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SWAT model for Integrated River Basin Management with application to the Mekong Basin

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Abstract The Soil and Water Assessment Tool, known as the SWAT model, is a GIS-based basin-scale model for simulating hydrological and water quality processes. It is a pseudo-physically based model that is capable of predicting long-term effects of land management. The model was applied to simulate rainfall–runoff process, streamflow pattern, soil erosion and sediment transport in the Lower Mekong River Basin. This paper reports the major findings of analysing the flow and sediment transport at major locations along the Mekong River and discusses the results from the first-cut preliminary analysis. In addition, the paper briefly describes the hydrology of the Mekong Basin in connection with the human impact on the basin's health and provides a critical review on the role of integrative models for the implementation of the IWRM concept.

Key words erosion; hydrology; IWRM; Mekong; modelling; sediment; SWAT

INTRODUCTION

Suspended sediments play a key role in controlling streamwater quality and pollutant transport and it is therefore important to have an understanding of sediment supply and transport dynamics, and to recognize the linkages between basin management and hydrological response. Recent studies on the human impacts in the Mekong Basin suggest sediments can cause a major reduction of streamwater quality and ultimately reduce the capacity for handling flood waves. Soil erosion patterns in the Mekong watersheds are heterogeneous and difficult to model or to predict, particularly when data availability becomes a constraint.

In the Mekong Basin, field investigations that identify and scientifically verify suspended sediment problems are limited. Carbonnel & Guiscafre (1963) carried out a study in which they concluded that for the period 1950-51 to 1955-56, around 4.5–6.0 $\times 10^6$ t year^{-1} entered Tonle Sap from the Mekong and around 3.0–6.7 $\times 10^6$ t year^{-1} passed to the Mekong from Tonle Sap. The rate of sedimentation of the Great Lake of Tonle Sap was estimated as less than 1 mm year^{-1}, possibly as low as 0.4 mm year^{-1}. This figure is consistent with information on sedimentation of the navigation channels in the Mekong Delta where dredging indicates that sedimentation rates of less than 1 mm year^{-1} are normal. Sedimentation may be much higher at specific locations in the system, particularly near Snoc Trou where Tonle Sap joins the Great Lake, and around Phnom Penh. Pantulu (1986) concluded that the annual sediment load of the basin is estimated at around 67 $\times 10^6$ t year^{-1} at Chiang Saen, 109 $\times 10^6$ t year^{-1} at Vientiane and 132 $\times 10^6$ t year^{-1} at Khone Falls.

Hården & Sundborg (1992) conducted a study in Laos and the northeast of Thailand on suspended sediment transport in the Mekong River network. They found that sediments vary very regularly with water discharge. At Luang Prabang, where heavy soil erosion occurs, the sub-catchments are mountainous areas with steep slopes. In a comparison between the suspended load at Chiang Saen and Mukdahan, Hården & Sundborg (1992) found that load values are lower at Mukdahan, indicating a dilution by less turbid water from the tributaries between the two locations. An interesting conclusion from their research is that no changes in sediment load with time were noticed in the upper parts of the river from the beginning of the 1960s until the year of their investigations, 1992. At Pakse, the published data indicated an increase in the sediment load of about 50% since the 1960s. This was attributed to the sediment inflow from tributaries in Laos.

The objective of this study is first to examine the integrative SWAT (Soil and Water Assessment Tool) model for simulating rainfall–runoff processes in a large-scale river basin, and second, to locate areas most prone to erosion in the Mekong Basin and to determine sediment loading in the river network. The paper also discusses the constraints that face the adoption of model results in basin planning when integrative models become the principal planning tool in the implementation of the Integrated Water Resources Management (IWRM) concept. In this context, the SWAT model can be regarded as a robust tool that assists planners to evaluate surface runoff from different agricultural and hydrological management practices.

THE HYDROLOGY OF THE MEKONG BASIN

The Mekong Basin covers an area of approximately 795 000 km^2 (Fig. 1). The basin consists of approximately 33% forests (ARCADIS, 2000). Compared to other major rivers of the world, the Mekong ranks 12th with respect to length (4880 km), 21st with respect to catchment area and 8th with respect to average annual runoff (475×10^9 m^3 $year^{-1}$ or 15 000 m^3 s^{-1}). The Mekong River flow at the Chinese border forms about 51% of the flow at Vientiane (Laos) and 16% of the flow at Kratie, which is the beginning of the lower flood plain. The wet season lasts from May to October, when the average rainfall reaches around 80–90% of the annual total. The dry season period begins in November and lasts until April. The minimum annual rainfall is 1000 mm $year^{-1}$ (northeast of Thailand) and the maximum is 4000 mm $year^{-1}$ (west of Vietnam).

The major water infrastructures in the basin are the dams, which were constructed over the last four decades in China, Laos, Vietnam and Thailand. In Cambodia and Vietnam the wetlands, Tonle Sap Lake and the numerous dykes, form the main water infrastructures that play a role, directly or indirectly, in the occurrence of floods and droughts in the basin. Major hydro-electric dams are planned and have already been constructed along the river course. In the lower flood plain in Cambodia, when the water level in the Mekong reduces and becomes lower than the level in the Great Lake, the flow in Tonle Sap then reverses, and starts flowing towards the Mekong River, replenishing its flow. The flow from the Tonle Sap continues until the end of the dry season when the water levels in both the Tonle Sap and the Mekong become more or less the same.

The diversion of water for agricultural purposes (shifting agriculture), may also have an impact. In recent years, the question has often been raised that the floods and droughts that occur in the Mekong Basin could be partially due to an increase in the

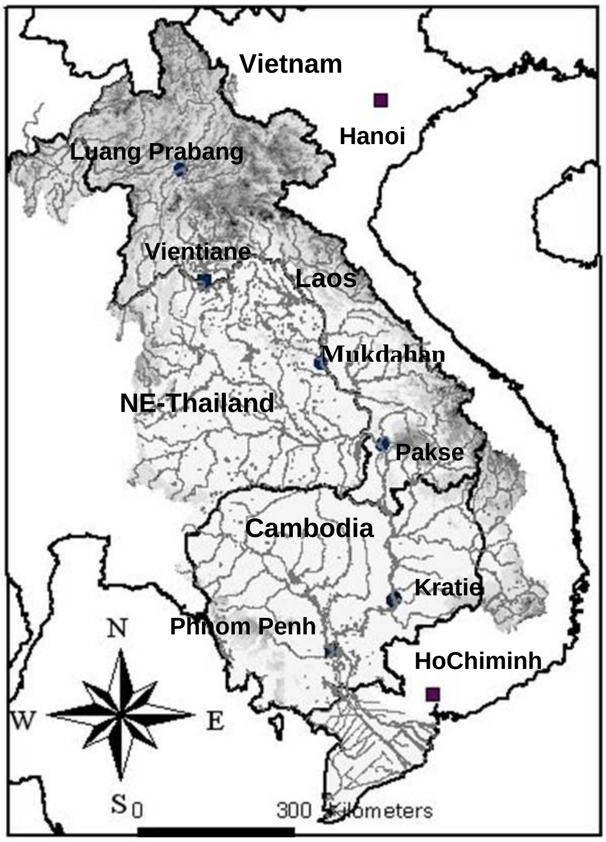


Fig. 1 The Mekong Basin.

deforestation rate, rather than being the result of natural climatic variability. Al-Soufi (2005) and Al-Soufi & Richey (2003) showed a clear downward trend in the river flow, particularly at Chiang Saen and Pakse stations. This cannot be attributed to global climatic changes since the rainfall does not indicate any corresponding down-trend. Moreover, it could further be concluded that, since the Mekong flow at Kratie showed rather a stable trend, the effect of low flow is diminished as the tributaries inflow to the Mekong over-compensate the decrease in flow at Pakse.

THE SOIL AND WATER ASSESSMENT TOOL (SWAT)

The Soil and Water Assessment Tool (SWAT) model was developed by the USDA-ARS (Arnold *et al.*, 1995) as a basin-scale model to simulate the impact of land management practices on the environmental-hydrological system over long periods. It consists of several modules that simulate varieties of agro-hydrological processes. The model can be considered as a pseudo-physically based model. The SWAT model includes GIS interfaces, weather generator and water management options. Runoff is simulated from daily rainfall series using the SCS curve number method and the Green and Ampt infiltration method. Water is routed through the channel network using the variable storage routing method or the well-known Muskingum routing method. The

SWAT model calculates soil erosion caused by rainfall–runoff processes using the Modified Universal Soil Loss Equation (MUSLE) presented by Williams (1975). The SWAT model requires a digital elevation model (DEM) from which it determines the drainage network and divides the basin into sub-basins, each of which is sub-divided into hydrological response units (HRU) that possess unique land-use and soil attributes. Detailed descriptions of all modules and the theoretical documentation can be found in Arnold *et al.* (1995) and in the model manual.

The modelled area and model adaptation

The study area comprises Laos, northeast Thailand and the upper part of Cambodia that is located in the central part of the Mekong Basin. Its height ranges from about 1200 to 20 m above mean sea level and it encompasses an area of 387 000 km^2. It extends north to Luang Prabang (Laos) and south to Phnom Penh (Cambodia). Luang Prabang station at the Mekong was selected as the inlet to the simulated area for the reason that hydrological data are available and relatively reliable. The study area, which consists of a mosaic of different land uses, is characterized predominantly by soils of the Acrisols association. These soils are mainly clay loam in the upper stratum to clay in the lower stratum and contain little organic matter. The land use is broadly classified into deciduous forest, mixed forest, evergreen forest, and agricultural land of two different categories. The identification of the extent of the study area as well as its boundary and the resolution of the grid system has been done using certain criteria. A full study has been conducted to derive soil physical parameters from the soil survey map of the basin, first deriving the sand, silt, clay, rock and organic matter components of each soil unit and then calculating the parameters using a computer program developed by the author. In determining those parameters, special attention was given to land use and land cover since the upper stratum of the soil profile has a great effect on the rainfall–runoff process. The soil parameters database has been derived and loaded into the SWAT model and can be regarded as the main factor behind the accuracy achieved in the current model application.

One of the major obstacles was to identify combinations of parameters required to operate the MUSLE module. In the absence of field investigations, careful examination of the soil map, DEM and land use were the only possibility to derive the parameters. Research papers and textbooks that provide values of parameters were also reviewed in this study. Information derived by SWAT from the DEM analyses was also helpful to calculate MUSLE parameters.

Hydraulic parameters were determined based upon a variety of information sources such as photographs, geomorphic characteristics of the Mekong River system at different locations, the profile of the river and land cover in the basin.

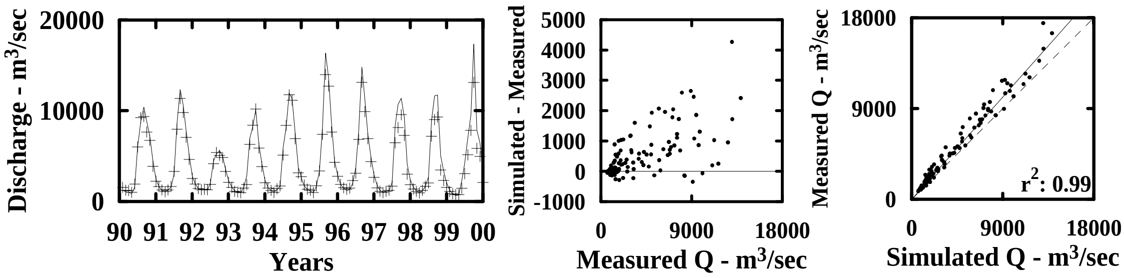
RESULTS AND CONCLUSIONS

The hydrological part of the model was first calibrated by using time series for 1990–1994, and then validated by using the records from 1995–1999. The calibration was only necessary to tune the hydraulic parameters required for operating the model. Soil parameters, as derived from the soil map, were not adjusted during the calibration process.

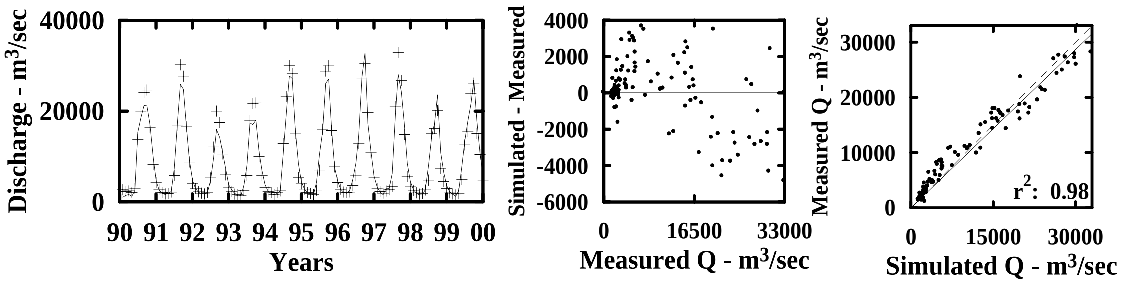
Flow during the flood season was dealt with carefully. Special attention was given to ensure the absence of negative outflows from channel reaches and to maintain numerical stability during the whole simulation period. Time series of the suspended sediments were re-constructed by utilizing the scattered field measurements of suspended sediments carried out between 1961 and the 1980s and by applying the regression equation that was developed by Hården & Sundborg (1992). Uncertainties in model simulation are expressed by the relative error (*RE*). In the light of data quality, the maximum allowable error (*RE*) was set to a threshold value of 15%.

Simulation results

Measured and predicted values of discharge are plotted in Fig. 2 (left side). Figure 2 (right side) visualizes how far the prediction is from the measurements. All points falling on the 45° line indicate perfect prediction capability. When data points in Fig. 2 were regressed, a fitting line (solid) was obtained with a coefficient of determination ranging from 0.99 to 0.98. At Vientiane the model is positively biased, as it tends to overestimate the discharges (Fig. 2, middle), whereas at Pakse the results are equally biased. In all cases, the SWAT has been shown to be incapable of simulating the peaks due to what are believed to be inaccurate discharge measurements during the flood seasons caused in some cases by the backwater flow effects. Accurate simulation of the baseflow was achieved indicating that the soil parameters were accurately derived.



Station: Vientiane



Station: Pakse

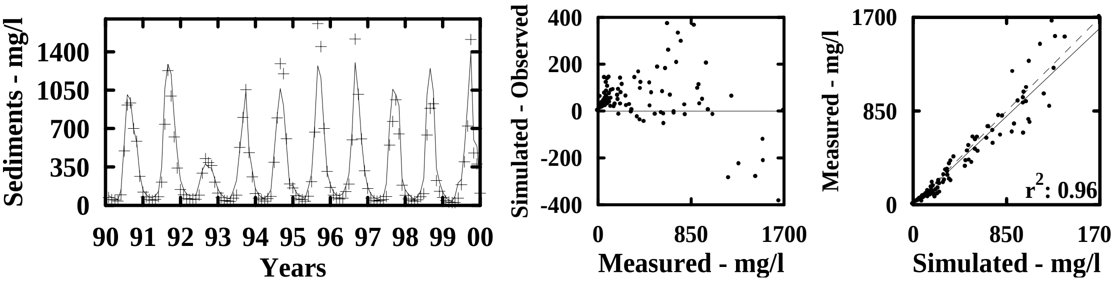
Fig. 2 Comparison between measured (crosses) and simulated river discharges at key stations along the River Mekong (left). Bias of the variance is shown in the middle. The deviation of the simulation from the optimum solution is shown on the right.

Table 1 Relative error (RE) in SWAT output. Values are for measured monthly averages during the 1990s.

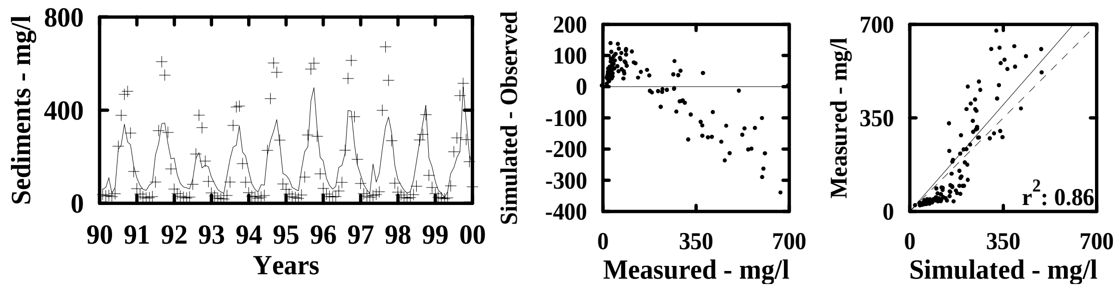
Location	Discharge ($m^3 s^{-1}$): Max	Min	*RE*%	Suspended sediments (mg L^{-1}): Max	Min	*RE*%
Vientiane	13986	756	13.5	1658	26	22
Mukdahan	26217	1343	14	515	57	21
Pakse	32941	1449	13	672	19	44

Table 1 lists values of the maximum and minimum observed monthly average discharge during the 1990s. The relative error (*RE*) values of the hydrological simulation obtained for the three benchmark stations were all below the threshold level of 15%. Errors can be minimized further by reducing the base cell size of the DEM theme and by reducing the "Threshold Area" required to define the beginning of a stream. The smaller the specified Threshold Area, the more detailed the drainage network delineated by the SWAT interface, which results in a longer computing time. The results show that the SWAT model has successfully simulated the hydrological behaviour of the Mekong Basin. The fact that the SWAT model uses the SCS Curve Number method, assumes runoff volume is independent of rainfall intensity, i.e. it is based on long duration storms, coincides with the conditions that prevail in the Mekong Basin.

Figure 3 shows the results of simulating sediment concentration in river water. The results are not as accurate as those of the hydrological simulation. At Pakse, the model is negatively biased for high concentrations and positively biased for low concentrations. The *RE* of the monthly averages of the predicted values ranges from 21% to



Station: Vientiane



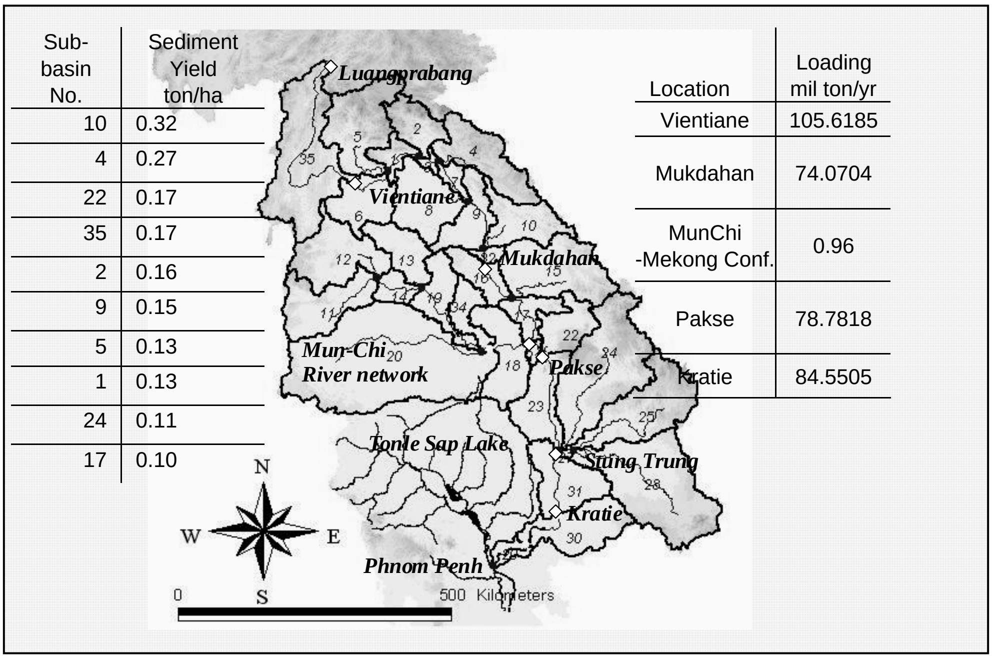
Station: Pakse

Fig. 3 Comparison between measured (crosses) and simulated suspended sediments in the Mekong River at two key stations. Bias of the variance is shown in the middle. The deviation of the simulation from the optimum solution is shown on the right.

44%. The *RE* at Vientiane and Mukdahan are slightly above the threshold level of 15%, whereas at Pakse, the *RE* is higher. The accuracy of the model to predict the actual value of sediment concentration is undermined by the fact that the regression coefficients presented by Hården & Sundborg (1992) were determined under different agro-hydrological conditions and need to be modified accordingly. Hården & Sundborg (1992) indicated an increase of sediment inflow at Pakse since the 1960s and pointed out no indications of changes in sediment loads with time in the upper parts of the basin from the beginning of the 1960s until the 1990s. This may explain the high simulation errors obtained at Pakse compared to those at Vientiane and Mukdahan.

The suspended sediment concentrations are high during the first heavy rains of the season (up to 1000 mg L^{-1}) and gradually decrease to the minimum of less than 10 mg L^{-1} in the dry season. At Mukdahan and Pakse, the load values are lower indicating a dilution by less turbid water from the tributaries. The SWAT model also estimated the average annual loading of the suspended sediments during the 1990s at key locations along the Mekong River (Fig. 4). The patterns of sediment loading are approximately similar to the figures presented by Kelin & Chun (1999) and slightly less than those of Pantulu (1986). However, field investigations are necessary to determine the parameters that operate the MUSLE equation in order to achieve an accurate simulation of sediment transport in the basin.

The results in Fig. 4 show that the east and north of Laos both have the highest rates of sediment yield, ranging from a monthly average of 0.32 to 0.1 t ha^{-1}. The sub-catchments are mountainous with steep slopes classified as mainly forest-mixed/deciduous with some scattered evergreen forests and agricultural/grass land. In north-east Thailand, where many irrigation schemes were developed, the majority of the predicted average monthly sediment yield was in the range 0.003–0.02 t ha^{-1}.



Sub-basin No.	Sediment Yield ton/ha
10	0.32
4	0.27
22	0.17
35	0.17
2	0.16
9	0.15
5	0.13
1	0.13
24	0.11
17	0.10

Location	Loading mil ton/yr
Vientiane	105.6185
Mukdahan	74.0704
MunChi -Mekong Conf.	0.96
Pakse	78.7818
Kratie	84.5505

Fig. 4 The modelled part of the Mekong Basin. The table on the left shows the top 10 sub-basins that have the highest sediment yields and the table to the right shows loading of suspended sediments at key locations.

It is necessary to highlight that, despite the fact that data availability is a common constraint in river basin modelling, the SWAT model visualizes sediment yield from the sub-basins relative to one another, which is useful to zone the critical areas most vulnerable to soil erosion. In order to determine the impact of land-use changes on soil erosion and river flow, the model is being prepared to be loaded with updated land cover data. The results will then serve as guidelines for establishing an effective river basin management plan.

Critical review of the role of integrative models in the policy making process

The SWAT model is a robust integrative model that couples many essential environmental-hydrological processes. However, determination of the various parameters and the correct set-up of the model, as with other integrative models in general, are crucial, but in many cases the results are difficult to validate and subsequently are not acknowledged by policy makers. On the other hand, integrating modelling results with other developing issues in the implementation of the IWRM concept remains a dilemma. The term Integrated Water Resources Management has been introduced to ensure the co-ordinated development and management of water, land and related resources by maximizing economic and social welfare without compromising the sustainability of vital environmental ecosystems. In recent years, several international institutions have emphasized the adoption of the IWRM concept in order to achieve the sustainable use of natural resources. Consequently, millions of dollars provided by donors have been spent and yet natural resources are depleting and the concept of “sustainability” cannot be recognized in many parts of the world. The main reason behind our failure to implement IWRM and “the underdevelopment” of sustainability of natural resources is the lack of communication between policy makers, “implementers” and academics. Moreover, the academic community is not working in an interactive manner. Kirshen *et al.* (2004) attributed the commonly inadequate implementation of the IWRM concept to the fact that the planning process known as “integrated and multidisciplinary”, involves people working independently from their disciplinary perspectives and, only at later stages, attempting to integrate the results.

As an example, the supply of water, whether for drinking or irrigation, the disposal of polluted water and the management of surface waters are some of the essential tasks that have to be considered in the adoption of the concept of sustainable development. From these essential tasks, human responses and demands emerge but unfortunately they have been forgotten by both water engineers and ecologists. The interaction between the components of water, soil, socio-economy and ecology is not easy to handle. These components have usually been treated as independent and managed by different agencies or experts of different academic backgrounds. For example, water has always been viewed as a commodity by policy makers, whereas water quality and management have been viewed by academics as issues that have great impact on the environment. Unfortunately, this way of thinking still exists and has played a role in widening the gap between policy makers and scientists. A different approach is therefore needed, in which river sub-basins are classified into categories of different qualities for different uses coupled with a comprehensive assessment of human needs/actions and their impacts on the ecosystem. This will eventually provide a variety of policy options that allow policy makers to choose the one that exerts the lowest impact on the ecosystem. Admittedly, such a planning scheme is not an easy one and requires advanced planning tools managed and run by qualified multi-disciplinary professionals. What is needed therefore is the implementation of a holistic approach, which includes an evaluation of human activities and the driving forces that exert pressures on the ecology of the river basin. It is necessary to examine carefully the social "responses" and policy makers' desire to develop their countries before addressing a specific plan to control human activities in the basin. Such a paradigm will help to improve understanding of the richness of social practices in policy making. A good understanding of the qualities of the environmental-hydrological system is required prior to attempting to explain, predict, or modify it. Therefore, instead of adopting a standardized "narrow minded" academic approach, it is recommended that maximum flexibility should inform the judgments made about the policy making process in the area. Bearing in mind that one should not assume a world of uniformity, instead, the IWRM concept should be designated to operate within a world of complexity, prepared for compromise in order to achieve the objectives required.

FINAL REMARKS

The SWAT model as an integrative planning tool can be useful in a wide range of studies, particularly for monitoring the deterioration in river basin health and in calculating the amount of sediments and surface applied chemicals that are washed out annually from agricultural fields. The challenge to the meaningful use of integrative models for the correct implementation of the IWRM concept is how to incorporate feedbacks from the environmental-hydrological models with the human dimensions. It will be necessary to develop sub-models that explore the socio-economic consequences of the biophysical dynamic changes in a region. Once such knowledge is developed, it would need to be integrated dynamically within the environmental-hydrological modelling system of the basin. The model output must be interpreted wisely in order to assist riparian policy makers to re-evaluate or re-shape their decisions and to provide the feedback to the technical staff to run their analyses in an iterative manner until the right policy option is reached. The conclusion provided by all individuals who participate in this proposed exercise is the primary source of knowledge for the correct implementation of the IWRM concept and the learning procedure itself occurs through the incremental adjustments of decisions and actions. It is therefore necessary to view the IWRM concept as an endless process of modelling of the type whose parameters are modified subject to the changes in the quality of human induced impact on the hydrological system.

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