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Modeling Water Demand and Supply for Future Water Resources Management

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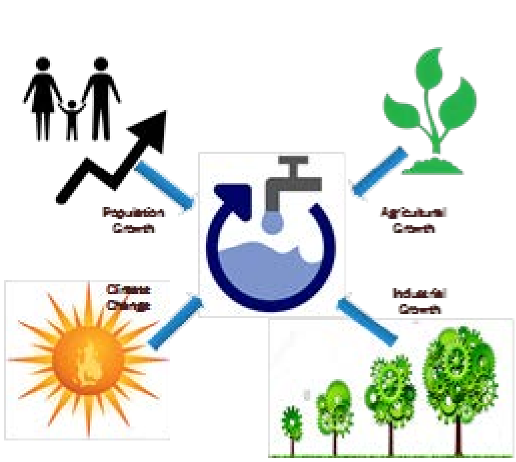
Graphical Abstract



Abstract— Sustainable water resources management is challenging when a region suffers from scarcity and experiences increasing anthropogenic water demand. The Lower Indus Basin is one of the most arid regions in South Asia. Various kinds of water users (i.e., rural, urban, subsistence and commercial irrigated agriculture) are present. The growing population, climate change, and the need to meet minimum flow requirements are leading to future water resources management conflicts in an already water-stressed area. Being able to assess the ability of the catchment to satisfy potential water demands is crucial to planning and making wise decisions about water use and distribution. The Water Evaluation and Planning System (WEAP) software has been widely used to analyze complex water resources systems and to examine supply and demand management strategies. In this study, a scenario analysis approach is used in WEAP, to assess the impacts of water demands and supplies on the water resources of the Lower Indus River in Sindh in the future. For each scenario, the water resource implications were compared to a 2015 "baseline." The model analyzed water demands and reliability in these scenarios, to help comprehend potential problems and devise water management strategies.

Key Words— Water Resources Management, Lower Indus Basin, Climate Change, Water Scarcity, Water Evaluation and Planning (WEAP), and Future Water Demands

1 INTRODUCTION

Water resources management has a significant impact on the socio-economic development of a catchment. The water demands and availability depends on the economic, ecological, land use, and climatic changes of a region [1,2]. Rapid population growth along with urbanization trends and unplanned industrial and agricultural expansion are leading to pressures on water resources and contribute to water conflicts [3]. Unmet water demands may bring conflicts, and intensified demands and frequency of drought further exacerbate the conditions. A wide array of tools and models have been developed by water resources planners and engineers to develop ways to balance supply and demand, and to manage deficits using various efficiency measures [4].

The Water Evaluation and Planning (WEAP) system software developed by the Stockholm Environment Institute is a powerfull computing tool for the planning, evaluation, and management of water resources. It can be applied in a wide range of catchments, having domestic, agricultural, and industrial water demands, along with complex hydropower operations [5]. With prioritization functions and other elements it can simulate the priority of demands, allocation, conservation, streamflow, and reservoir operations along with ecosystem requirements and cost-benefit explorations [6]. It employs two basic principles during simulations: 1) availability and assessment of water within a catchment by simulating the evapotranspiration, runoff, and infiltration and 2) analyses of the anthropogenic activities within the system and their impacts on water resources [7].

The aim of the present study is to determine the future water demand, and to develop a solution for future demand management in the Sindh Province of Pakistan, by examining demand-side management scenarios. The future demands were estimated using WEAP. The scenarios in the study were reduction in agricultural water demands (Drip and Sprinkler) and the lining of canals to avoid losses and water theft were introduced to compare to the baseline year 2015. The strategies to manage water demand and to increase demand side reliability of the three barrages managing the Lower Indus Basin in the future (2050) were analyzed.

1.1 Study Area

Unlike other provinces in Pakistan, the Sindh province has no feasible alternative water resources; it relies completely on whatever flow is available from the Indus. In Sindh Province, water is distributed from the Guddu Barrage that was constructed in Kashmore; Sukkur, the largest irrigation net-work in the world, supplies water to almost all parts of the Sindh Province. The Kotri Barrage is the last controlling structure on the Indus, and it is situated at Jamshoro. Below Kotri the Indus dumps into the Arabian Sea near Thatta. The segment of

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the Indus river under consideration in this research is the lower most basin, served and operated by the Guddu, Sukkur and Kotri barrages located in Sindh as shown in figure 1, and the climatic details are mentioned in Table-1. The annual entitlements of the Guddu, Sukkur, and KOtri barrages are 9.43, 28.24 and 11.02 MAF, respectively. These barrages feed almost all part of the Sindh province and make it the world's fourth largest irrigation system [8].

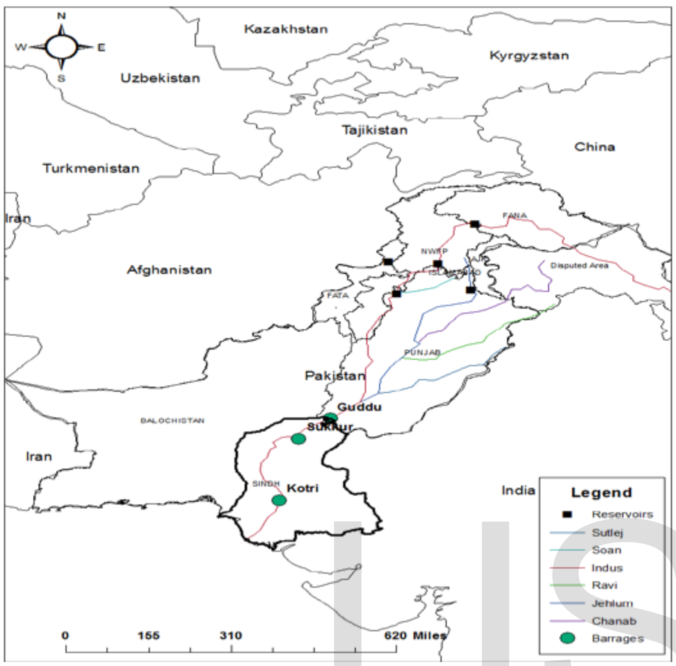

Fig.1. Location of Guddu, Sukkur, and Kotri

TABLE 1 CLIMATIC DETAILS OF LOWER INDUS BASIN (SINDH)

Station	Avg: Temp*	Rainfall (mm)	Irrigated Area**	With-Drawls (MAF)
Guddu	34	201	663	6.73
Sukkur	33	201	1768	23.5
Kotri	31	165	166	9.53

*Celsius, **000 -Hectares

2 LITERATURE REVIEW

Climate variability and increasing demand for water supply have contributed to the failure of the Indus River system in Pakistan to meet human and environmental needs. Being one of the major rivers of Asia and the longest river in Paki-stan, the 3,180-km river provides essential water for 121.7 million people for drinking, growing food, navigation, and economic development [9]. Effective management of the Lower Indus River Basin is especially critical for the future sustainability of more than 50 million people in the Sindh Province who depend on its flow. And since the Sindh Province is at the tail-end of the Indus and without adequate groundwater resources, it is affected by water shortages more than up-stream provinces [10].

WEAP has been used in numerous water associated projects throughout the world. For example, [7] used WEAP laboratory to measure future water demands and availability in the Olifants Catchment, South Africa. WEAP was applied to assess the expected impact of various possible growth scenarios on Lake Tana water levels, located in Ethiopia [15]. It was also used to provide simulations for Ethiopia's policy evaluation of reservoir construction in the Blue Nile River basin, by incorporating the impact of midrange climate change scenario (A1B-downscaled) on the performance of present and proposed hydropower and irrigation plans [16]. Mounir et al. (2011) conducted a research study using the WEAP model in the Niger River Basin, located in the Niger Republic, to explore various possible scenarios of future water resources management [17]. It was used to determine the potential climate change effects and adaptive capacity on irrigation water supply in the Cache Creek watershed in California [18]. Hence, the WEAP model has high global popularity in scenario analyses of water demands and supplies. Likewise, WEAP was also used to inspect the future of water demand and availability, under land use and land cover changes due to the climate in the Middle Dara Valley, Morocco [19]. The schematic of the WEAP model used in the present study is shown in fig.2.

3 METHODOLOGY

3.1 INPUT PARAMETERS

The population and per capita water use rate were obtained from the Federal and Provincial Bureau of Statistics. The per capita water consumption varies from 30 liters per capita per day (l/c/day) to 350 liters per capita per day [20]. The historical climatic data, i.e. precipitation, temperature, humidity, wind, and evapotranspiration (ET) are obtained from the Pakistan Meteorological Department. The crop trends, gross command, and irrigated area of Guddu, Sukkkur, and Kotri barrages were obtained from Irrigation and Power Department, Government of Sindh. The list of data sources is summarized in Table-2.

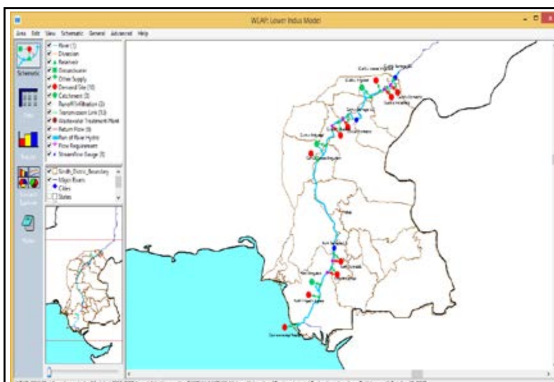

Fig.2. Schematic representing the lower Indus (Sindh) model in WEAP

TABLE 2 INPUT DATA REQUIRED FOR THE DEVELOPMENT OF WEAP MODEL AT LOWER INDUS BASIN, DATA-SOURCES & FORMAT

Data	Source	Format
Climatic data		
Temperature, Precipitation, Humidity, Wind Speed, Evapotranspiration	Pakistan Meteorological Department	Monthly excel sheets
Hydrological data		
Barrages/Stream-gauges	Pakistan Water and Power Development Authority (WAPDA)	Daily discharge data
Water demand		
Population, Water consumption, Growth rates	Pakistan Statistical year book 2009, Federal Bureau of Statistics, Statistics Division, Government of Pakistan.	Yearly record books
Crop trends, Gross commanded and Irrigated area	Irrigation and Power Department, Government of Sindh, Karachi.	Yearly record books

3.2 SCENARIO SIMULATION

The current year used in the model is 2015 since it was a normal year among the past 10 years (very wet and dry); it was also used for the calibration and validation of the barrages/catchments.

3.3 AGRICULTURAL, DOMESTIC, AND INDUSTRIAL GROWTH RATE

To forecast the effect of growth on the model, population growth was set at 3%, agricultural growth was set at 0.75%, and industrial growth was estimated to be 1.5%. The Water Apportionment Accord (WAA) entitlements are used as the supplies and water availability [21 & 22].

3.4 MODEL CALIBRATION

The model was calibrated for the year 2015; It was done by using a built-in calibration feature in WEAP called PEST. The factors deep water capacity, run-off resistance of all crops was adjusted during the calibration. The precision was computed using the Nash-Sutcliffe Efficiency (NSE)Index. It ranges from ∞ to 1, and used to measure the predictive skill of a model relative to the mean of observations. If the NSE has a result greater than 0.65 then the model can be judged to be performing well and greater than 0.5 it is judged to be performing satisfactorily.

$$NSE = 1 - \frac{\sum_{i=1}^{Nv} (yi - oi)^2}{\sum_{i=1}^{Nv} (oi - \bar{o})^2}$$

Here y, and o are representing the predicted, and observed values. The NSI parameters range from 0.88 to 0.96.

3.5 DEMAND SIDE MANAGEMENT

Water conservation strategies were introduced into the model as well. A Sprinkler Irrigation System (saves 35% of agricultural water), a Drip Irrigation System (saves 25% of agricultural water) and Canal lining (may reduce seepage losses by as much as 50%).

4 RESULTS

4.1 SCENARIO WITH GROWTH RATES

To forecast the growth rates in the model, a scenario was created that estimates the effect of growth rates (agricultural, domestic, and industrial) at the above-mentioned barrages during the period 2015 to 2050. Figures 3, 4, and 5 show the water demand projection based on the growth rates. In the year 2050, the total water demand for the Guddu, Sukkur and Kotri Barrages will be 6.93, 23.44 and 10 MAF respectively. Prior to 2030, water demand was equal to the water entitlements for all of Sindh Province. Further, if the population, as well as the industrial and agricultural sectors, growth continue, in 2050 the Sindh Province water demand will be increased to 56.6 MAF as shown in fig. 6 (including the Pat Feder's). Sindh Province cannot augment the water supply/availability; therefore, it must apply water conservation strategies to combat future water supply demand deficits.

4.2 SCENARIO 2: DEMAND SIDE MANAGEMENT

Using this demand-side management (DSM) scenario, the water conservation techniques described above were applied in the model to the Guddu, Sukkur and Kotri catchments. Figure 8 illustrates the amount of water savings that might be reduced through the implementation of DSM via the referenced scenarios. The water conservation strategies, Sprinkler (reduces 25% agricultural water consumption), Drip (reduces 35% agricultural water consumption), and Lining of Canals (50% reduction from seepage water losses) are introduced into the WEAP model. The basis of these conservation strategies is to improve the performance of the system and to examine the impact on the reliability separately.

4.3 FUTURE DEMAND RELIABILITY

At Guddu Barrage, during the year 2050, the reliability for growth rate scenarios, drip, sprinkler, and lining will be 0.58, 0.75, 0.67 and 0.58, respectively as shown in Table 3. At Sukkur Barrage, the reliability will be 0.67, 0.92, 0.75 and 0.83, respectively as shown in Table 4. As listed in Table 5 at Kotri Barrage, the water demand reliability will be 0.5, 0.75, 0.67 and 0.72, respectively. As the growth rate continues, the system will be more vulnerable to water scarcity.

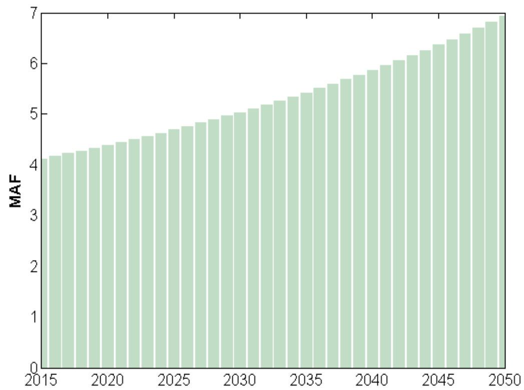

Fig.3. Future water demand at Guddu barrage commanded area in 2050

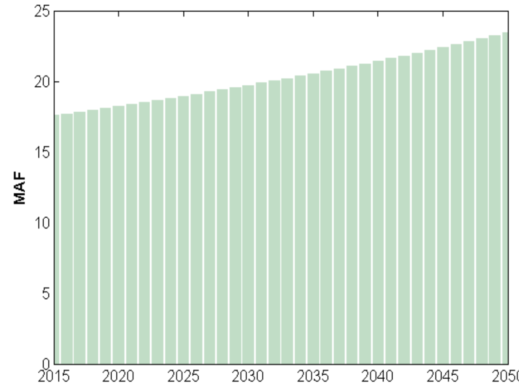

Fig.4. Future water demand at Sukkur barrage commanded area in 2050

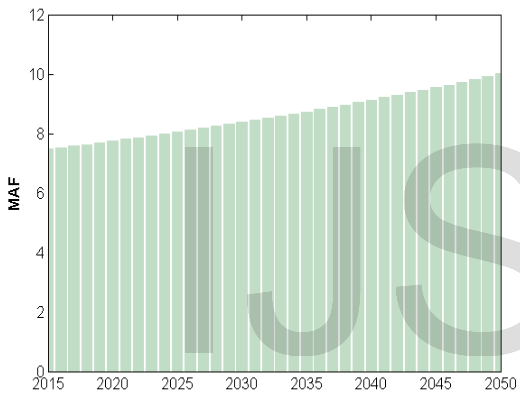

Fig.5. Future water demand at Kotri barrage commanded area in 2050

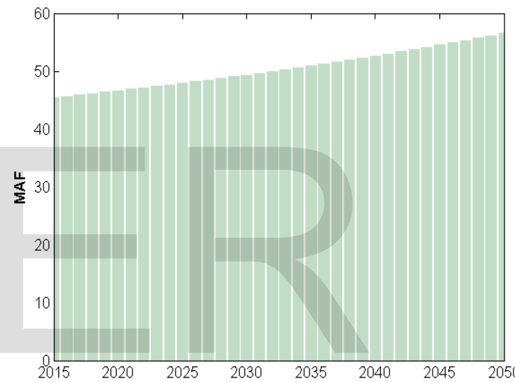

Fig.6. Total future water demand of Sindh province, including domestic, agricultural, industrial, and ecological water needs in 2050

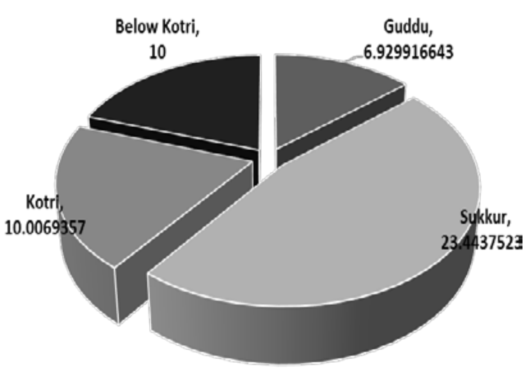

Fig.7. Sectoral water demand share at distribution level

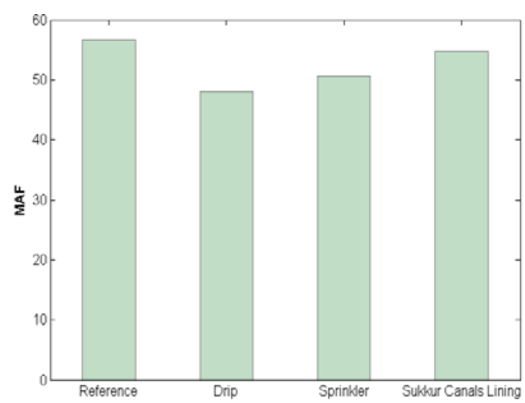

Fig.8. Future water demand in 2050 using demand side management measures

TABLE 3 DEMAND RELIABILITY AT GUDDU COMMANDED AREA, USING REFERENCE, DRIP, SPRINKLER, AND SUKKUR CANALS LINING

Year	Reference	Drip	Sprinkler	Sukkur Canals Lining
2030	0.75	0.81	0.75	0.75
2035	0.67	0.81	0.75	0.67
2040	0.67	0.75	0.75	0.67
2045	0.58	0.75	0.75	0.58
2050	0.58	0.75	0.67	0.58
Mean	0.64	0.78	0.73	0.64
Min	0.58	0.75	0.67	0.58
Max	0.75	0.81	0.75	0.75
Stand: Dev	0.05	0.03	0.04	0.05

TABLE 4 DEMAND RELIABILITY AT SUKKUR COMMANDED AREA, USING REFERENCE, DRIP, SPRINKLER, AND SUKKUR CANALS LINING

Year	Reference	Drip	Sprinkler	Sukkur Canals Lining
2030	0.75	0.92	0.83	0.83
2035	0.75	0.92	0.83	0.83
2040	0.67	0.92	0.83	0.83
2045	0.67	0.92	0.83	0.83
2050	0.67	0.92	0.75	0.83
Mean	0.71	0.92	0.83	0.83
Min	0.67	0.92	0.75	0.83
Max	0.75	0.92	0.83	0.83
Stand: Dev	0.04	0.00	0.02	0.00

TABLE 5 DEMAND RELIABILITY AT KOTRI COMMANDED AREA, USING REFERENCE, DRIP, SPRINKLER, AND SUKKUR CANALS LINING

Year	Reference	Drip	Sprinkler	Sukkur Canals Lining
2030	0.67	0.75	0.72	0.75
2035	0.67	0.75	0.72	0.75
2040	0.50	0.75	0.72	0.75
2045	0.50	0.75	0.72	0.72
2050	0.50	0.75	0.67	0.72
Mean	0.58	0.75	0.71	0.74
Min	0.50	0.75	0.67	0.72
Max	0.67	0.75	0.72	0.75
Stand: Dev	0.08	0.00	0.02	0.01

5 CONCLUSION

Being able to assess the ability of river basin to satisfy potential water demands is crucial to planning and wise decision making about water use and distribution. In this study, a scenario analysis approach was performed using the Water Evaluation and Planning (WEAP) model, to assess the impacts of possible water demands on the water resources of the Indus River at Sindh in the year 2050. The model was calibrated and validated for the year 2015. The WEAP results show if the present growth rates continue, in 2050 the Sindh Province water demand will be increased to 56.6 MAF (7.84 MAF more than the entitlements). As Sindh Province cannot augment the water supply, it must apply water conservation strategies to combat future water supply demand deficits. Three water conservation strategies, Sprinkler Irrigation, Drip Irrigation, and Lining of Canals are introduced into the WEAP model. The Sprinkler Irrigation system and lining of the Sukkur Barrage canals improve on average 17% and 25% reliability of the system. The combination of these two conservation strategies could be used for management of demands in the future.

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