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Analysis of Water Resource Allocation and Water Quality for Low Flow River in Mediterranean Watershed: Hydrological Simulation Model Overview

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Abstract: Global change impacts on water availability, water quality and ecosystem services in Mediterranean river basins of the Iberian Peninsula, as well as their impacts on the human society and economy makes it a key issue on the EU agenda. It is likely that Mediterranean countries could suffer ever-more frequent regional water shortages due to the twin problems of climate change and rising demand. Simulation with hydrological model provides insight into the nature and structure of connections between water resources and socio-economic and environmental changes. The general aim of this study is to provide a better overall understanding of water scarcity and results of loss of quality in low flow rivers by developing hydrological model under data-scarce conditions using DHIs' software MIKE BASIN. The simulated effects of a new water stress definition will incorporate both water quality and water quantity effects into the measurement of water scarcity. Moreover the proper allocation of water for an industrial, domestic and agricultural sector gets inevitable in the situation of water scarcity otherwise it would impose severe burdens on the economy as well as on the environment. The Catalan basin of Francolí (NE Spain) is selected for such purpose. The results obtained from this model will be helpful in the description and quantification of the bio-physical and socio-economic components of the watershed. Individual future objectives will cover the analysis of the river basin with respect to characteristics of the water bodies, impact assessments for human activities and economic analysis to achieve good water status for all waters to comply with European water framework directive for River Basin Management Plan. Watershed characteristics extracted from these simulated results would be helpful in the future to develop a DSS for water resource management and policy development for low flow river basins.

Keywords: water scarcity; MIKE BASIN; low flow; water allocation; water quality.

1   INTRODUCTION

Many Mediterranean catchments are currently water-stressed, if the per capita water availability or the ratio of withdrawals to annual runoff is considered. Anticipated amounts in the near future further threaten this precarious situation and it is required to protect rivers from degradation caused by hydrological conditions (Cui et al., 2010). However, the water demand is increasing whereas water resources are expected to decrease because of climate warming and the same or decreasing precipitation (Bates et al., 2008). The allocation of water resources in the river basin is one of the critical issues. An integrated analysis at basin-scale is important, where individual water related sectors, such as agriculture, municipal, and industrial water supply are brought together in a framework for an integrated analysis (Jha and Gupta, 2003).

The importance of receiving water body quality is addressed in the EU Water Framework Directive 60/2000, which proposes a water-quality oriented view of entire watershed systems (Chave, 2001). Reliable model calibration requires an extensive array of water quality data collection that are generally rare and resource-intensive, economically as well as in terms of human resources. In the case of small rivers, such data are scarce due to the fact that these rivers are generally considered too insignificant, from a practical and economic viewpoint, to justify the investment of such considerable time and resources (Mannina and Viviani, 2010).

The natural factors which influence the various aspects of the low-flow regime of the river include the distribution and infiltration characteristics of soils, the hydraulic characteristics and extent of the aquifers, the rate, frequency and amount of recharge, the evapotranspiration rates from the basin, distribution of vegetation types, topography and climate (Smakhtin, 2001). Mathematical models, like MIKE BASIN, have been used in several studies around the world for the catchment scale analyses of water availability and water allocation but for high flow rivers only. The simulation model MIKE BASIN shows its usefulness in analyzing the high flow river basin performance and thus establishing the best management approaches for the efficient use and allocation of water resources. For example, the model was applied in the Mun River Basin of Northeast Thailand (Jha and Gupta, 2003). Idaho Department of Water Resources (IDWR) United States had also developed a surface water budget model for Lemhi River Basin using MIKE BASIN. However, this model needs to be assessed for its applicability to low flow rivers considering all aspects of low flow regime. Moreover to quantify the water distribution to different sectors is inevitable under water stress conditions.

The aim of this study was to investigate the use of hydrological modeling software for water resource allocation and water quality simulation in low flow river. This study will be helpful to propose tools that could be used to support decision-making required for conformity with the EU Water Framework Directive (WFD). Analysis to opt for the appropriate model for our study that provides the best fit to the available data, MIKE BASIN is selected. Based on ArcGIS, MIKE BASIN is applied to the low flow Francolí River basin located NE of Spain. The special features of the model take account of watershed delineation, priority-based allocation principles, water supply and irrigation allocation, low flow controls and river routing in GIS interface. Moreover, in-built NAM rainfall-runoff model generates the sub-watershed (input of MIKE BASIN) runoff based on meteorological data, surface root zone and groundwater parameters. The classification as 'unsatisfactory' of one-third of data sets in two major water balance modelling studies is evidence that more attention to the quality of input data is needed (Boughton, 2009). Another purpose of this study is to gain insight into the effectiveness of MIKE BASIN as an integrated water resource model for low flow rivers, and explain it in terms of instrument's strengths and weaknesses.

2   METHODS

2.1   MIKE BASIN Overview

Integrating GIS and catchment models provide a tool to support integrated catchment management, defined as the co-ordinated planning and management of land, water and other environmental resources for their equitable, efficient and sustainable use at the catchment scale (Bathchelor, 1999). MIKE BASIN is an integrated water resource management and planning computer model that integrates GIS with water resource modelling (DHI, 2006). It is a mathematical representation basin scale simulation model that accommodates a basin-wide representation of water availability and water demand. Rivers and their main tributaries are represented by a network consisting of branches and nodes in the model. The branches represent individual tributary sections while the nodes represent confluence, locations where certain water activities may occur and important locations where model results are required. Technically, it is a quasi-steady-state mass balance model, however allowing for routed river flows and address multisectoral allocation and environmental issues in a river basin.

The model requires the entire catchment to be segmented into a series of subcatchments. The individual subcatchments are assumed to demonstrate relatively homogenous hydrologic and water quality behavior. It provides the basis for assigning identical inputs and/or parameter values to the whole of the land area or channel length contained within a model sub-catchment. River flow is the result of the complex natural processes, which operate on a catchment scale. Conceptually, a river catchment can be perceived as a series of interlinked reservoirs, each of which has components of recharge, storage and discharge. (Smakhtin, 2000).
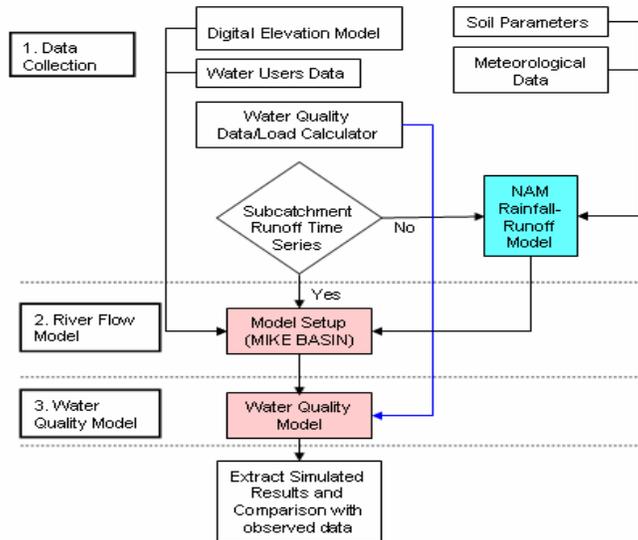
Figure 1. An integrated framework for watershed hydrological and water quality modelling with MIKE BASIN.

The soil parameters (surface root zone and groundwater storage zone) are introduced to analyse the components of recharge, storage and discharge. Figure 1 displays an integrated framework of the MIKE BASIN simulation procedure. The input data required for river flow simulation include: Digital Elevation Model (DEM), water users' data and sub-catchment runoff. The simulation time depends on the spatial resolution of DEM, the finer the spatial resolution, the shorter the time step, and the more time required to run the simulation. Individual water related sectors, such as agriculture, municipal, and industrial water supply are brought together in a

framework of an integrated analysis. The first priority of water withdrawal is set to water supply and second to irrigation. But the prioritization criteria vary place to place. All these sectors are presented in the basin by water withdrawal time series from surface and groundwater sources. However, it is rare to find historical runoff time series of all the subcatchments in a low flow river basin. A built in rainfall-runoff model in MIKE BASIN eases the process to attain such runoff time series by providing soil parameters (Table 1), meteorological time series as input data and manning's n roughness values (Fisher and Dawson, 2003).

The Load Calculator Module in the MIKE BASIN model is used to calculate average mass fluxes of pollutants for individual subcatchments (e.g. kg/ catchment/year). The Load Calculator is a convenient pre-processing tool that generates boundary conditions for the entire model, taking advantage of existing related GIS data (land use, population, etc) (DHI, 2006). These estimates are then passed to MIKE BASIN water quality model for approximate pollution loadings within the entire river basin. The Load Calculator take account of all point and non-point source contributions. Each sub-catchment tends to simulate separate hydrologic and water quality conditions in response to different driving forces. Specific routing approaches are defined (e.g. linear, Muskingum, wave translation) in individual reaches, such that the residence time and the effects of mixing between reach storage and inflows can be properly specified in the model.

Hydrologic records often do not cover the entire period of time for which a simulation is desired, resulting in a data shortage problem. At the same time, many hydrologic processes are cyclical with a period of one year. Hence, one can 'borrow' missing data from equivalent periods in other years for which data are available. In MIKE BASIN, this otherwise laborious task is performed automatically. It is referred to as 'recycling' and concerns all time series (DHI, 2006). The majority of the input data used are introduced as daily time series of historical records. Some of the collected data found as monthly time series and converted to daily time series using MIKE BASIN's conversion tool. Moreover, literature records are also very helpful to develop time series and represent meteorological situation of a river basin.

The results of water flow simulation and water quality simulation obtained in form of time series and compared with the observed data for calibration purpose.

2.2 NAM Rainfall-Runoff Overview

The NAM model is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in up to three different storages representing the surface zone, root zone and the groundwater storages (DHI, 2006). The basic input requirements for the NAM model consist of model parameters (surface root zone and groundwater zone), initial conditions and meteorological data. The basic meteorological data requirements are rainfall and potential evapotranspiration. That reproduces the effect of land-surface heterogeneity on circulation as imposed by such water balance model (D'Almeida et al., 2006). Subcatchment runoff time series obtained from NAM rainfall-runoff simulation are assigned to MIKE BASIN river model as input data.

3 FRANCOLÍ BASIN APPLICATION

3.1 Francolí River Basin

The low flow Francolí River is located in NE Spain and flows to the Mediterranean Sea. The total length of the Francolí River including main tributaries is about 109 km and constitutes approximately 855 km^2 catchment area. Length of the tributaries is in the range of 0.3 km to 11 km. The river basin has been under

considerable pressure for water availability and water quality over the last decades due to the population growth, climate change and increased demand in cities like Montblanc, La Riba and Tarragona. The main Francolí River is flowing through coastal mountains range and passing by Montblanc, La Riba, Tarragona and finally leads to west of the port of Tarragona (Figure 2).

Tarragona, located at the mouth of the Francolí River was solely dependent on groundwater and surface water from River Francolí before 1988. Sea water intrusion in the groundwater aquifers made the municipality dependent on inter-basin water supply schemes. Moreover, most of the industries in Francolí River basin are located close to Tarragona including a petrochemical industry and many other small industries are situated in neighbouring municipalities. The agriculture demand varies all along the river network depending on the crop type and cultivated area.
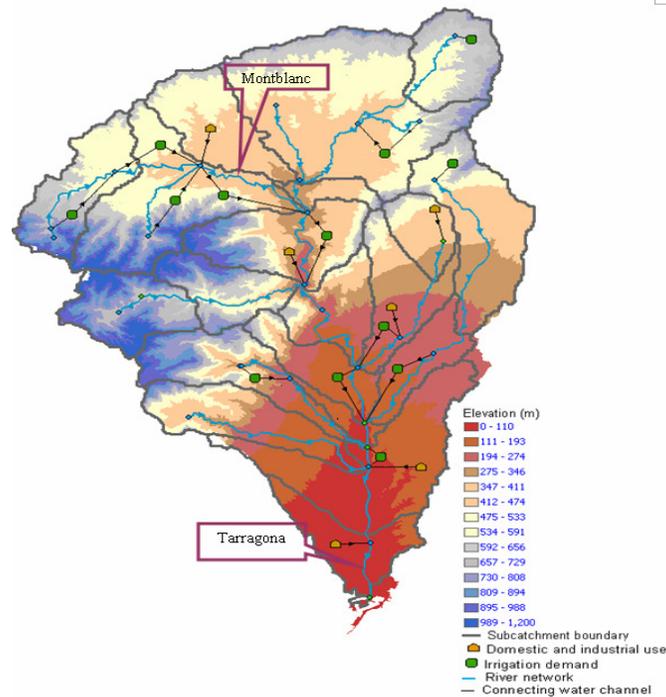
Figure 2. The Francolí MIKE BASIN model network, Digital Elevation Model (DEM) and subcatchments of Francolí River Basin

The lower reaches of the river run dry for much of the summer in low flow years due to minimal inflows from headwater areas and high temperature. Water management along the Francolí River basin is complex because the basin has a Mediterranean environment and there is a limited supply of water to satisfy the demand of all the sectors and environmental needs. Very less gauging stations for flow records and meteorological information are the limitations to develop a model for this river basin.

3.2   Francolí Rainfall-Runoff Model (NAM)

The NAM model for River Francolí was developed with several parameters specified for each representative subcatchment. The main input data required are precipitation, evapotranspiration and NAM parameters. Different parameter values are used for different sub-catchments, taken from the literature and observed data (Table 1).

Table 1. Main NAM parameters.

Zone	Symbol	Definition	Range of Values
Surface-Rootzone	Umax	Maximum water content in surface storage	10 – 20 mm
	Lmax	Max water content in root zone storage	50 – 300 mm
	CQOF	Overland flow runoff coefficient	0.0 – 1.0
	CKIF	Time constant for interflow	500 – 1000 hrs
	CK1_2	Time constant for routing overland flow	3 – 48 hrs
	TOF	Root zone threshold value for overland flow	0 – 0.99
	TIF	Root zone threshold value for inter flow	L/Lmax
Ground-Water	TG	Root zone threshold value for groundwater recharge	0 – 0.99
	C_{area}	Ratio of groundwater catchment to topographical (surface water) catchment area	1.0
	Sy	Specific yield for the groundwater storage	Clay (0.01– 0.10) and Sand (0.10 – 0.30)

The NAM model was prepared with the input of surface root zone and groundwater parameters. Initial values of overland flow, interflow, base flow and groundwater are also specified for each of the MIKE BASIN sub-catchment that required rainfall-runoff modelling. The type of model selected for simulation is NAM RR, 2-Layer GW, which considers both shallow as well as deep aquifers.

Rainfall was applied to sub-catchments using weighted average rainfall data acquired from the Catalan Water Agency (ACA). As the available data tends to vary less between sub-catchments, rainfall time series data were applied to adjacent sub-catchments using data from the gauging station nearest to the sub-catchment.

3.3   Francolí river flow and water quality model (MIKE BASIN)

In this study distributed physically-based MIKE BASIN hydrological model was used to assess the water allocation to different sectors and water quality in low flow Francolí River watershed.

A Digital Elevation Model (DEM) of highest available resolution of 30 m x 30 m is used to provide an appropriate resolution of elevation data over the entire catchment. The higher resolution DEM represents the watershed of small rivers more accurately as compared to lower resolution DEM. Moreover, DEM was useful to delineate river network and its tributaries (Figure 2). Sub-catchment runoff time series data simulated by NAM are associated with the representative subcatchments. Similar to many other hydrologic models, MIKE BASIN requires the entire watershed to be segmented into a series of sub-catchments. The individual sub-catchments are assumed to demonstrate relatively homogenous hydrologic/hydraulic behavior. Hydrological data and water demand data are the major model inputs while output includes the magnitude and frequency of any water shortages as well as simulated time-series of flows at all nodes, providing information on the performance of each sub-catchment. Water demand data (domestic, industrial and agricultural water consumption) are provided by Catalan Water Agency (ACA).

In order to better understand and manage water resources within the Francolí River Basin, we used GIS to assist with prioritizing watersheds while MIKE BASIN is

being used to understand water allocation in river basins and evaluate watershed priorities and develop new water transactions in sub catchments.

Water user's data (domestic, industrial and agricultural water consumption) were converted to daily time series followed by allocating it to the respective water user nodes. At least 2 time series are required for conversion in MIKE BASIN, one reference time series containing daily values of neighboring sub-catchment, and one or more monthly time series that will be converted to daily values. Input time series with non-monthly time step, instantaneous value type, or variable types that differ from the daily reference time series will not be converted. Most of the data was generated from accumulated data provided by Catalan Water Agency (ACA).The total number of river nodes is 23, and water user's nodes are added to the network according to real location. The model simulates the performance of the overall system by applying a water mass balance method at every node. The simulation takes into account the water allocation to multiple usages from individual extraction points throughout the system. Groundwater abstraction is usually for public water supply and Irrigation (fruit trees, olives, vines and citrus).

MIKE BASIN simulated water quality in surface and groundwater, with solute inputs from non-point and/or point sources (from wastewater treatment plants WWTP) followed by reactive steady-state simulation and transport of these substances. In general, first-order rate laws are assumed for all default substances predefined in the model including ammonium-nitrogen, nitrate-nitrogen, DO, BOD, total phosphorous and E-coli, and the steady state approach is consistent with MIKE BASIN's solution to the water allocation problem.

To measure the model performance, the coefficient of efficiency, R^2 (Nash and Shutcliff, 1970) is applied. Surface-root zone parameters are used for the calibration of lower Francolí river flow.

4   PRILIMINARY RESULTS

The surface flow in the entire Francolí river basin reaches to 0 m^3/sec during the dry season, thus encouraging water abstraction from deep aquifers. The wet season water availability is higher and a significant amount of water can be preserved for dry season, whereas dry season water availability is very low and cannot satisfy even a very low demand. MIKE BASIN model of Francolí River Basin considered all the water allocation sectors in calculations and the remaining unallocated water flows to the main river. This unallocated water flow is found higher in wet season as compared to flow in dry season (Figure 3).
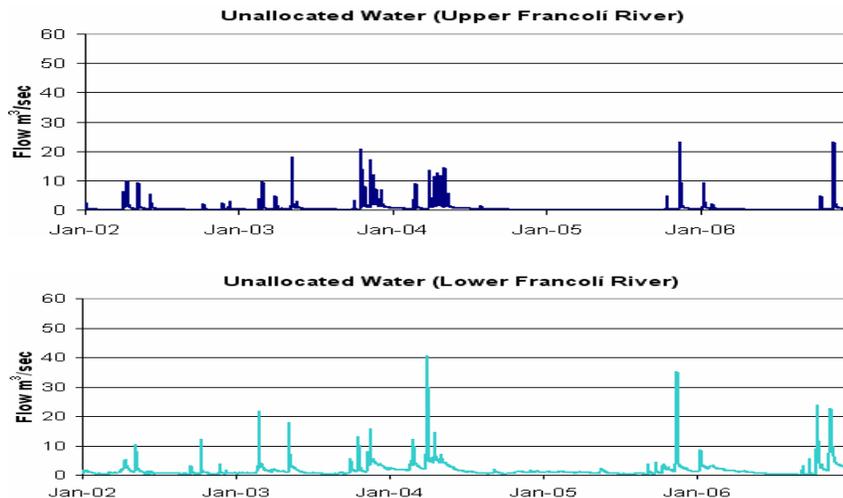
Figure 3 Unallocated water in Francolí River

The variations of water quality in the Francolí River basin are characterized based on the model simulation results. Seasonal flow causes short-term deterioration of surface water bodies because the emission from WWTP tends to be higher in the summer than in the winter.

The groundwater – surface water interplay and the temporal nature of water demands also lend complexity to the Francolí River system. Irrigation water causes groundwater levels to rise seasonally. This shallow groundwater storage is slowly released back to the Francolí River which sustains stream flows for couple of months later. Excess and quick percolation to the groundwater aquifers is one of the major reasons of low flow in Francolí River. About 70% of the water demand is allowed to abstract from groundwater aquifers. The amount of water and seasonal usage patterns vary among types of agricultural use, industry and population. And the total demand is higher at the lower part of the river as compared to the upper part. Importance of the interrelationship between surface water and groundwater bodies is often disregarded, although it is mainly relevant during dry seasons when groundwater is the only source for river flow.

The tendency that the model performances for the lower part of Francolí river is significantly higher, with the $R^2 = 0.75$, than expected for the data scarce river. The special features of the model take account of watershed delineation, priority-based allocation principles, water supply and irrigation allocation, low flow controls and river routing in GIS interface. Moreover, in-built NAM rainfall-runoff model generates the watershed runoff based on meteorological data, surface root zone and groundwater zone parameters. However, there are certain limitations such as it is incapable of simulation of erosion/sediment transport. Moreover, in water quality model, advection cannot be modelled properly, so that pulses of solute entering the stream do not travel downstream as simulation time advances.

Moreover, the model is not well documented for the equations and methods it uses in flow and water quality modelling, making its interpretation difficult at times.

5   CONCLUSIONS AND FUTURE WORK

This paper illustrates the application of a basin-scale simulation model MIKE BASIN integrated with ArcGIS and shows its efficacy in analyzing a low flow river basin. Moreover, it helps in establishing the best management approaches for the efficient use and allocation of water resources to different sectors. The model was applied in the low-flow Francolí River Basin located in NE Spain. The missing input data was regenerated from neighboring sub-catchment data. But the trend of simulated flow hydrographs and observed hydrographs at river nodes is found similar. NAM rainfall-runoff model (inside MIKE BSIN) is found helpful tool to calculate runoff of each and every sub-catchment. Based on the results, possibilities of new storage schemes or artificial aquifer recharge should be considered to store the excess wet season water and increase dry season reliability.

The water scarcity caused by global change is apparent in many Mediterranean watersheds. In the further studies, it is insight to analyze the emerging interactions of low-flow hydrological simulation results with other water related fields to comply with European Water Framework Directive (WFD) (EC, 2000) to achieve good water status for all waters by implementing River Basin Management Plan.

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