]. Although the SCS method was originally developed in the United States and mainly for the evaluation of storm runoff in small agricultural watersheds, it soon evolved well beyond its original objective and was adopted for various land uses [Rawls et al. 1981, Mishra and Singh 1999] and it became an integral part of more complex, long-term, simulation models [Choi et al. 2002, Mishra and Singh 2004, Zhan and Hang 2004, Tyagi et al. 2008].

Based on the water balance equation and on the assumptions that the ratio of runoff to effective rainfall is the same as the ratio of actual retention to potential retention, and that the amount of initial abstraction is a fraction of the potential maximum retention $I_a = \lambda S$, the basic equation of the SCS-CN method is obtained:

$$Q = (P - \lambda S)^2 \big/ P + (1 - \lambda) S , \qquad (2)$$

where P (mm) is the total rainfall, Q (mm) is the direct runoff and S (mm) is the potential maximum retention, which is valid for $P \geq \lambda S$; otherwise $Q = 0$. In Eq. (2), the initial abstraction rate is normally set to a constant value ($\lambda = 0.2$) in order for S to be the only parameter of the method. Furthermore, the potential retention S is expressed in terms of the dimensionless curve number (CN) through the relationship

$$S = 25400 \big/ CN - 254 \qquad (3)$$

taking values from 0, when $S \to \infty$, to 100, when $S = 0$. In this application the CN values can be dynamically calculated from the soil and land cover data, which are stored in the geographical database and the knowledge base. The resulting CN values apply for normal antecedent moisture conditions (AMC II). For dry (AMC I) or wet (AMC III) conditions, equivalent curve numbers can be computed by:

$$CNI = \frac{4.2CNII}{10 - 0.058CNII} \quad \text{and} \quad CNIII = \frac{23CNII}{10 + 0.13CNII} \qquad (4), (5)$$

In the model, CN value is justified each day, depending on the actual soil moisture.

Deep Infiltration

The determination of the drainage through the soil profile is based on the Brooks and Corey [1964] equation:

$$K = K_s \left(\theta / \theta_s \right)^{1/n} \qquad (6)$$

where K represents the soil unsaturated hydraulic conductivity when soil moisture equal to θ, θ_s is the saturated soil moisture, K_s is the saturated hydraulic conductivity, and n is a shape factor, assuming a free drainage (zero pressure head) boundary condition at the bottom of the reference soil volume.

Base Flow

Base flow is simulated based on the equation proposed by Arnold et al. [1993] and Hattermann et al. [2004]:

$$Q_{b,i} = Q_{b,i-1} e^{(-a_b)} + W_{rch} (1 - e^{(-a_b)}) \qquad \text{when } aq > aq_q$$
$$Q_{b,i} = 0 \qquad \text{when } aq \leq aq_q \qquad (7)$$

where $Q_{b,i}$ (mm) is the base flow in day i, $Q_{b,i-1}$ (mm) is the base flow in day i-1, α_b is the base flow reduction, W_{rch} (mm) is the aquifer recharge in day i, aq (mm) is the water quantity stored in the aquifer in day i, and aq_q (mm) is the limit of stored water, below which there is no base flow.

Evapotranspiration

Actual Evapotranspiration (*aET*) rate is depending on weather parameters, land cover and water availability. In this study reference evapotranspiration (*ET_o*) is calculated from weather parameters and then *aET* is determined taking into account the land cover characteristics and the soil moisture. The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data. ET_o

expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the plant characteristics and soil factors. The FAO Penman-Monteith [FAO 1998] method is used for determining ET_o in this model. This physically based method has been selected because it closely approximates ET_o and explicitly incorporates both physiological and aerodynamic parameters. The required weather parameters are temperature, humidity, wind speed, and solar radiation. Alternatively, in case that the only available weather parameter is temperature, the Hargreaves method can be used [Hargreaves and Samani 1985].

Differences in leaf anatomy, stomatal characteristics, aerodynamic properties, and even albedo cause the plant evapotranspiration ET_c to differ from ET_o under the same climatic conditions. ET_c is related to ET_o using experimentally determined ratios of ET_c/ET_o, called crop coefficients (K_c).

$$ET_c = K_c ET_o \tag{8}$$

Due to variations in the plant characteristics throughout its growing season, K_c for a given plant also changes during the year. The *aET* is finally calculated by using a water stress coefficient K_{st} expressing the effect of water availability on crop evapotranspiration.

$$aET = K_{st} ET_c \tag{9}$$

The K_{st} parameter is related to soil moisture but differs for different land cover characteristics [FAO 1998]. The values of K_c and K_{st} are determined for each grid cell and each day, depending on the vegetation characteristics of each place, based on the knowledge base, which contains information for a wide range of land cover types. Using the above described methodology, the model efficiently describes vegetation-water dynamics and is able to calculate plants water stress. The model is also able to simulate irrigation and to calculate irrigation water needs for selected land cover types.

Runoff Routing

Daily accumulated runoff is estimated for each grid cell of the river network, for every time step, by adding the accumulated surface runoff for this time period to the accumulated base flow. Runoff routing through overland flow and through the hydrographical network is performed with a simplified travel time approach. Travel time varies depending on the accumulated runoff in each grid cell, it is calculated with the kinematic wave approach and it is relative to the topographical slope, and to a roughness coefficient based on land cover type. In every time step, the daily accumulated runoff of each grid cell is travelling downhill until the total travel time is equal to the time step interval (Fig. 2). The methodology used does not aim to produce very detailed hydrographs but it is sufficient for this application, which is mainly focused on water balance components estimation and uses a relatively large calculation time step. The parameters involved in the flow routing procedure can be directly estimated using data from the knowledge base.
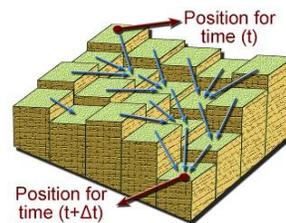

Figure 2. Schematic representation of runoff routing method.

3. MODEL APPLICATION

3.1 Site Description and Input Data

The model was applied to the small scale experimental watershed of Lykorrema stream (7.84 km²), situated on the east side of Penteli Mountain, Attica, Greece (Coordinates: UL 23°53'33"E-38°04'13"N; LR 23°56'00"E-38°02'28"N) (Fig. 3a). The region is characterized by a Mediterranean semi-arid climate with mild, wet winters and hot, dry summers. Precipitation occurs mostly in the autumn–spring period. The yearly average precipitation value for the five years studied is 595mm. The reference evapotranspiration rate varies from about 1mm/day during winter to 7mm/day during summer. The watershed presents a relatively sharp relief, with elevations ranging between 280 m and 950 m. Its average elevation is 560 m and its average slope is as high as 36%. Geologically it is characterized by schists formations covering 96% of its area, while the rest is covered by

marbles. Schist formations in the area are not impervious. They are tectonically intensely fractured and their upper layer is eroded. The aquifers system developed within the intensely fractured bedrock contributes significantly to the base flow of the watershed, which is continuous throughout the year. A soil survey in the area showed that the watershed is dominated by coarse soils with high hydraulic conductivities and a smaller part is covered with medium textured soils presenting relatively high hydraulic conductivities. A detailed land cover classification based on remote sensing techniques, showed that the dominant vegetation type is pasture with a few scattered tufts of trees (Fig. 3a). A small part of the watershed is covered by bare rock [Soulis et al. 2009].

The study area is equipped with a dense hydro-meteorological network, which is fully operational since September 2004. The installed equipment consists of five rain-gauges, one hydrometric station at the outlet of the watershed, one meteorological station and four temperature-relative humidity recorders. The data are recorded with a time step of 10 min. In the current application the period from September 2004 to August 2008 was simulated.

The required data layers where produced based on detailed DEM and the above described information. These data layers are: weather stations, DEM, land cover, flow direction, flow accumulation, curve number, soil water holding capacity, saturated hydraulic conductivity, roughness coefficient, base flow reduction constant, base flow initiation limit (Fig. 3).
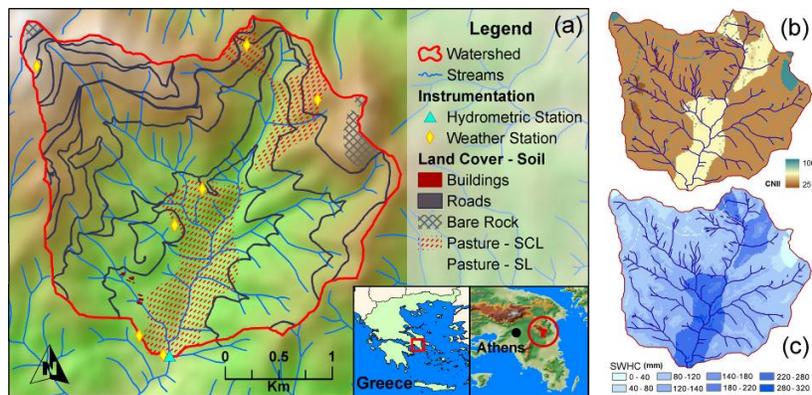

Figure 3. (a) Map of Lykorrema stream experimental watershed. (b,c) Input data layers, (b) CN spatial distribution. (c) SWHC spatial distribution.

3.2 Results and Discussion

Calibration of complex, spatial distributed hydrological models is a difficult task. The involvement of many parameters in spatial distributed form intensifies the problem of the existence of a number of local optima rather than a global optimum. Furthermore, the calibration of hydrological models requires extensive and detailed datasets of measured data. However, these models are used in regions with lack of data or for future projections under different conditions. Even when calibration data exist, those normally concern only runoff recordings at specific locations, while their accuracy is limited due to the great difficulties related to flow rate recordings in natural streams. In order to overcome the above mentioned-difficulties the approach included firstly the use of simplified but well established methods having a physical basis for the simulation of the various hydrological processes and the involvement of a limited number of easily available spatial data and parameters. Secondly, calibration efforts target to the most uncertain parameters and exploit the modeler experience on the studied site and the involved processes. In order to explore the use of the developed model in the above described framework, the model was calibrated using only the first year of the available data (Sept. 2004 – Aug. 2005), and by adjusting only the average values of the *SWHC* and α_b parameters. In figure 4 are

Table 1. Total yearly measured rainfall and runoff values and total yearly predicted runoff values.

Year	Rain (mm)	Runoff Meas. (mm)	Runoff Pred. (mm)
04-05	660	116	118
05-06	794	151	147
06-07	726	61	80
07-08	490	27	53

illustrated the measured daily rainfall and runoff values in comparison with the predicted daily runoff values by the model application for the period from September 2004 to August 2008. In table 1 are shown the total yearly measured rainfall and runoff values and the total yearly runoff values predicted by the model for the same period. It can be observed that the model performance is quite good for the first two years, sufficiently good for the third year, and modest for the last year. It can also be observed that the last year of the modelling period is very dry and that in the last two years the main part of the rainfall occurs in a small number of intense storm events. The main remark is that the model significantly overestimates base flow during dry years, probably because the first year, which was used for the model calibration, is characterized by high base flow and low rainfall intensity values. In figure 5 are presented the predicted spatial distribution of the average yearly runoff, aET and aquifer recharge values. These results demonstrate the great temporal and spatial variability of the water balance components and the importance of a model capable to produce results in such a form as to promote integrated water resources management. It can be also observed that *aET* and runoff spatial distribution is related to the spatial distribution of the soil and land cover characteristics.
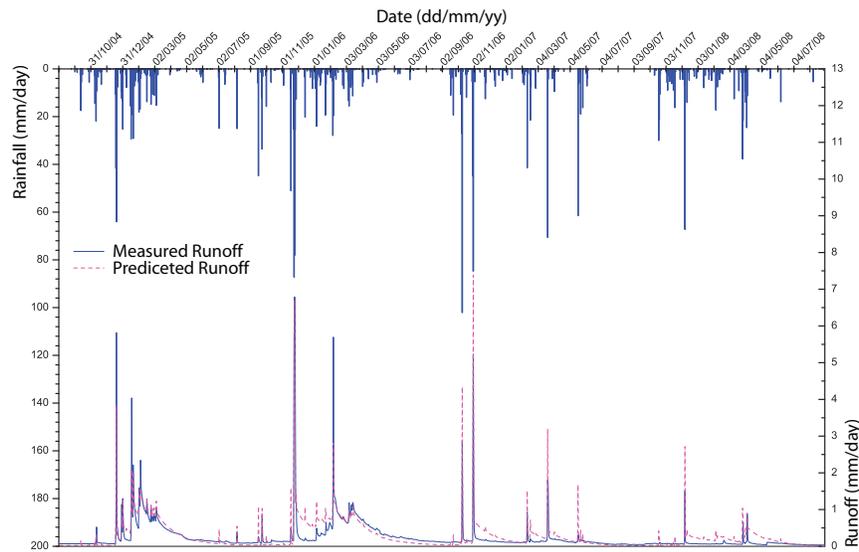

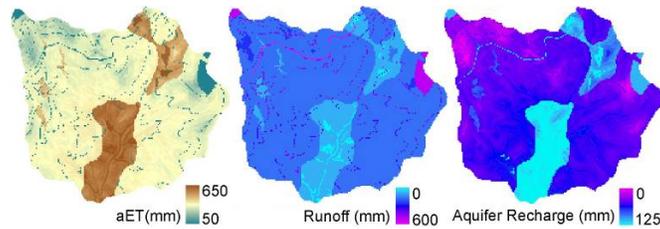**Figure 4.** Daily rainfall values and daily measured vs. predicted runoff values.

Figure 5. Predicted spatial distribution of average yearly runoff, aET and aquifer recharge.

4. SUMMARY AND CONCLUSIONS

AgroHydroLogos is a new spatially distributed, continuous hydrological model. The model was developed as an extension of ESRI ArcGIS, in order to facilitate the fully spatially distributed calculation of the hydrological balance components, and to make use of the advanced capabilities of GIS in managing, editing, analyzing and visualizing geographical data. The model calculates, on a daily basis, the main hydrological balance components, such as soil moisture, direct runoff, deep infiltration, actual evapotranspiration, and base flow, and other important parameters, including plant water stress and irrigation water needs in order to constitute a valuable software tool for agro-hydrological analysis. The

hydrological model is being developed using OOP techniques, thus facilitating further development. Its Graphical User Interface is very easy to use and it follows the standard ArcGIS software extensions form. Its conceptual scheme was based on simplified but well established methods, which have a physical basis, for the simulation of the various hydrological processes. It was especially designed in order to enable the efficient description of vegetation water dynamics.

The model was applied to a Mediterranean experimental watershed in Greece. This application demonstrated the ability of the model to produce satisfactory results based on a limited set of input data and parameters and on a modest calibration effort. The final conclusion is that AgroHydroLogos is simple and flexible and it can produce valuable information concerning water resources management and especially agricultural water management. Additionally, it can produce important information for the assessment of climate change impacts on water resources and for the evaluation of various adaptation and mitigation strategies.

REFERENCES

Alemaw, B.F., and T.R. Chaoka, A continental scale water balance model: a GIS-approach for Southern Africa, *Physics and Chemistry of the Earth, 28*, 957–966, 2003.

Band, L.E., D.E. Tenenbaum, S.E. Brun, and R.A. Fernandes, Modelling watersheds as spatial object hierarchies: structure and dynamics, *Transactions in GIS, 4*, 181–196, 2000.

Beven, K.J., and M.J. Kirkby, A physically based, variable contributing area model of basin hydrology, *Hydrological Science Bulletin, 24*(1), 43-69, 1979.

Brito, E., L.S Pereira, and B. Itier, Modeling the local climate in island environments: water balance applications, *Agricultural Water Management, 40*, 393-403, 1999.

Choi, J., B.A. Engel, and H.W. Chung, Daily streamflow modelling and assessment based on the curve-number technique, *Hydrological Processes, 16*(16), 3131-3150, 2002.

Dingman, S. L., Physical Hydrology (second edition). *Prentice-Hall, Inc*, 2002.

Dooge, J., Looking for hydrologic laws, *Water Resources Research, 22*, 46-48, 1986.

Efstratiadis, A., I. Nalbantis, A. Koukouvinos, E. Rozos, and D. Koutsoyiannis, HYDROGEIOS: A semi-distributed GIS-based hydrological model for modified river basins, *Hydrology and Earth System Sciences, 12*(4), 989-1006, 2008.

Ewen, J., G. Parkin, and P.E. O'Connell, SHETRAN: distributed river basin flow and transport modeling system, *Proceedings of the American Society of Civil Engineering. Journal of Hydrologic Engineering, 5*, 250-258, 2000.

FAO, Crop Evapotranspiration, *FAO Irrigation and Drainage Paper No. 56,* 1998.

Garbrecht, J., and L.W. Martz, Grid Size Dependency of Parameters Extracted From Digital Elevation Models, *Computers & Geosciences, 20*(1), 85-87, 1994.

Hargreaves, G.L., and Z.A. Samani, Reference crop évapotranspiration from temperature, *Applied Engineering in. Agriculture, ASAE 1*(2), 96-99, 1985.

Jain, M.K., U.C. Kothyari, and K.G. Ranga Raju, A GIS based distributed rainfall-runoff model, *Journal of Hydrology, 299*(1-2), 107-135, 2004.

Krol, M., A. Jaeger, A. Bronstert, and A. Güntner, Integrated modelling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil, *Journal of Hydrology, 328*(3-4), 417-431, 2006.

Krol, M.S., and A. Bronstert, Regional integrated modelling of climate change impacts on natural resources and resource usage in semi-arid northeast Brazil, *Environmental Modelling and Software, 22*(2), 259-268, 2007.

Krysanova, V., F. Hattermann, and F. Wechsung, Implications of complexity and uncertainty for integrated modelling and impact assessment in river basins. *Environmental Modelling and Software, 22*(5), 701-709, 2007.

Leone A. and D. Chen, Implementation of an object oriented data model in an information system for water catchment management: Java JDO and Db4o Object Database, *Environmental Modelling & Software, 22,* 1805-1810, 2007.

Li, Z., and K. Zhang, Comparison of three GIS-based hydrological models. *Journal of Hydrologic Engineering, 13*(5), 364-370, 2008.

Martinez, C.J., K. Campbell, M.D. Annable and G.A Kiker, An object-oriented hydrologic model for humid, shallow water-table environments, *Journal of Hydrology, 351*, 368–381, 2008.

Meng, H., T.R. Green, J.D. Salas, and L.R. Ahuja, Development and testing of a terrain-based hydrologic model for spatial hortonian infiltration and Runoff, *Environmental Modelling and Software, 23*(6), 794-812, 2008.

Mishra, S.K., and V.P Singh, Long-term hydrological simulation based on the soil conservation service curve number, *Hydrological Processes, 18*(7), 1291-1313, 2004.

Mishra, S.K., and V.P. Singh, Another look at SCS-CN method, *Journal of Hydrologic Engineering, ASCE, 4*(3), 257-264, 1999.

Mishra, S.K., and V.P. Singh, A relook at NEH-4 curve number data and antecedent moisture condition criteria, *Hydrological Processes, 20*(13), 2755-2768, 2006.

Moretti, G., and A. Montanari, AFFDEF: A spatially distributed grid based rainfall-runoff model for continuous time simulations of river discharge, *Environmental Modelling & Software, 22*, 823-836, 2007.

Ogden, F.L., CASC2D Reference Manual. *Department of Civil & Environmental Engineering, University of Connecticut, Storrs,* 1997.

Pietroniro, A., R. Leconte, B. Toth, D.L Peters, N. Kouwen, F.M. Conly, and T Prowse, Modelling climate change impacts in the Peace and Athabasca catchment and delta: III - integrated model assessment, *Hydrological Processes, 20*(19), 4231-4245, 2006.

Ponce, V.M., and R.H. Hawkins, Runoff curve number: Has it reached maturity?, *Journal of Hydrologic Engineering, ASCE, 1*(1), 11-18, 1996.

Rawls, W.J., A. Shalaby, and R.H McCuen, Evaluation of methods for determining urban runoff curve numbers, *Transactions of ASAE, 24*, 1562-1566, 1981.

Refsgaard, J.C., B. Storm, MIKE SHE, In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. *Water Resource Publications, Highlands Ranch, CO*, 1995.

Schumann A.H., J. Geyer, GIS-based ways for considering spatial heterogeneity of catchment characteristics, *Physics and Chemistry of the Earth 25,* 691-694, 2000.

SCS National Engineering Handbook, Section 4: Hydrology, *Soil Conservation Service, USDA, Washington, D.C*, 1956, 1964, 1971, 1985, 1993.

Shena, J., A. Parker and J. Riverson, A new approach for a Windows-based watershed modeling system based on a database-supporting architecture, *Environmental Modelling & Software, 20,* 1127–1138, 2005.

Silberstein, R.P., The Hydrological models are so good, do we still need data? *Environmental Modelling & Software, 21*, 1340-1352, 2006.

Soulis, K.X., J.D. Valiantzas, N. Dercas, and P.A. Londra, Analysis of the runoff generation mechanism for the investigation of the SCS-CN method applicability to a partial area experimental watershed, *Hydrology and Earth System Science, 13*, 605–615, 2009.

Teng, J., J. Vaze, N.K. Tuteja, and J.C Gallant, A GIS-based tool for spatial and distributed hydrological modelling: CLASS spatial analyst, *Transactions in GIS, 12*(2), 209-225, 2008.

Thieken, A.H., A. Lücke, B. Diekkrüger, O. Richter, Scaling Input Data by GIS for Hydrological Modelling, *Hydrological Processes, 13*(4): 611-630, 1999.

Tyagi, J.V., S.K. Mishra, R. Singh, and V.P. Singh, SCS-CN based time-distributed sediment yield model, *Journal of Hydrology, 352*(3-4), 388-403, 2008.

Wang J., J.M. Hassett, and T. Endreny, An object oriented approach to the description and simulation of watershed scale hydrologic processes. *Computers & Geosciences, 31*, 425–435, 2005.

Wang, M., A.T. Hjelmfelt, and J. Garbrecht, DEM Aggregation for Watershed Modeling. *Journal of the American Water Resources Association, 36*(3), 579-584, 2000.

Zhan, X., and M. Huang, ArcCN-runoff: An ArcGIS tool for generating curve number and runoff maps, *Environmental Modelling and Software, 19*(10), 875-879, 2004.

Zhang, W., and D.R. Montgomery, Digital elevation model grid size, landscape representation, and hydrologic simulation, *Journal of Hydrology, 102,* 1019-1028, 1994.