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Hydrological Modeling of Upper Indus Basin and Assessment of Deltaic Ecology

A. D. Khan[1], Shimaa Ghoraba[2], Jeff G. Arnold[3] , Mauro Di Luzio[4]

[1]*Director (GIS & Modeling), Pakistan Council of Research in Water Resources, Islamabad, Pakistan.*
[2]*Irrigation and Hydraulic Engineering Department, Faculty of Engineering, Tanta University, Egypt.*
[3]*Grassland Soil and Water Research Laboratory, United States Department of Agriculture, Temple Texas, USA*
[4]*Texas Agricultural Experiment Station, Blackland Research Center, Texas, USA*

ABSTRACT : *Managing water resources is mostly required at watershed scale where the complex hydrology processes and interactions linking land surface, climatic factors and human activities can be studied. Geographical Information System based watershed model; Soil and Water Assessment Tool (SWAT) is applied for study of hydrology of Upper Indus River Basin and assessment the impact of dry periods on environmental flow. The model is calibrated at two stations on Indus and Kabul Rivers. Climatic data of 22 weather stations falling in Pakistan, India, China and Afghanistan has been used for simulation period of 11 years (1994-2004). The model calibration for various water balance components yielded good agreement as indicated by coefficient of determination and Nash-Sutcliffe efficiency. The model output is for analysis of environmental flow in lower reaches and assessment of the Indus Delta ecohydrology. Results revealed that SWAT model can be used efficiently in semi-arid regions to support water management policies.*

Keywords: *Indus watershed modeling, hydrology, environmental flows, deltaic ecosystem, Indus Basin irrigation system, SWAT.*

I. INTRODUCTION

Indus is a Tran- boundary river with its catchment falling in Afghanistan, Pakistan, China and India. It has the length of about 2748 Kms and its system is the prime source of water in water resource of Pakistan. Inflow to the Indus River system is derived from snow, glacier melt and rainfall upstream of the Indus Plain. The upper part of the Indus basin consists of glaciated mountains which receive snowfall in the winter season. The mountains with unbroken snow cover became the primary source of water for Indus [1]. Hydrologic impacts in the upper basin depend to a large extend upon climate change which has its effect on seasonal inflows and the peak discharges at the main rivers in the Indus River System.

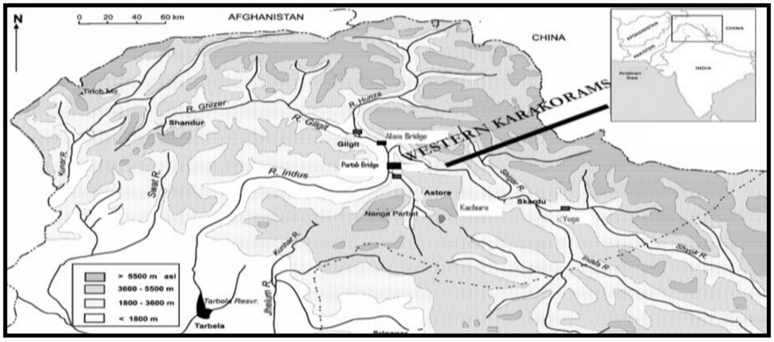
The Indus basin has a total drainage area of 364,700 square miles, some 60 percent of which lies in Pakistan [2]. The Indus River and its tributaries rise in the sparsely populated glaciated mountains of western and central Asia. The Indus River itself contributes more than half the total flow and has a controlling storage at Tarbela Dam as the river emerges from the mountains [3]. The mountainous upper basin is influenced by continental climates of central Asia which have a westerlies pattern of circulation, late winter snowfalls, cold winters and short warm summer [4] This regional climatic pattern becomes highly complex within the high mountain renges of Indus basin watershed.

The water quality of Indus River and its tributaries is generally considered excellent for irrigation purposes. The total dissolved solids range from 60 mg/l in the upper reaches to 375 mg/l in the lower reaches of the Indus, which are at reasonable levels for irrigated agriculture and also as raw water for domestic use [5] . Sedimentation data collected by Water and Power Development Authority (WAPDA)[6] at 50 stations on River Indus revealed that the Indus and its tributaries carry about 0.135 Billion Cubic Meters (BCM) of sediment annually. Of this, nearly 60% remains in the system where it deposits in the reservoirs, canals, and irrigation fields. Annual silt clearance is undertaken in the canal systems to remove the deposited silt.

The main user of Indus River flows is Indus Basin Irrigation System (IBIS). The IBIS has been developed over the last 140 years [7]. This system comprises three western rivers, namely the Indus, the Jhelum and the Chenab, four reservoirs (Warsak, Tarbela, Mangla and Chashma), 23 diversion structures (barrages, headwork’s and siphons), 12 inter-river link canals, and 45 canal commands. The length of the main irrigation canals is 61,000 km in addition to the 1.6 million km of 100,000 watercourses. This system irrigates brings in about 195 BCM of water and irrigates about 18 million hectares of land in Indus Basin.

The objective of this study is to model the hydrology of Upper Indus Basin for development and management of water resources for irrigation and hydropower generation and study of ecohydrology in Indus Delta, Fig.(1). It also provides a baseline for study of climate changes and variability on various components of water balance, irrigated agriculture and environmental flow.

Figure 1: Location map of upper Indus River Basin



II. LITERATURE REVIEW

Watershed models simulate natural processes of the flow of water, sediment, chemicals, nutrients, and microbial organisms within watersheds, as well as quantify the impact of human activities on these processes. Simulation of these processes plays a fundamental role in addressing a range of water resources, environmental, and social problems [8]. Many models were developed for watershed hydrology but the availability of temporally and spatially data was the main constraint hindering the implementation of these models especially in developing countries [9]. Indus Basin is one of the World’s well documented river basins. Modern age research and development activities are extending over one. These research activities included filed and laboratory experimentation on irrigation and drainage, soil and water salinity, hydrology, water resources management and related agri- socio-economic disciplines. Modeling of water system started during late sixties and some of initial models were physical and prototype in nature. Short-term forecasting of river inflows was conducted by the Water & Power Development Authority (WAPDA) through lumped and semi-distributed models like the University of British Columbia Watershed Model (UBC) [10]. The output of this UBC model was taken as input to MODSIM for simulation of irrigation network in Indus Irrigation System [11]. The MODSIM simulations were made for hydrological studies and then impact assessment studies for the climate changes on water resources. Adaptation strategies were also proposed in this study. Another comprehensive model; applied in Indus Basin was; .Indus Basin Model Revised (IBMR). This model addressed almost all important parameters; hydrology, cropping, economic, etc. All these models are lumped type hydrologic simulation models which are unable to represent the spatial variability of hydrologic processes and catchment parameters [12]. Therefore distributed models are now being applied in Indus Basin to assess the spatial variability of various watershed parameters. At 2013, a Distributed Hydrology Soil Vegetation Model (DHSVM) is applied in Sirn River (a tributary of Indus) by Winston [13] to predict the effects of land use change on the water resources.

For this case study, the soil and water assessment tool (SWAT) was chosen because it includes many useful components and functions for simulating the water balance components and the other watershed processes. SWAT is a distributed hydrological model which is developed by United State Department of Agriculture, Agricultural Research Services (USAD, ARS)[14] . The AVSWAT (Arc View- SWAT) provides an efficient preprocessor interface and postprocessor of SWAT model. AVSWAT is implemented within Arc View 3.x GIS and distributed as an extension of this software. A brief introduction to the SWAT model, AVSWAT and its illustrative application to the Upper North Bosque river watershed was discussed by Di Luzio[15]. SWAT model has an efficiency and reliability which confirmed in several areas around the world. It was tested and used in many regions of Africa by Shimelis [16], Asharge [17], and Fadil [18] and Asian Monsoon zone by Cindy [19].

III. MATERIAL AND METHODS

A GIS based watershed model; Soil and Water Assessment Tool (SWAT) is applied for study of hydrology of upper Indus River Basin (UIB). The methodologies used for this study include a description of hydrological model and the special dataset which used in the simulation. The details are given in the following sections.

3.1. Description of the Study Area

The Indus River and its tributaries, the Jhelum, Chenab, and Sutlej rivers originate in the mountain headwaters of the Karakoram Himalaya, western Himalaya, and Hindu Kush Mountains which are located at the central Asia. The Upper Indus Basin (UIB) extends from the Tibetan Plateau to northeast Afghanistan, Fig.(1). It is considered to be the glacierized catchment basins of the Mountains. The main rivers are Indus River (3180km), and its Tributaries from the western Himalaya are the Jhelum, Chenab, Ravi, and Sutlez Rivers, from the Indian states of Jammu Kashmir and Himachal Pradesh, and the Kabul, Swat, and Chitral Rivers from the Hindu Kush Mountains. The ultimate source of the Indus is in Tibetan Plateau in China; it begins at the confluence of the Sengge and Gar rivers that drain the Nganglong Kangri and Gangdise Shan mountain ranges. The total surface area of the (UIB) is approximately 220,000 km^2 without Tibetan Plateau′s rivers basin. Of this surface area, more than 60,000 km^2 is above 5000 m, the estimated mean altitude of the summer season freezing level.

The glaciers of the region flowing outward from this zone have been estimated to have a surface area of approximately 20,000 km^2, of which 7,000–8,000 km^2 is below the summer-season freezing level [13]. Winter precipitation is a principal sources of runoff from the UIB as snow that melts the following summer and glacier melt. Climatic variables are strongly influenced by altitude. Northern valley floors are arid with annual precipitation from 100 to 200 mm. Totals increase to 600 mm at 4400 m, and glaciological studies suggest accumulation rates of 1500 to 2000 mm at 5500 m [20]. Regression analysis of seasonal and annual temperatures of nine karakoram stations ranging in elevation from 1000 to 4700m give correlation coefficients greater than 0.98 and lapse rate ranging from 0.65 to 0.75° C/100 m [21]. Analysis of relationships between seasonal climate and runoff by Archer [22] suggested that the UIB could be divided into three distinct hydrological regimes in which rivers may differ significantly in their runoff response to changes in the driving variables of temperature and precipitation.

3.2. Description of SWAT Model

SWAT is a continuous time model that operates on daily time steps and uses a command structure for routing runoff and chemical through watershed. The model includes eight major components: hydrology, weather, erosion/sedimentation, soil temperature, and plant growth, nutrients, pesticide and land management. Integration of Geographic information system (GIS) and use of remote sensing data has further enhanced capability of hydrological model for solution of complex problems with large quantities of data associated with water systems and distributed nature of hydrological elements with much better resolution. (GIS) data for topography, soils and land-cover were used in the AVSWAT, an ArcView-GIS interface for the SWAT model [15]. Climate, precipitation, stream flow and water quality data were sourced and prepared according to SWAT input requirements. The topography of watershed was defined by a Digital Elevation Model (DEM). The DEM was used to calculate sub-basin parameters such as slope and to define the stream network. The soil data is required by the SWAT to define soil characteristics and attributes. The land-cover data provides vegetation information on ground and their ecological processes in lands and soils. The global view of SWAT model components including input, output and the spatial and GIS parts is given in Fig (2).

The hydrologic cycle is simulated by SWAT model based on the following water balance equation, which considers the unsaturated zone and shallow aquifer above the impermeable layer as a unit.

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})_i \qquad (1)$$

where:

t is the time in days , SW_t is the final soil water content (mm), SW_o is the initial soil water content (mm), R_{day} is amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} is the amount of return flow on day i (mm).

The watershed are spatially distributed in nature because of it specially distributed vegetation and topography, soil and precipitation. The calibration of model needs stream flow data in temporal pattern. So in general two types of dataset are required; spatial data sets and temporal datasets. The used data and methodology applied is discussed in following section.

3.3. Spatial Dataset

The topography, landuse/landcover and soil characteristics are spatial datasets which defines the land system of any area. In hydrology, all these datasets contributes and controls the flow direction, runoff generation, infiltration, stream flow, sediment and nutrient transportation. First step in using SWAT model is to delineate the studied watershed and then divide it into multiple sub- basins based on Digital Elevation Model (DEM), Fig.(3). Thereafter, each sub-basin is sub-divided into homogeneous areas called hydrologic response units (HRUs) that GIS derives from the overlaying of slope, land use and soil layers. The aim is to set up and run the SWAT model on Upper Indus catchment with the existing multisource data to illustrate the possibility and the adaptability of the model to simulate the functioning of large-scale semi- arid watersheds. The main sets of data used are briefly explained below.

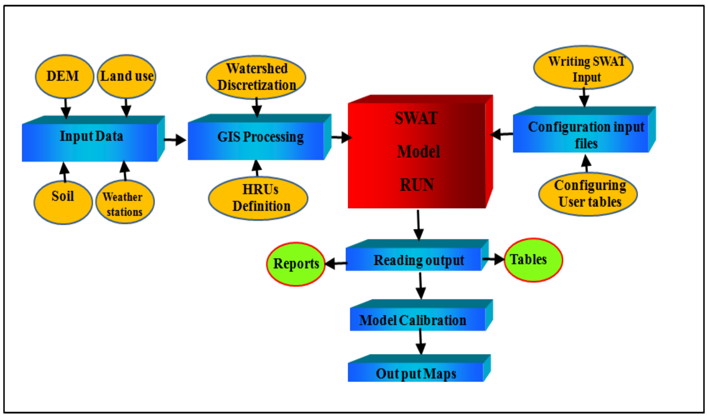


Figure 2: Components and input/output data of SWAT model

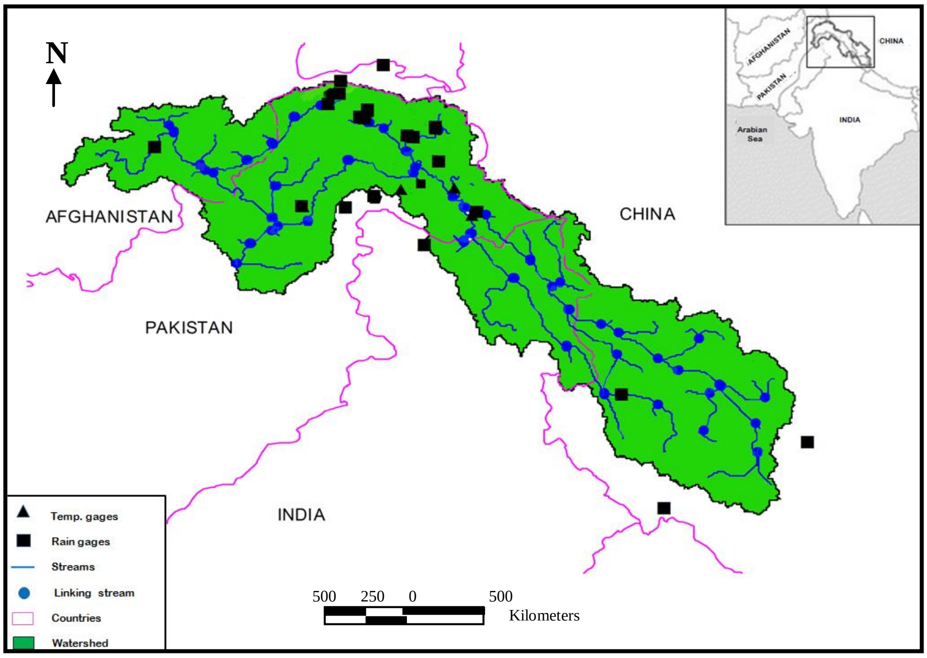


Figure3: Upper Indus Basin whole watershed and location of meteorological station
(for key to Station positions and elevations, see Table II)

3.3.1. Catchment Delineation

Topography plays primary role in delineation of any catchment. The direction and pattern of flow is governed by the watershed divide drawn on the bases of elevations, stream network generation, slope and shape of the catchment. The delineation and definition of the topographic characteristics of the catchment has been derived form GTOPO30, Global Digital Elevation Model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer)[23]. From the present SWAT application, the average elevation of catchment is 2033 meters with the minimum value of 201 meters and maximum of 3864 meters from mean sea level. Total catchment area is about 397986 Km2 which extends from the Tibetan Plateau to northeast Afghanistan with hilly terrain and steep slopes. The whole Upper Indus Watershed is segmented in a total number of 101 sub–basins depending on topographic characteristics, Fig.(4).

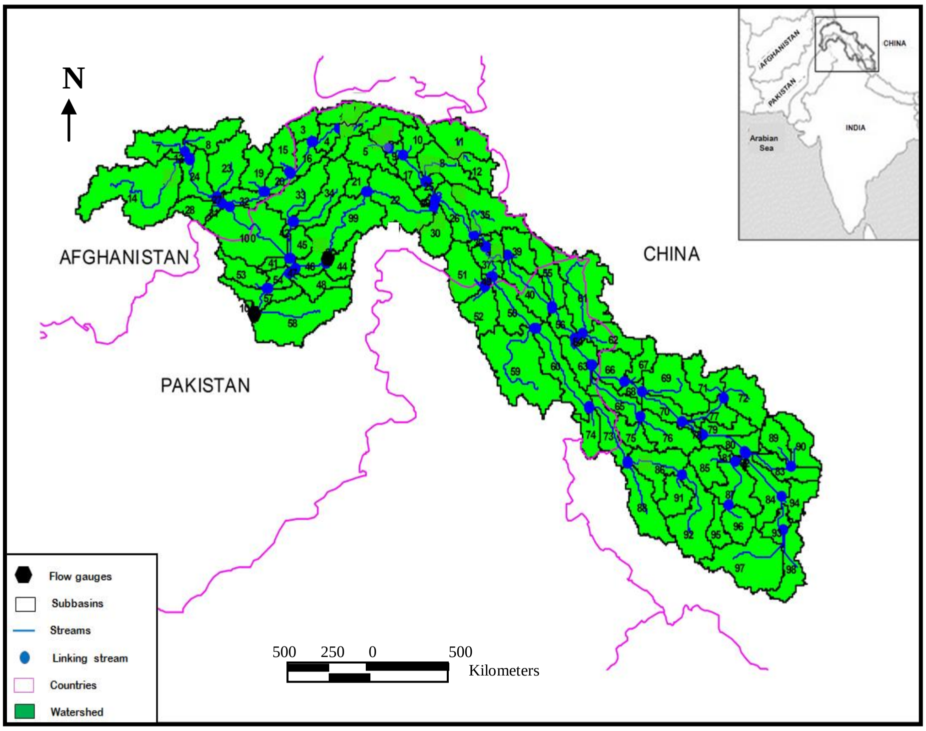


Figure 4: Delineation of sub-basin of Upper Indus Basin watershed

3.3.2. Land use

Land use can significantly affect the water cycle. As rainfalls, the canopy interception reduces the erosive energy of droplets and traps a portion of rainfall within canopy. The influence that land use exerted on these processes is a function of the density of plant cover and morphology of plant species. The land use data in project has been derived from the Global Environment Monitoring Unit site of the Institute for Environment and Sustainability at the European Commission's Joint Research Centre [24]. Land cover in catchment was distributed into 12 classes. The distribution of these classes resulted as: Residential-High Density: 0.14 %, Range-Brush;; 0.01%, Pasture; 4.26 %, Range-Grasses; 34.25%, Water; 0.34%, Oak; 1.54%, Southwestern US (Arid) Range ; 39.55 %, Pine; 6.96 %, Forest-Deciduous; 0.66 %, Forest-Evergreen; 1.1 3%, Agricultural Land-Close-grown; 0.48% and Agricultural Land-Row Crops; 10.68%. These land use types were reclassified using SWAT land use classes. The land use classes were converted from original land use classes to SWAT classes and defined using a look up table. Table I shows the land uses conversion from original land uses classes to SWAT classes.

3.3.3. Soil Data

Hydrological behavior of soil is characterized by its physical properties. To obtain this information, at a regional scale, 1:1 million soil vector maps was used where each cartographic unit was associated with one or two delineations corresponding to sub soil group of USDA[25]. Three soil delineated in the catchment; M-RM, GRV-CL, RM>GPZ have their corresponding USA series of Merino, Breswste and San Antrio series respectively. Soil parameters were determined by linking the soil map unit to the respective soil record and elaborated by using MUUF (Map Unit User File) method [26]. Derived Soil properties are given in Table II and briefly described as follows.

Table I: Land use - land cover classes used for AVSWAT in UIB watershed. The corresponding SWAT model crop growth or urban classes are also indicated

Land use - Land cover class	*SWAT classes*	*% Watershed Area*
Residential-High Density	URHD	0.14 %
Range-Brush	RNGB	0.01%
Pasture	PAST	4.26 %
Range-Grasses	RNGE	34.25%
Water	WATR	0.34%
Oak	OAK	1.54%
Southwestern US (Arid) Range	SWRN	39.55 %
, Pine	PINE	6.96 %
Forest-Deciduous	FRSD	0.66 %
Forest-Evergreen	FRSE	1.1 3%
Agricultural Land-Close-grown	AGRR	0.48%
Agricultural Land-Row Crops	AGRC	10.68%

The Merino series consists of very shallow and shallow, well drained soils formed in residuum and colluvium from monzonite and other granitic rocks, gneiss, tuff, and breccia. Merino soils are on undulating plateaus, ridgetops, and side slopes of intermontane basins and on mountainsides and mountain ridges. Slope ranges from 5 to 65 percent. The mean annual precipitation is about 22 inches, and the mean annual temperature is about 38 degrees F.

The Brewster series consists of very shallow or shallow, well drained, moderately permeable soils that formed in loamy materials weathered from igneous bedrock. These soils are on rolling to very steep hills and mountains. Slopes range from 5 to 60 percent.

The San Antonio series consists of deep, well drained, slowly permeable soils formed in ancient alluvial sediments. These soils are on nearly level to gently sloping uplands and stream terraces. Slopes range from 0 to 5 percent.

Table II: Derived Soil properties delineated in the catchment

Soil Name	*Merino*	*Brewster*	*San Antonio*
Soil Hydrologic Group:	A	A	A
Maximum rooting depth(mm):	2000	2000	200
Porosity fraction from which anions are excluded	0.50	0.50	0.5
Crack volume potential of soil:	000	0.00	0.00
Texture 1 :	Grv_SL	Grv-CL	CL
Depth (mm)	330mm	300mm	1520m
Bulk Density Moist (g/cc):	1.38	1.61	1.4
Ave. AW Incl. Rock Frag :	0.13	0.10	0.17
Ksat. (est.) (mm/hr)	883	672	0.9
Organic Carbon (weight %):	0.5	1.25	0.5
Clay (weight %):	16	27	39
Silt (weight %):	40	38	32
Sand (weight %):	44	35	29
Rock Fragments (vol. %):	27	47	4
Soil Albedo (Moist)	0.1	0.1	0.1
Erosion K	0.18	0.13	0.16
Salinity (EC, Form 5)	0 .00	0	0

3.3.4. Delineations of Hydrological Response Units

Land cover and soils in catchment system response to precipitation physically and governs the distribution of precipitation into; infiltration, evaporation and runoff after meeting the depression storage and abstraction. As combination of soil and land cover makes important responding units, therefore runoff generation process in SWAT is accomplished by subdividing the watershed into areas having unique land use and soil combination which are called; Hydrological Response Units (HRU's) .Practically HRU's are derived by overlying the land use and soil type layer in each of the topographically derived sub-basin [27]. Total 101 topographically derived sub-basins are divided into 346 HRU's by keeping the threshold values 5 % for land use and 0 % for soils. This threshold is supposed to give full soil classes and maximum land use classes coverage in formation of the HRU's in watershed modeling.

3.4. Temporal Data

Rivers in the hydrological regimes may differ significantly in their runoff response to changes in the driving variables of temperature and precipitation. These varied responses to changes in the driving variables mean that caution must be exercised in the prediction of runoff response to climate change, especially in complex catchments with a mix of hydrological regimes. Therefore the long term meteorological datasets are required for the hydrological modeling.

3.4.1. Climate Data

The simulation is mainly for assessment of hydrological parameters; therefore temporal input to the model is hydrometeorology and stream flow. Snow and hydrology research division of Water and Power Development Authority (WAPDA) Pakistan has installed 17 recording type meteorological stations in Pakistani part of catchment in a well distributed manner. These stations record maximum and minimum temperature, relative humidity, solar radiation and snow melt equivalence of water on daily basis. This hydro- meteorological stations network covers only Pakistan part of the catchment. For coverage of catchment out of territorial boundary of Pakistan i.e. Afghanistan, China and India, World Meteorological Organization (WMO) network was used. Good quality data was available for three stations in China part of the catchment with full coverage. However the constraint of non availability of most recent data (1994 to 2004) has reduced the coverage in India and Afghanistan part as data of only one station for each of these countries was available in the catchment area. The location of weather station and data used in simulation is given in Table III.

Table III: List of stations used for meteorological datasets

3.4.2. Stream flow Data

S. NO	***Station Name***	***Country***	***Location***			***Record Length (years)***
			Long (deg.)	Lat. (deg.)	Elevation (meters)	
1	Bruzilp	Pakistan	75.09	35.90	4030	6/10/94 to 16/9/2004
2	Desoai	Pakistan	74.01	34.95	4356	12/1997 to10/1/2004
3	Gilgit	Pakistan	72.43	36.33	1550	3/1/997 to 9/16/2004
4	Hushey	Pakistan	76.20	35.20	2995	9/13/1994 to10/20/2004
5	Kelashp	Pakistan	73.17	36.28	3000	6/1/1994 to10/22/2004
6	Khod	Pakistan	72.58	36.58	3455	6/1/1994 to 3/3/2004
7	Naltar	Pakistan	74.27	36.22	2810	6/6/1994 to10/19/2004
8	Rama	Pakistan	74.82	35.37	3000	6/1/94 to12/31/03
9	Rattu	Pakistan	74.82	36.50	2570	6/1/1994 to 2/31/2003
10	Saif-ul-Maluk	Pakistan	74.82	36.50	3200	10/16/1995 to 9 /15/2004
11	Shangla	Pakistan	72.60	34.38	2100	6/1/1994 to 9/26/2004
12	Shendup	Pakistan	72.53	36.83	3560	9/26/2004 to 9/26/2004
13	Shogran	Pakistan	73.47	34.60	2930	9/20/2000 to 9/28/2004
14	Uskorep	Pakistan	73.30	37.33	2977	7/13/1994 to 12/31/2003
15	Yasinp	Pakistan	73.30	36.45	3150	6/9/1994 to 10/1/2004
16	Zanipas	Pakistan	73.28	36.28	3000	7/3/1994 to 10/1/2004
17	Ziarat	Pakistan	74.43	36.22	3669	1/6/1994 to 1/10/2004
18	Kabul	Afghanistan	69.22	34.55	1791	1/6/1996 to 31/12/2004
19	Lumar	India	84.05	32.30	4420	1/1/2004 to 31/12/2004
20	Shiqua	China	80.08	32.50	4280	1/1/2004 to 31/12/2004
21	Sonap	China	75.32	34.32	2515	1/1/2004 to 31/12/2004
22	Tuko	China	81.43	30.55	4736	1/1/2004 to 31/12/2004

Stream flow data of Indus River System is gauged and well maintained at several stations along its course from its origin in mountains in north to its last takeout at Kotri in lower Indus Plain in south at Indus Delta region. The historic daily flow data was available for the period 1962- 2004 for calibration of flow simulations. Two gauging stations for stream flow data are used: Kakabagh Dam (Upstream) on Indus and Nowshera at Kabul River before it discharges into Indus at Attock and becomes the part of marvelous Indus Basin Irrigation System.

IV. MODEL SIMULATION

After completing all the model inputs pertaining to special and temporal datasets, the model is ready for simulation. The simulation is done for a period of 10 years from 1994 to 2004 which is the same period of availability of climate data. This simulation is saved as default one. The model is simulated many more times by changing the value of Curve Number (CN2), Soil Evaporation Compensation (ESCO), Lateral Flow Travel (lLAT_TTIME) and Groundwater Re-evaporation (GW_REEVAP) to get the best match between model output and observed data.

V. RESULTS AND DISCUSSIONS

The model calibration and the output maps are presented in this section. The details and discussions are given as following:

5.1. Model Calibration

The calibration step aims to determine the optimal values for the parameters specified by the user. Calibration of models at a watershed scale is a challenging task because of the possible uncertainties that may exist in the form of process simplification, processes not accounted for by the model, and processes in the watershed that are unknown to the modeler. The process of calibration was adopted to adjust parameters related to hydrology of the catchment. The stream flow data is processed for annual values to calibrate SWAT. The practice was carried out by referring stream flow data at two gauging stations. The river Kabul was calibrated at Nowshera in KPK province, before it joins the Indus near Attock. Discharge data for years 1994 to 2004 was used for comparison with the simulated flow. Indus has been also calibrated at the Kalabagh just before it enters into the Indus Plain. Kalabagh is a site proposed for construction of large dam for generation of hydropower and storage of water to meet increasing water demand of Worlds Largest Contiguous Indus Basin Irrigation System (IBIS). The comparison of simulated and measured flows are for the eleven years from 1994 to 2002. Fig. (5) and Fig. (6) show generally well respected for both calibration periods. The calibration of any surface water model in Indus is complicated because complexities and large size of watershed. The watershed contains high peaks, glaciated and snow melts as well as rained areas. Five model parameters are adjusted to bring simulated values close to the observed values model values close to the observed ones in the process of calibration. The Curve Number (CN2) is increased by 3 in all sub-watersheds; Soil Evaporation Compensation (ESCO) is increased by 0.1 and Lateral Flow Travel (lLAT_TTIME) is adjusted to 500. Similarly Groundwater Re-evaporation (GW_REEVAP) is adjusted as 0.3 and Hargreaves method selected for estimation of potential evpotranspiration for adjustment of mass balance components.

The result of flow calibration show a good correlation of observed and model simulated as shown in Figures (5&6) . At Nowshera station the average flow for the simulation period is 248 mm with the standard deviation of 78 whereas the average observed flow during the same period is about 292 mm with the standard deviation in series is 75. The correlation coefficients for simulated and observed flow are 67.5. For the second station at Kalabagh, the average flow for the simulation period is 290 mm with the standard deviation of 74 whereas the average observed flow during the same period is about 247 mm with the standard deviation in series is 74. The correlation coefficients for simulated and observed flow are 69, which can be termed as good.

To evaluate the performance of the model with calibrated parameters, the coefficient of Determination (R^2) and one of three statistic coefficients recommended by Moriasi [28] , Nash-Sutcliffe efficiency coefficient (NSE) were carried out. Coefficient of determination (R^2) is a good method to signify the consistently among observed and simulated data by following a best fit line. It ranges from zero with no linear relationship to1.0 which is perfect linear relationship. Generally, values greater than 0.50 are considered acceptable and similarly the higher values represent the less error between the simulated and observed values [29], [30]. The value R^2 test of flow stands 0.54. It indicates that model results produced for the sedimentation are very good as well as the results for flow are good enough.

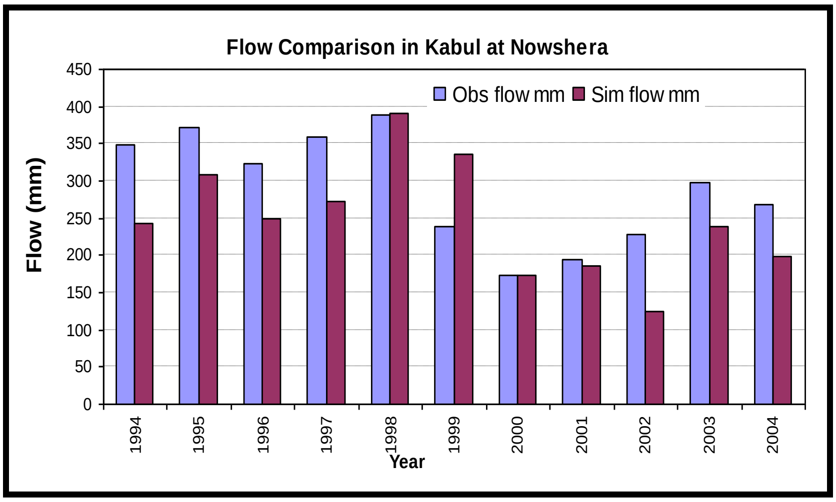


Figure 5: Comparison of annually observed and simulated stream flow at Nowshera

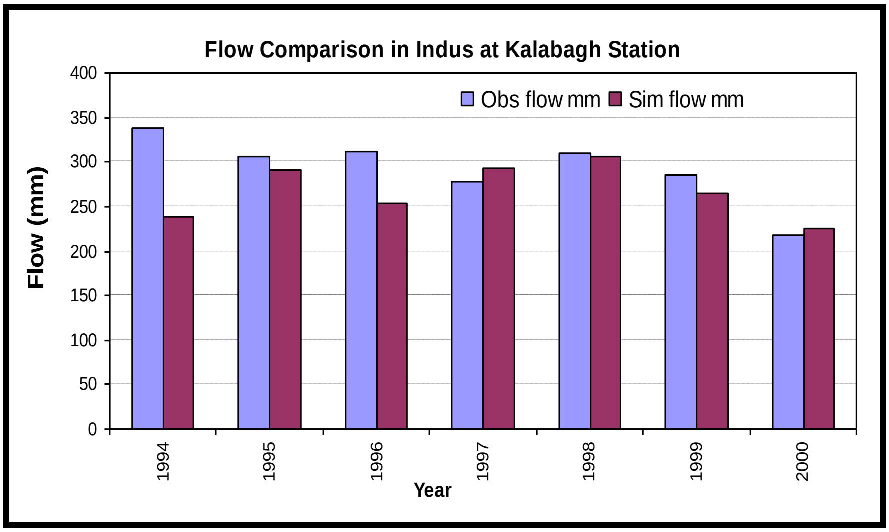


Figure 6: Comparison of annually observed and simulated stream flow at Kalabagh

The statistic operator Nash-Sutcliffe efficiency coefficient (NSE) [31] is a normalized statistic method use for the prediction of relative amount of the residual variance (“noise”) compared with measured data variance (“information”) as explained in the following equation:

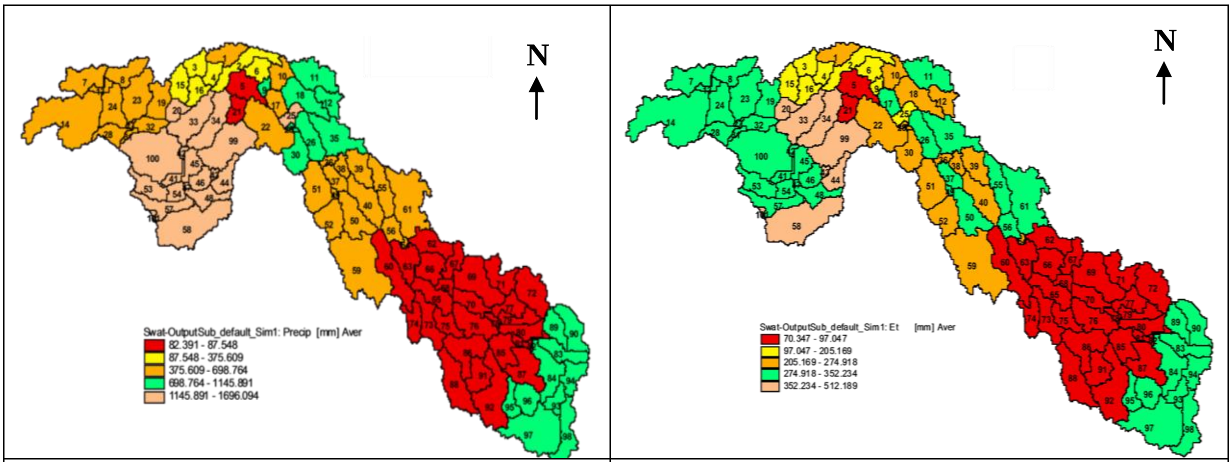
$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{mean})^2} \right] \quad (2)$$

Where Y_i^{obs} is the ith observation (streamflow), Y_i^{sim} is the ith simulated value, Y^{mean} is the mean of observed data and n is the total number of observations.

NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE=1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance [28]. According to NSE method, the model result of 0.98 which is quite acceptable

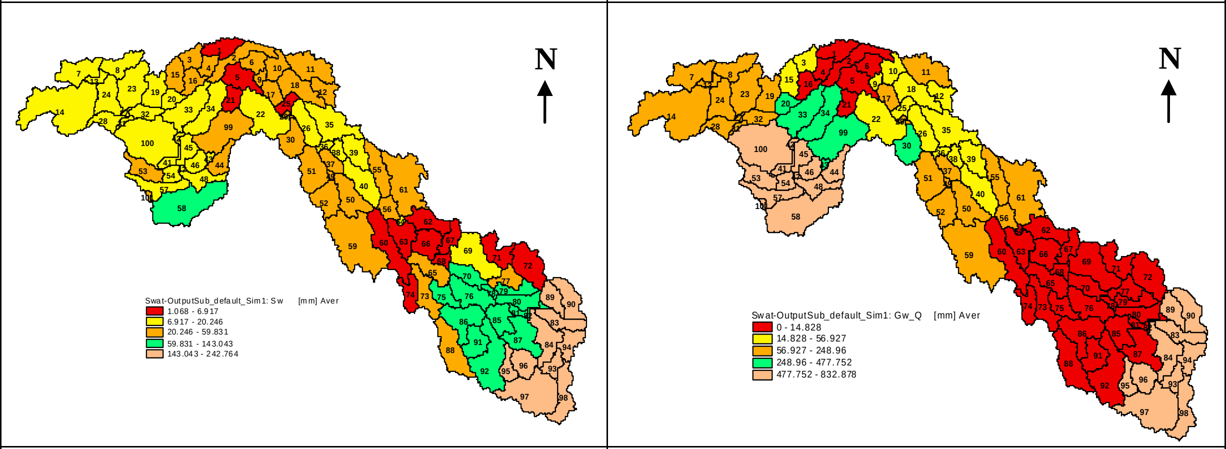
5.2. Output Maps

SWAT model used the input data for soil, climate and land use to simulate the hydrology of Upper Indus River Basin and assessment of impact of drought and dry periods on environmental flow. A large watershed system in Pakistan, India, China and Afghanistan has been used for simulation. The simulation period is 11 years from 1994 to 2004. The model results are briefly summarized in the following output maps, Fig.(7)



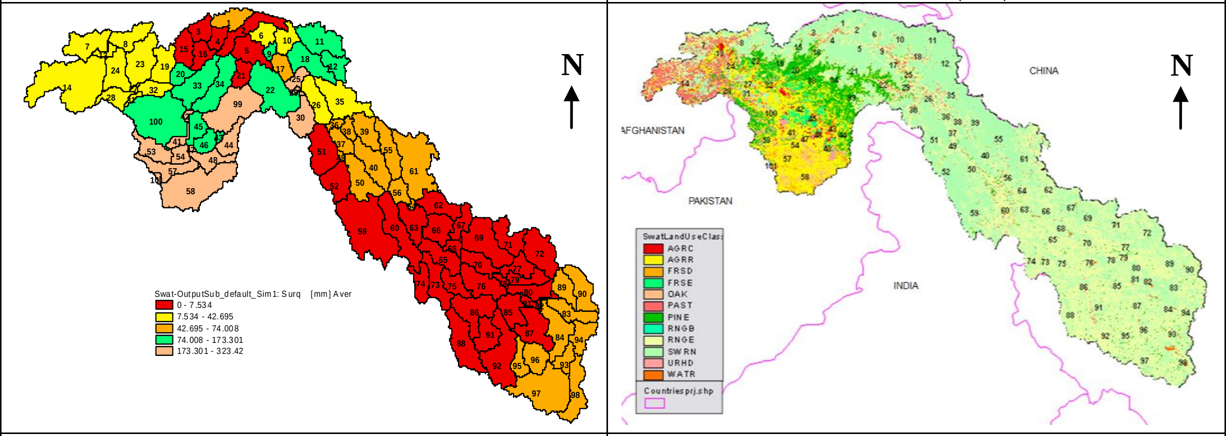
(a) Average annual precipitation (mm)

(b) Average annual evapotranspiration (mm)



(c) Average annual soil water contents (mm)

(d) Average annual contribution of groundwater to stream flow (mm)



(e) Average annual surface water yield (mm)

(f) SWAT land use classes

Figure 7: Distribution of Basic output hydrological components and land use of Upper Indus Basin watershed through 101 sub-basins for simulation period of 11years (1994-2004).

The analysis of Figure 7 illustrates that: the precipitation varies very much spatially. The average annual precipitation of 652 mm with maximum of 1696 mm and minimum of 82 mm. the occurrence and magnitude of precipitation are influenced by the distribution of areas within each elevation band in the study area as shown in Fig.7(a). High mountain regions are characterized by altitudinal variations in the contribution of rainfall, snowmelt and glacier melt to runoff. Waters captured at high altitudes flow under gravity via the stream network or groundwater aquifers to the lowlands resulting in quite different hydrological regimes.

Changes in land use and vegetation affect not only runoff but also evapotranspiration. Increased evapotranspiration reduces the groundwater recharge and the contribution to river flow. However, great differences occur according to the plant species and the rate of production. Fig. 7(b) represents the amount and variation of evapotranspiration over the whole catchment, which ranges from 512mm to 70 mm with an average annual of 236 mm. The distribution of annual soil water content is presented by Fig. 7(c), the maximum value is 243 mm with the average annual of 51mm and minimum as low as 1mm.

Streams and other surface-water bodies may either gain water from ground water or lose (recharge) water to ground water. The contribution of ground water to total streamflow varies widely among streams.The effect of ground-water contribution to headwater streams on the volume of streamflow lower in a watershed is related partly to the volume of ground water contri-buted in the headwater area; that is, the larger flow is initially, the farther downstream that water will extend. Fig. 7(d) illustrates that the average annual contribution of groundwater in UIB to steam flow is about 202 mm with the maximum 832 mm and minimum of zero (for low precipitation), and total average annual surface water yield is 152 mm with the average maximum of 323 mm and minimum of even less than one mm as shown in Figures 7(d & e) respectively. These results of Upper Basin have practical consequences for flow forecasting on the River Indus and a significance for water resource use in the lower Indus.

VI. ECOHYDROLOGY

The river Indus intercepts mountains, feeds great Indus Basin Irrigation System (IBIS), transverses deserts and deltaic systems and finally drains into Arabian Sea. The last ecosystem intercepted by this mighty river is deltaic. The main use of Indus water is agriculture and provinces own right of its use. The survival of the Indus Delta is dependent on the silt-laden freshwater discharges from river which has been curtailed due to diversion of water for agriculture, power generation, and other uses in the upper reaches. The distributing of water among provinces is governed under water appointment accord signed in 1991 among provinces. It was agreed in accord that 12 Bm3 flow will be allocated for sustainability of freshwater dependent deltaic ecosystem. The freshwater flows into the delta during the recent years have been inconsistent and mostly below the minimum required quantity as shown in Fig.(8).

Figure 8 indicates that release of environmental flow to delta rather than the hydrological as the flow below Kotri Brage is highly variable for the same range of runoff in Upper Indus Watershed. The reduction in the inflow of freshwater has exposed complex deltaic ecosystem to several environmental and social stresses in the form of loss of habitat and biodiversity and a decline in the productive values of the ecosystem. The reasons for continuous reduction in discharges and consequent silt load are mainly due to construction of dams and diversion of water in canals. From 1992 onwards the reduction in water discharges below Kotri Barrage and natural drought periods are very conspicuous and so is the drastic reduction in silt load. This has not only degraded the development and health of mangroves but has facilitated the sea intrusion in the Indus delta.

Because of the volume and sustainability of stream flow is generated in head-waters areas, the model out put was used to analyze the environmental flow in lower delta. Figure 8 illustrates that the average precipitation is sufficient to generate runoff and groundwater recharge. The simulated runoff by the model have practical consequences for flow forecasting on the River Indus and its delta. The figure shows that there is enough water for downstream release so that freshwater release for sustainability of Deltaic ecosystem should taken at second erred during dry periods which deg

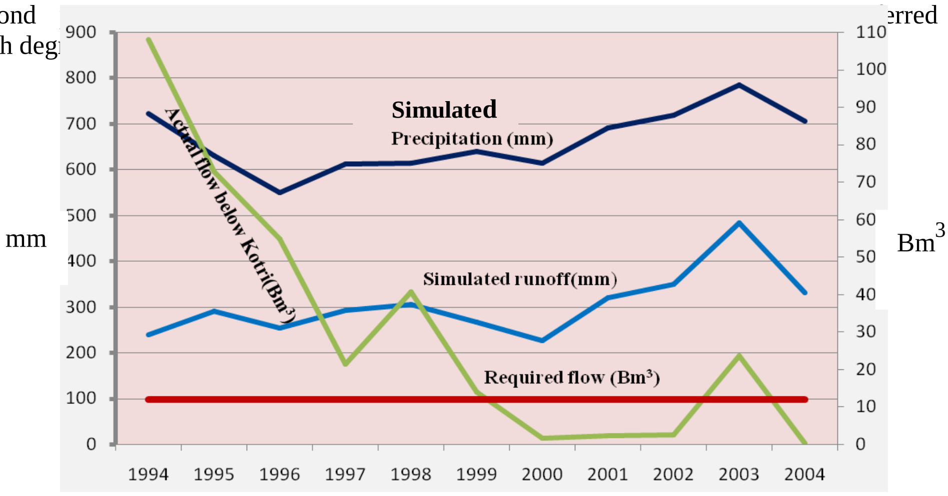


Figure 8: Availability of Water and Environmental Flow in Indus River

VII. CONCLUSIONS

The mountains region of UIB is a critical source of water for Pakistan and provide the main water source for the IBIS, one of the world's largest integrated irrigation networks. The River Indus is fed by a combination of melt water from seasonal and permanent snow fields and glaciers, and runoff from rainfall both during the winter and monsoon season. The hydrology of Upper Indus River Basin and the linkage between climatic variables and river flow is investigated by A GIS based watershed model Soil and Water Assessment Tool (SWAT). The impact of drought and dry periods on the ecohydrology of Indus Delta also assessed. Swat model was successfully calibrated in the UIB watershed. The evaluation of the model performance was carried out successfully with the recommended statistical coefficients. The comparison of observed and simulated flow stream at two gauging stations revealed a Nash-Sutcliffe coefficient superior to 0.98 and R^2 to 0.54 for calibration periods.

The analysis of output maps concluded that: the hydrological components of Upper Indus Basin watershed (precipitation, evapotranspiration, soil water content, surface water yield and contribution of groundwater to stream flow) differ between basins in the region and these affect the environmental flow of Indus River and the water resource use in the lower Indus. The variation of hydrological components within the basin due to the elevation range and the distribution of areas within each elevation band in the in the catchment, temperature variations, permanent snowfields and the glacierised proportion.

Freshwater release for sustainability of Deltaic ecosystem should taken at second priority whereas other uses like ; irrigation, power, drinking etc. are preferred during dry periods which degrades the deltaic ecosystem. Thereafter differing hydrological regimes over the mountains of northern Pakistan must be taken into account in the planning , design, management and operation of water resources of the River Indus and its delta.

This study had showed the utility of GIS to create combine and generate the necessary data to set up and run the hydrological models especially for those distributed and continuous. It also had demonstrated that the SWAT model works well in large mountainous watersheds and in semi-arid regions.

RECOMMEDATION

1- The calibrated model can be well used in UIB watershed to assess or predict other watershed components such as the impacts of land and climate changes on water quality and sediment yield.
2- The performances can be enhanced using some other global climate data and emissions scenarios to assess the potential impacts of climate change on the hydrology of whole Indus River basin as a macro scale model.
3- Solute transport model should be developed for Indus Delta to predict the saline water intrusions and for different scenarios of pumping of aquifer at different depths

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