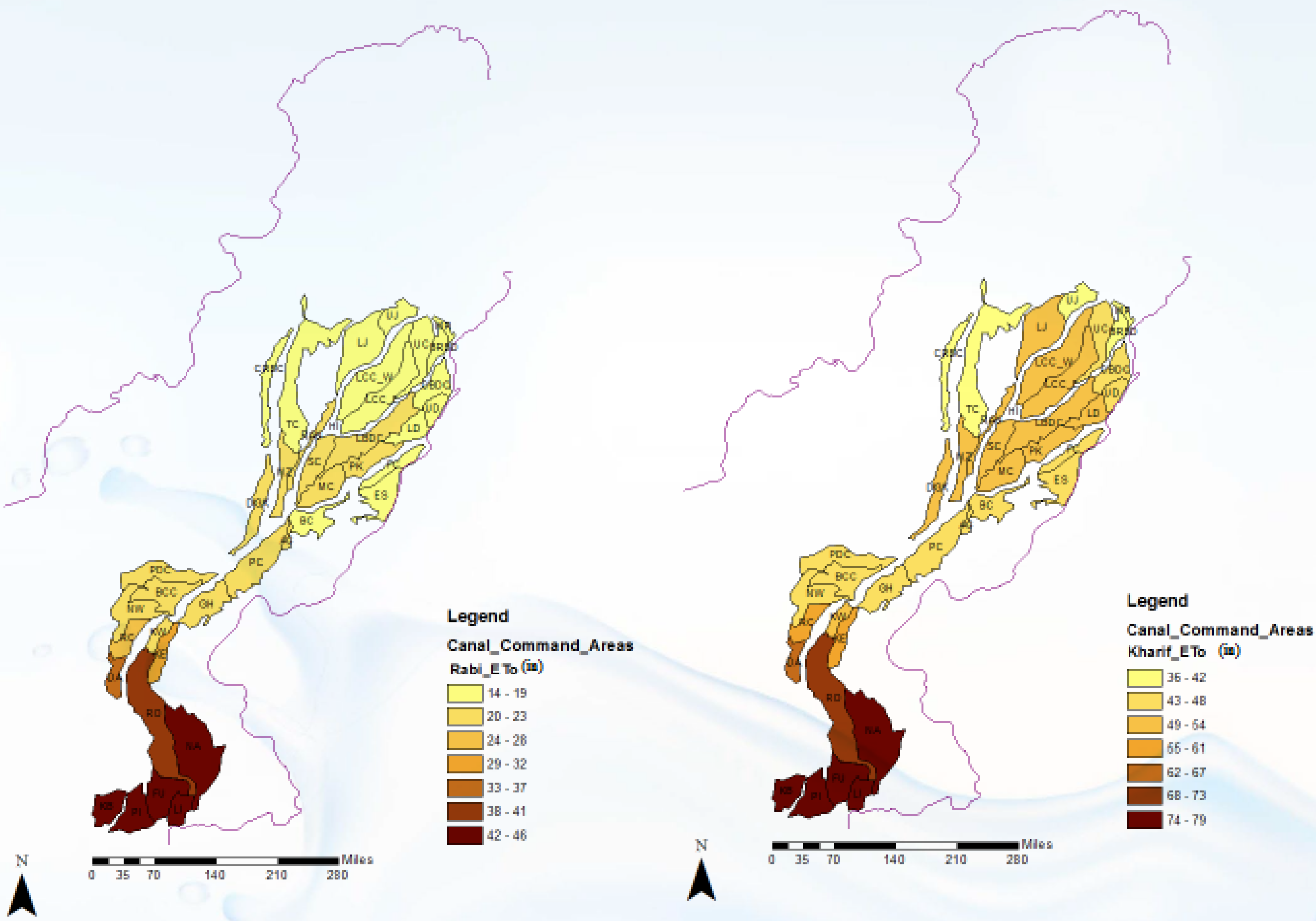
U.S.-Pakistan
Centers for Advanced Studies in Water

Decision Support System for Water Resources Planning and Management in Pakistan

Final Report 2018



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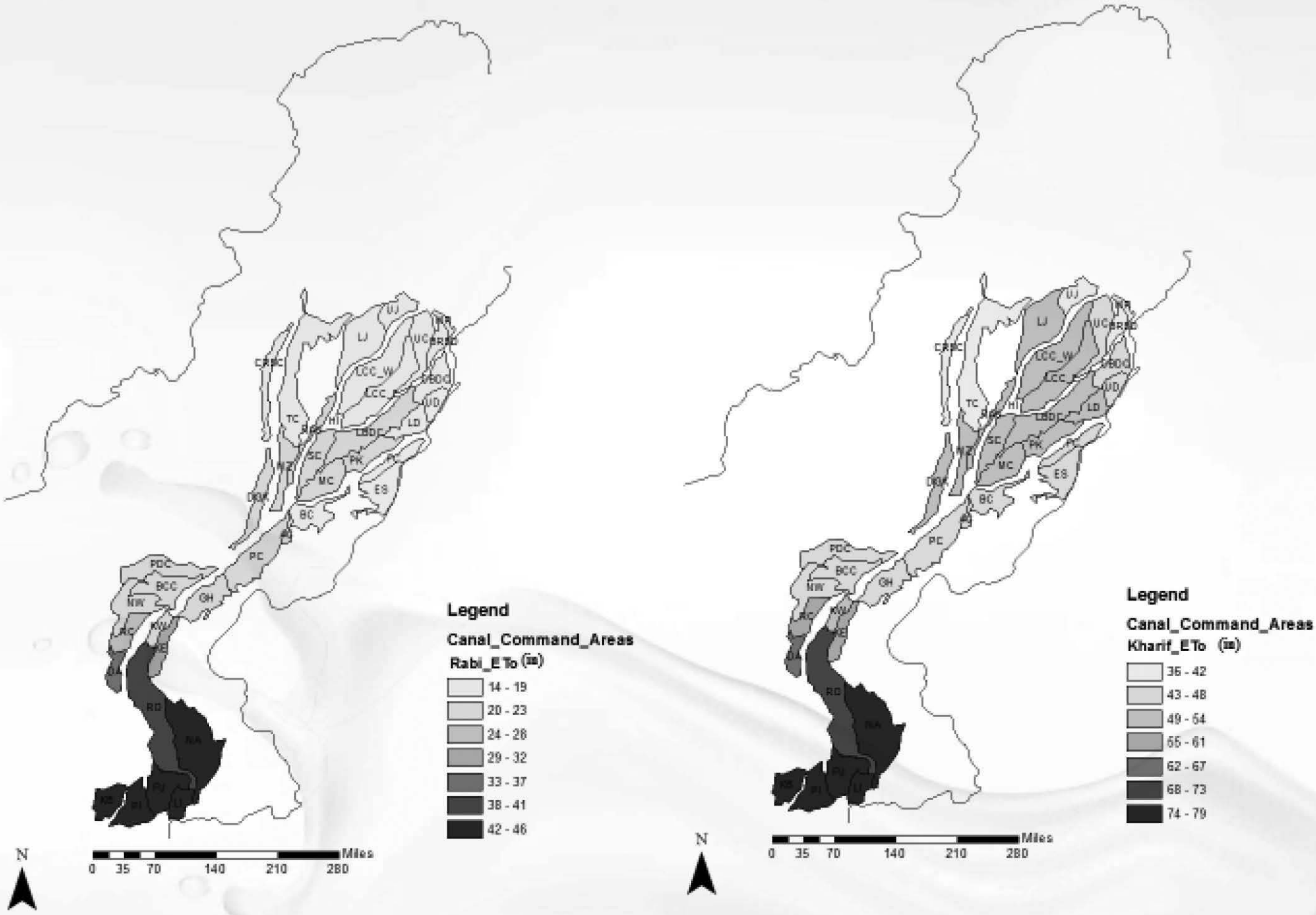

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We would like to acknowledge the support of the US-Pakistan Center for Advanced Studies in Water (U.S.PCAS-W), Mehran University of Engineering and Technology (MUET), Jamshoro, Sindh which was established with the grant of United States Agency for International Development (USAID), for financing this study under its small grants program. We also acknowledge the support of: Pakistan Metrological Department (PMD), Water and Power Development Authority (WAPDA), Sindh Irrigation Department (SID), Government of Sindh, and Program Monitoring and Implementation Unit (PMIU), Punjab Irrigation Department, Government of Punjab for providing the data free of cost to carry out this research work. We are also sincerely grateful for the support provided by Dr. Kazi Suleman Memon, Manager Research, USPCAS-W, Mehran University of Engineering and Technology, Jamshoro and Mr. Ali Hyder Sial in review and editing of the report.

ACRONYMS AND SYMBOLS

CCI	Council of Common Interests
CFS	Cubic Feet per Second
DSS	Decision Support System
DSS-PAK	Decision Support System for Pakistan
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GIS	Geographic Information System
IBIS	Indus Basin Irrigation System
IBMR	Indus Basin Model Revised
IIS	Internet Information Service
IP	Internet Protocol
IRSA	Indus River System Authority
LEAP	Long Range Energy Alternatives Planning
LP	Linear Programming
MAF	Million Acre Feet
MVC	Model–View–Controller
NARC	National Agricultural Research Center
NGO	Non-Governmental Organization
PARC	Pakistan Agricultural Research Council
PBS	Pakistan Bureau of Statistics
PCRWR	Pakistan Council of Research in Water Resources
PIMU	Punjab Irrigation Monitoring Unit
PMD	Pakistan Metrological Department
PMIU	Program Monitoring and Implementation Unit

PST	Process Specification Tool
SA	Software Architecture
SDG	Sustainable Development Goal
SID	Sindh Irrigation Department
SQL	Structured Query Language
SUPARCO	Space and Upper Atmosphere Research Commission
SWHP	Surface Water Hydrology Project
TCP	Transmission Control Protocol
UML	Unified Modeling Language
USAID	United States Agency for International Development
WAA	Water Apportionment Accord
WAPDA	Water and Power Development Authority
WEAP	Water Evaluation and Planning
WEF	Water-Energy-Food

EXECUTIVE SUMMARY

The Indus River Basin Irrigation System (IBIS) is the fourth largest irrigation system in the world, contributing up to 25% of Pakistan's gross domestic product and 90% of its food production. Various kinds of water users (i.e., rural, urban, environmental and irrigated agriculture) exist in the IBIS. The rising local population—in conjunction with climate change and the need to meet environmental flow requirements—will significantly exacerbate the complexity of future water resources management in an already water-stressed IBIS. It is essential to have an evidence based decision support system (DSS) for analysis of the complex water resources systems, and to examine supply and demand management strategies. Keeping in view the need of evidence based decision support system this study was conducted to setup a decision support system for water resources planning and management in Pakistan. The prime goal of the study was to develop a data repository, baseline model and data dissemination portal for decision making for water resources and planning at the barrage command level.

In the first phase, a data sharing platform is designed and implemented on the web based server that have standard protocols for data sharing and formats. In this particular project it has been demonstrated that how the time series and geo-spatial data (that occurs mostly in water resources) can be arranged in a standard format and can be shared among the registered users. Implemented web portal has capability to upload the data, so any registered organization can upload the relevant data and can be shared to other registered organization. This sets up a standard sharing mechanism within and among the organizations. We have also promulgated a work flow for associating targets and indicators for international monitoring. This will allow the organization(s) to map the shared data with respect to the monitoring indicators.

In the second phase, a baseline node-link system model has been setup in Water Evaluation and Planning (WEAP) framework that represents the major reservoirs, barrages and link canals of the irrigation system in Pakistan. Model was calibrated for inflows, and model performance was found satisfactory. In last phase of the project, two scenarios were simulated, which includes baseline scenario, and growth scenario.

In baseline scenario, historical demand and supply situation was assessed. It was observed that in Kharif Season, the canal command areas of Sindh and Punjab had not received the allocated shared. Sindh faced extreme shortage in the year of 1999 and 2002, Sindh has faced 69.47% and 77.23% shortage of its allocated share; and Punjab 17.92% and 19.20% shortage of its allocated share. The extreme deficiency faced by Punjab was 29.12% in the year of 2001, and in that year Sindh shared shortage of 32.91%.

In growth scenario, population growth was set to as per 2017 census, and agricultural growth was set at 0.1%. Results indicate that the combined water demand of Sindh, Punjab, upper Jhelum, upper Chenab, upper and lower Depalpur, BRBD, CBDC agriculture systems, Thal canal, supply delivered to Baluchistan from Taunsa and Seawater requirements is expected to rise from 140.8 MAF in 2015 to 141.9 MAF in 2020, 143.5 MAF in 2025, 145.4 MAF in 2030, 147.6 MAF in 2035, and 150.1 MAF in 2040.

As a result of present study, it is recommended to:

- Register departments to the data portal that intend to share their data and need technical help. Once departments are registered and starts sharing the data, then it can be used as a demonstration case to attract other departments to manage and share their data in an efficient manner. Once the departments will come in the loop then it will be easy to standardize the data in one database.
- Build capacity of the registered departments to upload and share the data on the web based portal. Initially that can be done on the web portal implemented in this research project, which further can be modified at the departmental level, considering the specific requirements of the departments in the water sector.
- Approve standard protocols for central data sharing in water sector.
- Approve control vocabulary of the variables that departments intend to share nationally and internationally.
- Extend the implemented model to canal command area to address the issues at the canal command level. Further for more detail analysis, model should be extended to distributary level, which can answer the question related to the management questions and livelihood of people.
- Extend the implemented model to include the upper Indus basin that needs to be implemented to answer the question of climate change. Catchment modelling need to be implemented to see the response on the hydrograph due to changing climate.
- Encourage the water conservation techniques to reduce water use because the water demand of Punjab and Sindh Provinces will increase to 150.1 MAF by 2040, which is more than the current entitlements and availability.
- Implement policies to reduce water use, especially in Sindh, as it is at disadvantage for being a lower riparian, and highly dependent on the surface water. It also have canal command area that will have higher domestic demand in the future. Proper management policies should be implemented in Sindh to meet the domestic and agriculture demand in future.

1 INTRODUCTION

1.1 Background

Water scarcity is a problem in all of the water basins around the world; increasing population leads to increase in water demand and over exploitation of water resources (Falkenmark and Molden, 2008). Pakistan, which is mostly fed by Indus basin irrigation system (IBIS), is not an exception. With 146 million acre feet (MAF) of water availability, it is one of the largest contiguous irrigation systems covering canal command area of over 18 million ha. Pakistan is projected to be affected by water scarcity by 2035 (Reinsch and Pearce, 2005), so water management is essential to ensure water security.

Pakistan's water crisis is not merely about the water scarcity but it is also related to poor governance which has been responsible for ineffective water management. According to the Global Water Partnership (2000) "the water crisis is often a crisis of governance"; inefficient supply of services due to mismanagement has resulted in the insufficiency of water in the country. Thus, the governance which is all about making choices, decisions and tradeoffs needs evidence-based analyses and information, which can help improve the water governance through informed decision making (Falkenmark and Molden, 2008; Olsson and Head, 2015). Keeping in mind the present and future water crisis there are different management options, the approval and execution of these options is only possible when all the stakeholders agree on feasible options that can solve water related issues in Pakistan. This is only possible when all the options are evaluated in an integrated way and presented to stakeholders with strong evidence supported by the scientific data.

Keeping in view the need of evidence based decision support system (DSS), the US Pakistan Center for Advanced Studies in Water (USPCAS-W) at Mehran University of Engineering and Technology, Jamshoro awarded a research study titled as "Development of a decision support system for water resources planning and management in Pakistan" under the theme of strengthening the water governance. The prime goal of the study was to develop a baseline model and data dissemination portal for decision making for water resources planning and management at the barrage command level.

1.2 Objectives

1. To develop a central data repository for water related data in Pakistan.
2. To develop a web portal for data dissemination.
3. To setup a WEAP system model and test it for;
    - ☐ Baseline scenario
    - ☐ Growth scenario

2 REVIEW OF LITERATURE

2.1 Indus Basin Irrigation System in Pakistan

The Indus is one of the major rivers of Asia and the longest one in Pakistan, having a length of 3,180 km. It originates in Tibet (China) and enters Pakistan at Ladakh, Gilgit-Baltistan; while the Shyok, Shigar and Gilgit rivers that usually contain glacial melts join the Indus in Gilgit. Then, Indus curves towards the south and joins the Peshawar's hilly region, flows quickly through the Hazara, and is controlled at the Tarbela reservoir. The Kabul River joins the Indus near Attock. It then enters the Punjab region and travels the entire length of Punjab, where four other rivers, Jhelum, Chenab, Ravi, and Sutlej make confluence with the Indus. Ahead of the confluence of these four Rivers, the Indus enters the Sindh Province. In Sindh Province, water is distributed from the Guddu, Sukkur, and Kotri Barrages. The Kotri Barrage is the last controlling structure on the Indus, and it is situated at Jamshoro. Below Kotri the Indus enters the Arabian Sea near Thatta.

The Indus Basin Irrigation System (IBIS) in Pakistan comprises of 3 major reservoirs, 45 canal comands, 12 inter-river link canals and 19 barrages, covering the gigantic Indus plains of Pakistan (Kahlown and Majeed, 2003). Vast variety of crops are grown in Pakistan. Wheat, rice, sugarcane, and cotton are regarded as major crops. In addition to that, Pakistan also produces pulses, maize, sorghum, different oilseeds, vegetables and different fruits.

Approximately 84% of the flow occurs in Kharif (summer) season, and only 16% of the flow is received in Rabi (winter) season (Kahlown and Majeed, 2003). The rainfall is not only insufficient but also irregular, most of the rainfall occurs in the months of July to September (Ethan *et al.*, 2014). The Indus Basin has extensive area which is underlain by groundwater aquifer and it is estimated at about 16.2 million hectares (Ahmed *et al.*, 2002). In brief, the contribution of surface water, groundwater and rainfall at farm gate is 62.3 MAF, 42 MAF and 5 MAF, respectively (PILDAT, 2011).

2.2 Water Sharing and Conflicts in Pakistan

Long history of conflicts exists in Indus river basin. In 1901, Sindh complained of water shortage, as a result, Punjab was prohibited from withdrawing water from Indus without permission of Sindh (Memon, 2002). In 1919, Cotton Commission of Government of British India issued a report, whereby Punjab was precluded from construction of any irrigation project till the construction of Sukkur Barrage. In 1925, Punjab requested to draw water from Thal canal, which was rejected by Viceroy Lord Reading, but afterwards it was allowed by Anderson Commission in sheer violation of Viceroys orders (Memon, 2002). Therefore, Sindh lodged a complaint under Government of India Act 1935.

As a result Rao Commission was formed, which recognized the right of Sindh over water of Indus River. Consequently, water sharing agreement was signed in 1945, which is known as “Sindh Punjab Agreement”. This agreement was the recognition of the right of Sindh over Indus River and Punjab was precluded from doing any activity without prior consent of Sindh.

After partition of British India in 1947, Pakistan emerged on the map of the world as a sovereign state. As a result Indus Basin acquired the status of trans-boundary Basin with many head works in the upstream. Ultimately, after the expiration of stand still period, the water was stopped by the India which created chaos in the newly born state of Pakistan. The water which was eventually stopped by India was of Punjab share and after losing that share in the hands of India, the Punjab started using water of Indus River (Sindh’s share), in violation of Sindh Punjab Agreement 1945 (Memon, 2002). Later, the dialogue and mutual consultations between the two states led to signing of Delhi Agreement on 4^{th} May 1948 which said that India will not stop the water suddenly before informing Pakistan and sufficient time will be provided to Pakistan to arrange some alternate source (Iyer, 2008). This interim arrangement was followed until 1960 when Pakistan and India entered into a treaty known as Indus Water Treaty 1960, which recognized the right of Pakistan over Indus, Jhelum and Chenab. Subsequently, Pakistan received funding from donor countries to carry out new arrangement for water distribution in the country. However, the conflict started again and Punjab is constantly blamed for overusing the water of other provinces. As a part of the mitigation efforts to resolve this controversy and to address the water allocation issue, Rates Committee was formed in 1968 under the leadership of Justice Fazl-e-Akbar but it failed to resolve the conflict (Salman *et al.*, 2002). Finally in 1991, Federal Government under the leadership of the then Prime Minister Nawaz Sharif expedited the efforts to resolve the matter of water distribution. On 16th of March 1991, the accord was signed with consensus of all the provinces which is known as Indus Water Apportionment Accord (WAA) 1991. An authority known as Indus River System Authority (IRSA) was formed for monitoring the implementation of Accord. Ten-daily basis allocation were given to provinces according to this accord and shortages were promised to be shared in equal proportion. Within three years of signing of accord this accord failed to hold the trust of most of the stakeholders and the performance of IRSA became controversial. The conflict was further intensified in the drought years of 2001 and 2002. Due to absence of Council of Common Interests (CCI), a constitutional body, the President of Pakistan took the matter in hand. Efforts were made to check the ground realities. Another conflict cropped up in 2010 regarding opening of the Chashma-Jhelum (CJ) link canal (PILDAT, 2011). In times of excess supplies there was no any controversy or conflict but in drought years it intensifies.

In fact, in times of excessive supply the country would face riverine floods. Further, this mistrust among provinces is also a hurdle in construction of new storage projects for storage of excessive supplies that can be used in times of drought.

Although WAA settled the issue of allocation of water among the provinces, yet there have been some reservations and therefore, the WAA has been a historical point of conflict, and in the future with growing demands, climate change and water shortages, the conflict may increase in magnitude (Kanwal, 2014; Anwar and Bhatti, 2017). The current water distribution to each province includes 37% to each Punjab and Sindh, 12% to Balochistan and 14% to Khyber Pakhtunkhwa. The conflicts arise mostly during extreme conditions i.e. both during flood and drought periods. During drought periods, the lower riparian areas receive less water than minimum required, and during floods the downstream areas receive most of the flood water with all sorts of effluents, leading to degradation of the ecology. It is further argued that the water distribution formula is not being enforced as per accord which is based on ten-daily average use and seasonal adjustments (IUCN, 2010). A reliable system of water management is needed to provide reliable information which can help in making rational decisions about the water distribution. This would be helpful in ensuring a transparent water distribution system and thus the inter-provincial disputes could be minimized (IUCN, 2010).

Furthermore, the water allocation scheme between the provinces based on the WAA is not formulated according to the changing climatic, economic, social and technological situations in the country (Wescoat *et al*., 2000). Clause 14b of WAA 1991 used by the IRSA for water allocation is based on the averages of the flow, which makes the system more like a supply side driven rather than demand driven. As the impact of climate change becomes more adverse, the conflicts on fixed percentage sharing will rise and the system may divert more towards the demand side (IUCN, 2010). Yang *et al*. (2014) concluded that under different future climatic conditions the overall net economic benefit from irrigated agriculture will not change significantly, if the allocation between the provinces is varied as of WAA (1991). However, the sharing within the province at the canal command area will affect the net economic benefit the most. Water sharing is multidimensional issue, which needs transparent data sharing, and decision making for sustainable use of water resources.

2.3 Integrated Water Resources Management

Water management is a complex problem due to the involvement of multiple sectors, which makes consensus building in water sector a difficult task. It requires evaluating the problem in the context of hydrological, political, economic and social dimensions in an integrated way based on strong evidence supported by scientific data. Development of a decision support system for water resources planning and management is a challenging task. Besides data and modeling challenges, there are multiple stakeholders involve that include NGO's, politicians, engineers, farmers, industrialists, concerned citizens for environment and media (Cunge and Erlich, 1999). For example, the question of building a large storage reservoir in Pakistan has been debated for a long time now. Though, stakeholders agree in general with the need to ensure water supply to the cities/agriculture, power generation, and downstream flood protection, but faces political disagreements. This is partly because of mistrust among provinces since the reservations of different stakeholders have not been addressed to gain their confidence.

Especially in the large basins where the goal is not just optimizing the operations, economy or just looking at the climatic uncertainties, the goal is to improve the livelihood of stakeholders by operating the system under different stresses without damaging the ecosystem of the basin. Basin level studies become more complex, when one or more nations are dependent on the basin on one river. In such cases, suppose if upper riparian decides to divert the water to agriculture sector for maximum economic benefits without considering the impact on lower riparian, then this may lead to unprecedented consequences. In reality, the local, national and inter-regional political/ social conditions govern the decision making for national development. In terms of policy implications- if the regulations for the ecological flows are removed then the water flow into sea will reduce, which will ultimately lead to reduction in the biodiversity of the delta, increase in the seawater intrusion, and subsequent land degradation and loss of agricultural production. Similarly, for the control and mitigation of the greenhouse gasses (GHG), international agenda/ legislature is enforced on the countries to reduce the GHG emissions. If none of the country(s) abides by the law, their tendency to exploit natural resources will be excessively larger and more focused on fulfilling the energy requirements no matter what resource type has been availed. By doing so, the local needs of energy for local and surrounding areas will be acquired at the cost of environment and health degradation. Considering the similar condition in the Indus basin, if the international obligations are removed, then livelihood and environment of lower riparian will suffer on Indus River.

2.4 Review of Water System Modelling Framework

Adopting an integrated approach to water management is a daunting task. Of the various models currently in use, review of these models will provide the most valuable direction forward for codifying research aims. We have reviewed the existing tools keeping in view the following questions: "What conceptual approach is better representative of water system?"; "what type of data input are required?"; "which scale to consider in modelling?", and "how the models could be coupled with database?".

Based on the review, we adopted a Water Evaluation and Planning (WEAP) modeling framework that uses a common data structure to unify the coupling of existing tools. WEAP system is a scenario based node-link tool for studying water system at municipal, agriculture, sub-basin and basin scale. WEAP is a water centric (i.e. having detailed water calculation) model having capabilities of modelling water-food nexus. This type of model is capable of integrating with LEAP (Long Range Energy Alternatives Planning) model that has capabilities of performing detailed energy calculations. The WEAP model uses linear programming (LP) approach to solve the water allocation problems based on the user defined demand priorities and supply preferences. WEAP incorporates the physical processes via coupling hydrologic sub modules i.e. lumped rainfall-runoff model, ground water model and surface water quality. Data input in the model is based on the modeling object defined in the modules. Data input/output is divided into the following main groups i.e. demand, hydrology, supply, resources, water quality and finance. The model itself has a good data structure but lacks in coupling with standard structured data models although it has a structured data reporting mechanism.

The LEAP system (Heaps, 2016) is a scenario based tool that addresses the energy system at national scale. It has generic structure that can be implemented at multiple scales i.e. local, regional, basin and national scale. LEAP is structured such that it divides the system in to four levels: sector; subsector; end use; and device. Analysis and data requirement in the LEAP is dependent on the modeling approach: i) top down approach (which includes the total consumption in each sector); ii) bottom up approach (which considers the fuel consumption in each device and end uses in each sub sector of the economy). Datasets are grouped as: i) demographic data; ii) economic data; iii) general energy data; iv) demand data; v) transformation data; vi) environmental data, and vii) fuels data. LEAP has capabilities of coupling with structured databases. In addition to these datasets, LEAP has also range of functions that can quantify the output in terms of different social, economic and energy related development indicators. It includes a technology and environment database (TED) that includes data on technical characteristics, costs and environmental impact for different energy technologies.

Climate, Land-use, Energy, and Water (CLEW) (Howells *et al*., 2013) is a framework in which the existing tools in each sector are integrated into a modular modeling approach. Models are coupled such that output from one becomes input to other model. Howells *et al*. (2013) applied the CLEW approach in the Mauritius for assessing the policy scenario. WEAP-LEAP model were developed using agro-ecological zones as the modeling scale and integrated into the framework to get the answer to policy questions.

PODIUM model (De Fraiture *et al*., 2001) is a spreadsheet based tool that addresses the water-food interaction at the national scale. Model uses scenario based approach taking in account the complex feedback between water and food sectors. Four modules in the model represent this feedback: Module-I estimates the national food requirement based on the population growth; Module-II estimates the national food production based on the crop yield for irrigated and rain fed areas; Module-III calculates the water demand based on estimated food production and system efficiencies; and Module-IV determines the industrial and domestic water use based on the income growth production. The Model is adaptive with respect to the modeling scale, i.e. the model takes country as the basic unit but it can aggregate demand-supply analysis at basin, sub-basin or even at global scales. PODIUM also has the capabilities to use the data from the structured databases, for example De Fraiture *et al*. (2001) used data from AGROSAT, Water Resources Institute database, United States Department of Agriculture database, and World Water and Climate Atlas for performing analysis in the development of the World Water Vision.

The Indus Basin Model Revised (IBMR) is an economic optimization model that addresses the water-food sectors at the national or basin scale (Ahmed *et al*., 1990; Yang *et al*., 2013). The model uses agro-climatic zones as the basic modeling unit and node link system to represent the irrigation system. The data inputs are divided into the following groups: economic, agronomic, resource inventory, livestock, and water and irrigation system. Outputs include surface and ground water balance, resource usage, crop and livestock commodity, hydropower generation, and salt balance. The model is setup to optimize the consumer and producer surplus using demand- supply relationships for crop commodities. It takes the piecewise linear programing approach to solve the relationships. It does not include detailed energy calculation but has the capabilities to include ex-post analysis for energy calculation in agriculture sector. Yang *et al*. (2016) used IBMR for addressing Water-Energy-Food Nexus (WEFN) in Indus basin via incorporating the energy use in agriculture sector in the model.

WEFN tool 2.0 (Daher *et al*., 2015) is a scenario based tool that addresses the water-food-energy sectors at the national scale. It performs the analysis on user based developed scenarios. User can develop scenarios by varying the self-sufficiency of food products, agriculture methods (i.e. open or protected), water sources, energy sources and food imports. Once the scenario is selected, the tool calculates the sustainability index (defined as the amount of resources required by the scenario divided by allowable limit, where allowable limit is based on the expert opinion of the region under study). Sustainability index prioritizes the importance of the scenario under the local characteristics of the nation selected for analysis. Local characteristics are derived from the local data inputs, which include data for water, energy, land, food, risk, and carbon emissions. Based on the scenario input, tools quantify the results in terms of water requirements, local energy requirement, local carbon emission, land requirement, financial requirement and energy consumptions through import. WEFN tool 2.0 defines the feedbacks between the WEF systems using linear empirical relationships. It calculates the system for one time step and does not include the dynamic behavior of the system. Data inputs are based on model data excluding the data from structured database. As far as scale is considered, it is only capable of considering variable sensitivity with respect to national scale.

Tools reviewed above have capability to define the nexus with focus on one sector, considering different scale. For example WEAP can be used to answer the cross sectoral (i.e. WEF) questions at national or basin scale considering water as a focus sector. Similarly IBMR considers detailed feedback for water and food but only for agriculture usage. It lacks in the definition of different uses of water and energy. While answering the policy level questions at larger scale, robust models with less data requirement are desired but the tradeoff on counter feedback loops from all the sectors at the considered modeling scale are not acceptable. WEF nexus tool 2.0 is a good example of such consideration but it still lacks in dynamic consideration of sectoral feedbacks on different scales.

Despite progress on different fronts, there is still lack of the tool that can be dynamic to the scale on the definition of the water-energy-food interactions to be considered. Such kind of modeling tool is complex to build, so there is need of a framework that can unify the structure between the existing models that consider the water interactions with energy and food sectors at various scales. This kind of framework will only be possible when all the community in these sectors can agree on a standardized structure for storing and sharing of the data.

Based on the reviewed tools, the following suggestions are proposed;

- A control vocabulary defining the data inputs should be standardized. The existing tools seem consistent with the data input groups such as demand, supply, hydrology, economics, environment, demographic and energy transformation. Each data input has model specific parameters that need to be consistent to avoid redundancy for data compilation and storage.

- A system perspective should be adapted for the model integration in the framework. Most of the tools define the system by node-link structure. Structured data models should be able to store the location of data while maintaining the network topology between the node-link in the system.

- Water, energy and food sectors are dynamic with respect to scale and resource usage within and among the sectors. Models defining these interactions have to be adaptable with respect to modeling scale and resource.

3 MATERIALS AND METHODS

This study involved a three-step approach to develop a tool that evaluates the scenarios to see the response of different water resources planning and management options (Fig. 3.1). The first step was to develop a central data repository for data storage and retrieval. The second step was to setup a decision support system (DSS) for integrated water resources planning in Pakistan. Main modeling tool used in this DSS is water evaluation and planning (WEAP). The last step was to develop a mechanism for the dissemination of information via web portal. In this Chapter, materials and the methodology used to accomplish the objectives of the present study are described in detail.

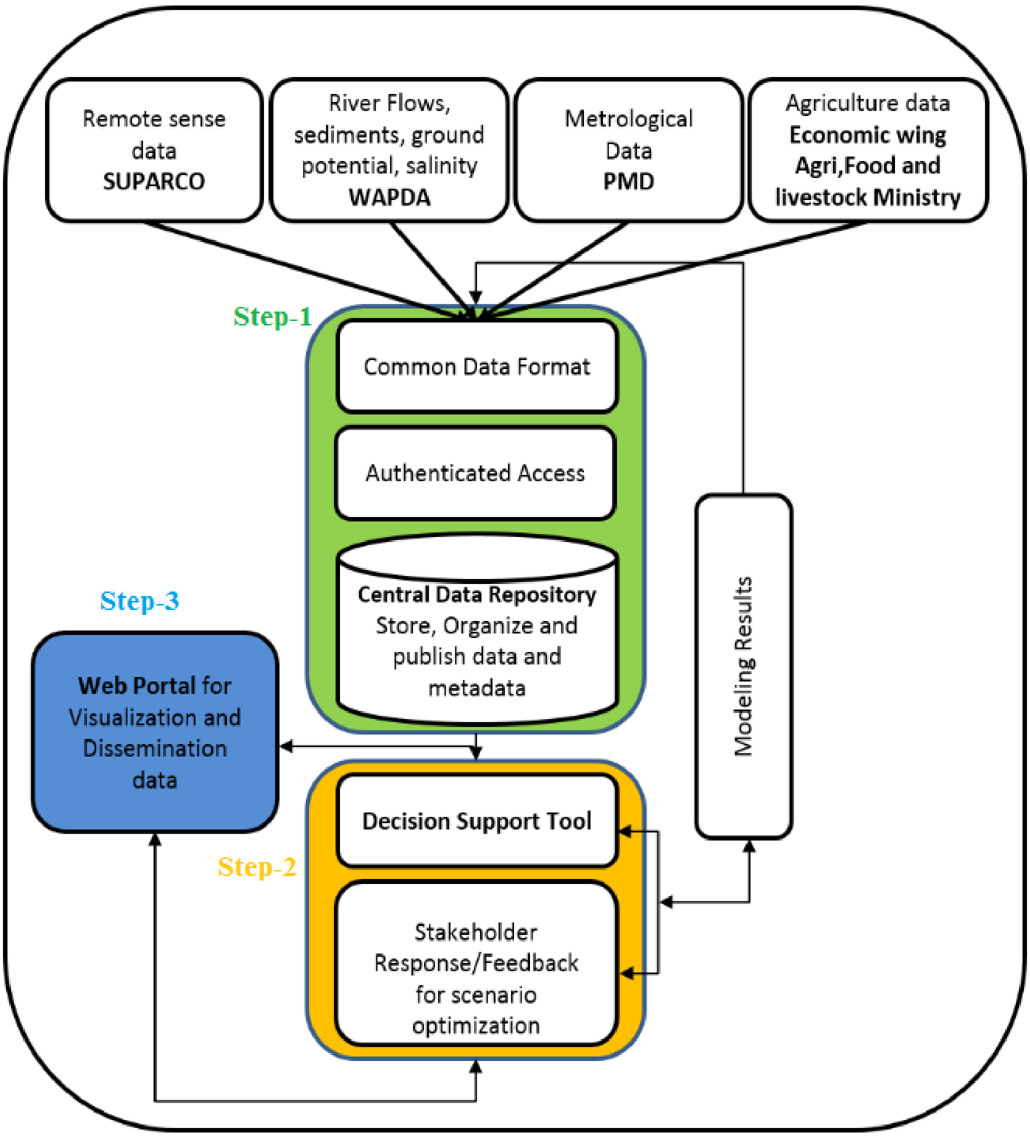


Fig. 3.1: Three-step approach used for DSS development

3.1 Central Data Repository for Data Storage and Retrieval

Central data repository was designed as a relational database. Data model implemented in this study is based on the Observation Data Model (ODM) (Horsburgh *et al*., 2008). ODM is designed to store the point data, which keeps it in data values entity which are interconnected with other entities that store the ancillary information related to observations (Fig. 3.2). We have extended the ODM with new entities of Target, Target

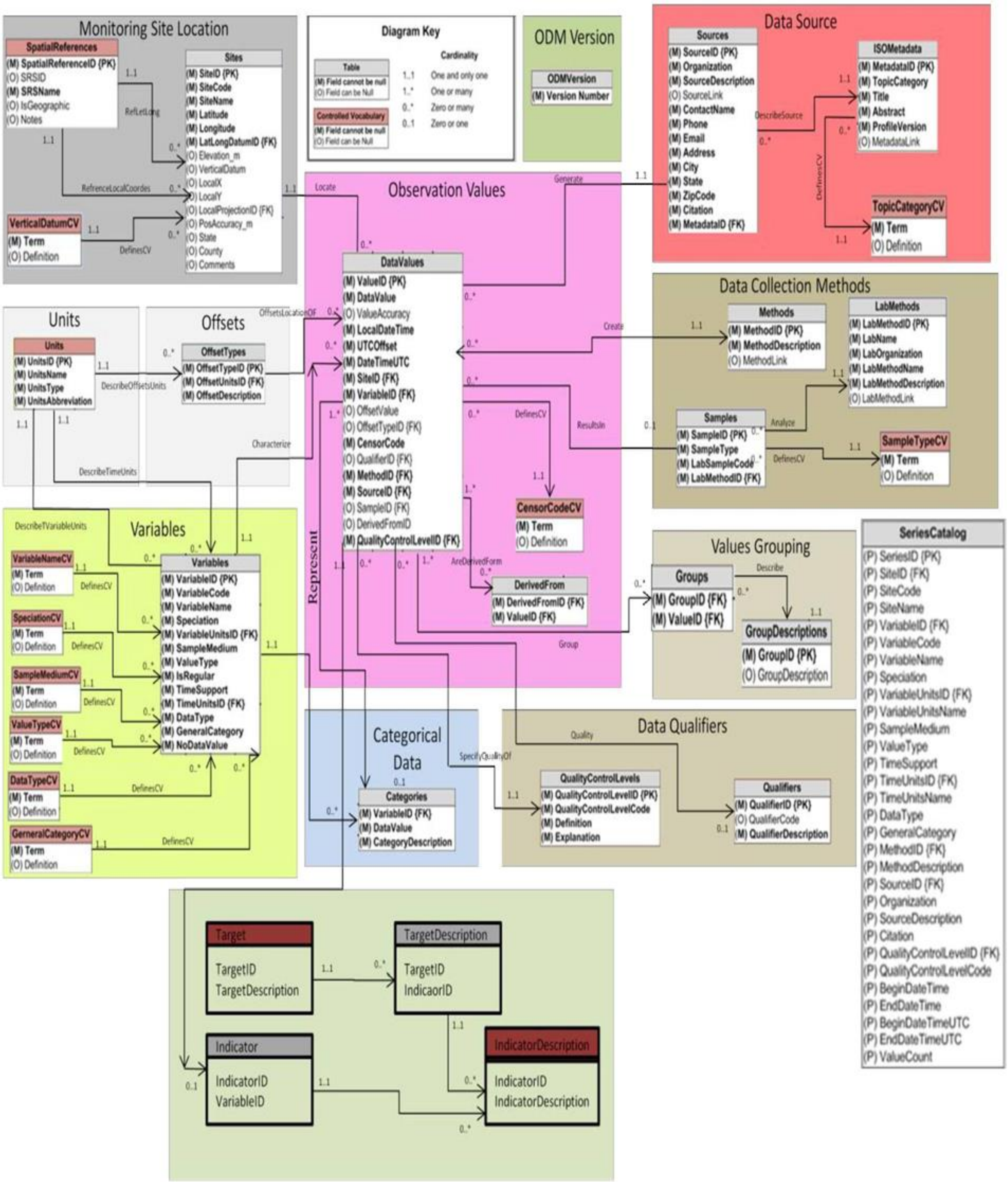


Fig. 3.2: Data model for the relational database. The primary key field for each table is designated with a {PK} label. Foreign keys are designated with a {FK} label. The lines between tables show relationships with cardinality indicated by numbers and labeled with the name and directionality of the relationship.

description, Indicator and Indicator description. These entities can be used to relate the SDG targets and indicators associated with the variables defined in the variable definition table. Implementation is generic in that the Target description, Indicator and Indicator description can be more than SDG related but the vision for now is to store information that can relate SDG to measured variable.

3.2 Web Portal

The design of the web portal is based on the "4+1" model view (Fig. 3.3). There are five views of the data portal, which are: i) Use case view; ii) Logical view; iii) Process view; iv) Deployment view; and v) Data view. Use case view is visible to all the stakeholders; this is general website that is visible to all audience. Logical view is specific to designers, who are responsible for functional requirements of the website. Process view is visible to integrators, integrators handle non-functional requirement of the website. Programmers use deployment view that is for the software requirement that includes describing the modules and sub-systems of the application. Architecturally, significant persistent elements in the data model are described in the data view, which is handled by database administrators. Web portal is developed using ASP.net MVC framework, and hosted on a dedicated domain, which is www.beta.dsspak.org.

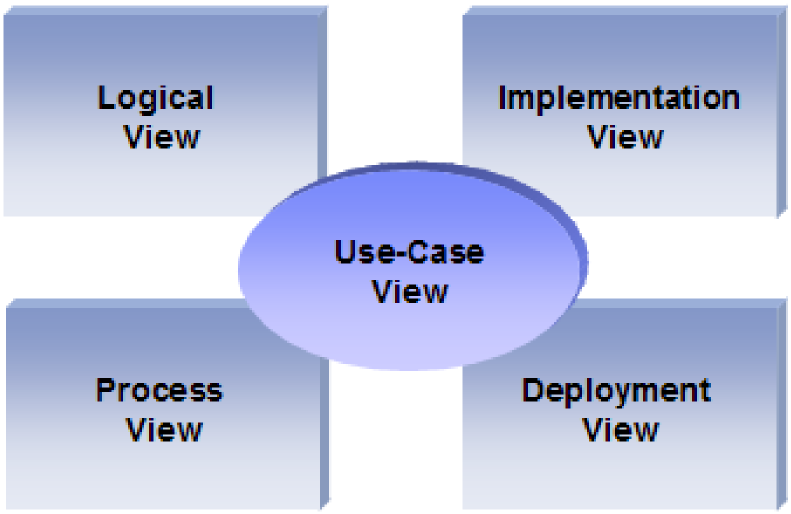


Fig. 3.3: "4+1" model view of the web portal

3.3 Water Evaluation and Planning (WEAP) System Modeling

The Indus Basin has 45 canals, and the command of each differs in terms of climatic and meteorological factors. A detailed analysis is conducted to determine the future water demands of canal commands in the Indus Basin. The two chief water demands determined in this study include: (1) irrigation water requirements, estimated using climatic conditions and the cropping pattern of the area; and (2) domestic water demands, calculated using population growth rates available from the Federal Bureau of Statistics. The segments of the Indus River Basin under consideration in this study are the Baloki, Islam, Jinnah, Khanki, Rasul, Sindhnai, Sulemanki, Taunsa, Trimmu, Punjnad Barrages and the lowermost barrages of Guddu, Sukkur, and Kotri (Fig. 3.4).

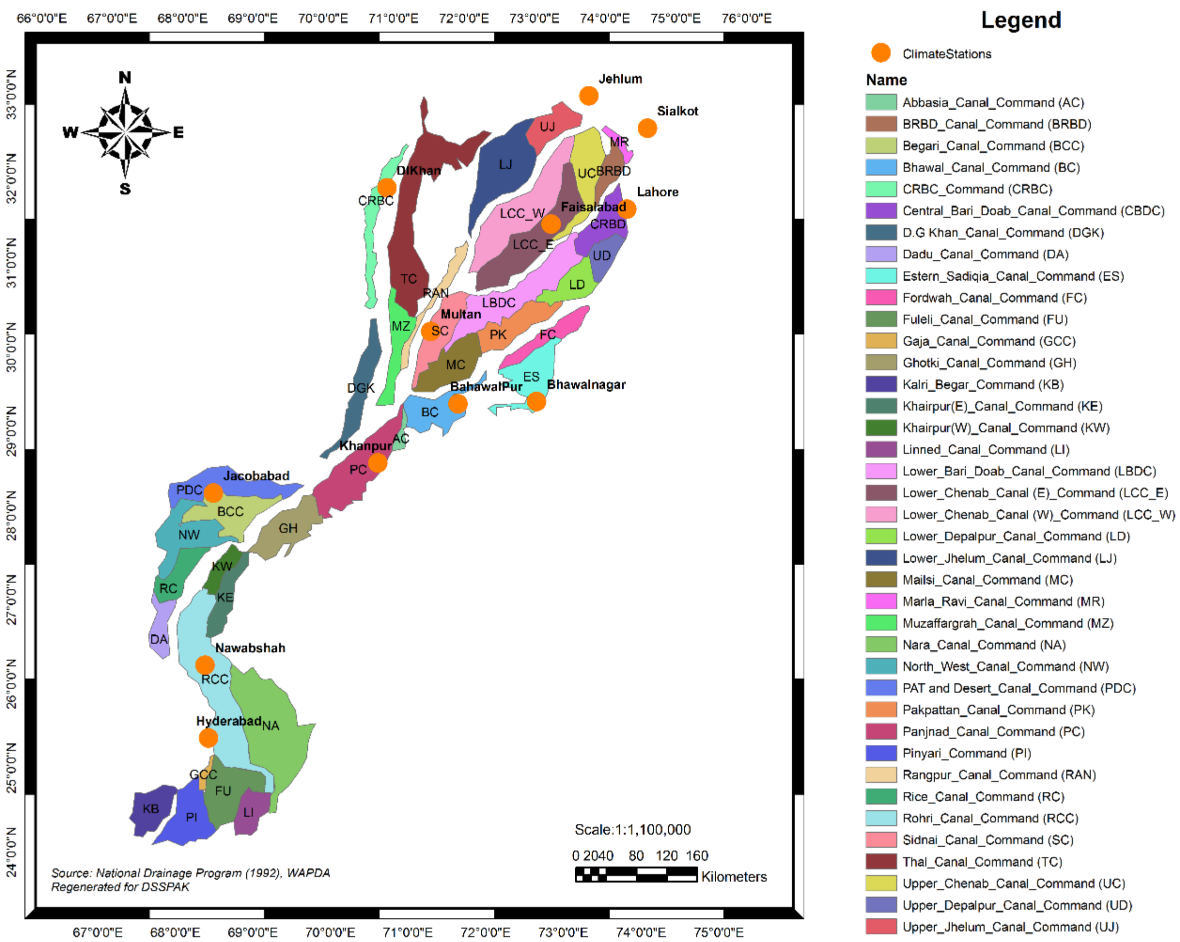


Fig. 3.4: Indus basin irrigation system (IBIS)—Indus, Jhelum, Chenab, Sutlej, and Ravi Rivers in Pakistan. Study Area includes Baloki, Islam, Jinnah, Khanki, Rasul, Sindhnai, Sulemanki, Taunsa, Trimmu, Punjnad barrages of Punjab and lowermost barrages Guddu, Sukkur, and Kotri of Sindh, and their culturable command areas.

3.3.1 Estimation of evapotranspiration

Several methods are used to measure evapotranspiration, including the Lysimeter (Watson and Burnett 1995; Davie, 2008), the budget equation assessing energy balance and mass transfer (Pruitt et al., 1973; Allen *et al*., 1998), and the evaporation pan (Barnett *et al*., 1998) methods. The combinational models, such as those recommended by the Food and Agriculture Organization (FAO), and especially the Penman and Monteith model (Allen *et al*., 1998), have been found to be more accurate than other models (Qiu *et al*., 2002; Ghamarnia *et al*., 2015; Djaman *et al*., 2015). Thus, this study uses the Penman–Monteith model for crop water demand estimations. The model requires four climatic variables: minimum and maximum temperature, relative humidity, wind speed, and sunshine hours.

3.3.2 Node-Link system model

In the WEAP modeling, demand sites, reservoirs, river/canal off take points, and groundwater reservoirs are conceptualized via nodes. These nodes are linked together with lines (i.e. links) representing off take structures, such as canals, pipelines, and river diversions. The main conceptual elements used to develop a baseline model are explained in the sections below.

3.3.3 Demand sites

A demand site represents water user that depends on the common water distribution system. In this study, the barrage command area is used as a modeling unit. Demands are calculated at the canal command area, and then lumped at the barrage command. Two demand nodes— agricultural and domestic—are recorded and connected to river nodes via transmission links.

3.3.4 Rivers, diversions, and river nodes

Rivers and diversions are represented by reach element connected between the river nodes. Diversions like link canals and other contributing tributaries can be connected to the river. In the applied model, the following rivers were considered in the system: Indus, Chenab, Jhelum, Ravi, Sutlej, Kabul and Soan.

3.3.5 Withdrawal

Withdrawal nodes, where water is directly removed from the river, are provided at each barrage in the rivers considered in the system.

3.3.6 Diversions

In diversion nodes, water is diverted from the river to another river or canal. The following diversion nodes represent the 11 link canals: Chashma-Jhelum link, Taunsa-Panjnad link, Upper Jhelum link, Rasul-Qadirabad link, Marala-Ravi link, Upper Chenab link, B.R.B.D link, Qadirabad-Baloki link, Trimmu-Sindhnai link, and Sindhnai- and Mailsi-Bhalwal link, which divert water from western to eastern rivers.

3.3.7 Reservoirs

Reservoir nodes represent the reservoir sites on the river. We have considered Tarbela and Mangla as the reservoir nodes. These nodes are applied such that the water can be released directly to the downstream nodes and to the demand sites. As per scope of the study we have not modeled the hydropower production but it can easily be extended in future development of the model.

3.3.8 Flow requirements

Flow requirement nodes represent minimum flow requirement for in-stream flow for river or at the diversion. We have used these nodes to control the outflow from reservoir, water diversion into the link canals and downstream requirement at the barrages withdrawal nodes.

3.3.9 Stream flow gauges

Gauges represent actual measurement stations and are installed on the downstream of barrages and reservoirs to compare model outputs with observed measurements.

3.3.10 Priorities of water allocations

Priorities are user-defined for the model and include demand priorities and supply preferences. Priorities range from 1 to 99; 1 is the highest priority, and 99, the lowest. The priorities are set to 1 for domestic demand and 2 for agricultural demand, which are further adjusted in calibration. Summary of all the data used as input is given in Table 3.1.

3.3.11 Time horizon

In WEAP, the “Current Accounts Year” (CAY) is used as the start of the analysis and “Last Year of Scenario” (LYS) is taken as the end of the simulation. Time horizon is easy to adjust in the WEAP but the limitation is with the available input data. We have taken CAY as the year 1991. Reference scenario is simulated till 2013 to perform the baseline analysis. Then the LYS scenario was extended to 2015 while comparing with growth scenario that are simulated till 2040.

3.3.12 Model calibration

The initial simulated flow differed from measured flow gauge data because WEAP allocates water, based on mass balance approach by taking priority of each demand node into account. A stream gauge option, for matching simulated flow with measured flow, was placed at each barrage location and calibration was started for CAY 1991. The calibration was started from the top of the river. For instance, taking the example of Indus River; Tarbela reservoir is located on the Indus River and is considered as the beginning point of the river. The initial model was provided with the head flow of Indus River above Tarbela reservoir, and then the outflow of the reservoir was to be calibrated. For that, filling of the reservoir was assigned the priority 2 and outflow was assigned as priority 1. The outflow simulated after this step was more than measured flow, therefore maximum hydraulic outflow of the reservoir was adjusted, so that model simulated flow may be in agreement with the measured flow at downstream of the reservoir. The next step was the calibration at downstream of Jinnah barrage. Losses were adjusted for calibration of flows at downstream of Jinnah barrage.

Table 3.1: Data used in the WEAP model, along with sources, and temporal resolution

Data	Source	Temporal resolution
Metrological data: minimum and maximum temperature, relative humidity, wind speed and sunshine hours for 11 stations from 1991 to 2015	Pakistan Metrological Department (PMD), Karachi Pakistan.	Mean monthly
Cropping pattern, growth rate, and yield	Pakistan Agricultural Bureau Report 2009.	Annual
Monthly crop coefficients (Kc)	Agriculture University Faisalabad.	Monthly
District wise population data	Population Census Report 2017.	1998 and 2017
Head flows of Indus, Jhelum, Kabul, Soan and Haro from 1991 to 2015	Surface Water Hydrology Project (SWHP), WAPDA.	Daily
Flows of Chenab, Ravi and Sutlej from 1991 to 2015	PMIU, Irrigation Department, Government of Punjab.	Daily
Upstream and downstream data for barrages under the jurisdiction of Punjab from 1991 to 2015	Irrigation Department, Government of Punjab.	Daily
Upstream and downstream data for barrages under the jurisdiction of Sindh from 1991 to 2015.	Irrigation Department, Government of Sindh.	Daily
Operational data of reservoirs viz. storage capacity, dead storage, volume elevation curves and maximum hydraulic outflows.	Water and Power Development Authority (WAPDA), head office Lahore, Pakistan.	-

Third step was the calibration at downstream of Taunsa barrage consisting of a link canal "Taunsa-Panjnad Link". This link canal was assigned with the minimum flow requirement in WEAP software, as the system allows an option to fulfill the minimum requirement of flow before assigning it to any location. The upstream flow of the Taunsa barrage was diverted into the link canal and remaining flow was allowed at downstream of the Taunsa barrage node. The conditions for the remaining flow were not satisfied. Therefore losses and priorities were adjusted accordingly.

The calibration of the flows of other rivers was also carried out in a similar order. The model was validated from 1992 to 2013. After the calibration and validation of the model simulated, observed flows were statistically analyzed to check the reliability of the results i.e. Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2) and percent bias (PBIAS).

3.3.13 Model limitations and assumptions

Models are the representation of real world scenarios but possess a margin of error to accuracy, therefore model limitations and assumptions are implied to get the nearest possible results. Considering such facts, following limitations and assumptions were adopted for this model:

1. Only eight (8) crops, which cover 80% of cropping area in Pakistan, are taken into consideration.
2. Surface water irrigation is focused in the model. We have compared the demand with the surface water supplied to canal command. Groundwater use is not simulated, which is also one of the source in the canal commands.
3. Industrial water consumption was neglected.
4. Subsurface interaction of river streams was not taken into account due to concerned boundaries of this project.
5. Evaporation losses were not considered directly, but the calibration process accounted for the losses in the system.
6. Catchment modeling that includes rainfall runoff was not modeled; therefore, historical data were used as the basis of modeling

3.4 Scenario 1: Baseline Scenario

In baseline scenario, we assessed the present and historical situation in the canal command area. Productivity potential is estimated for crops in each canal command. The demands satisfied by the surface water resources are estimated by the analyses of demand and supply data covering the baseline simulation period (i.e. 1991-2013). Supply withdrawn by the canals from barrages was compared with the allocations.

3.5 Scenario 2: Growth Scenario

To forecast the effect of growth on the model, population growth was set as per 2017 census, and agricultural growth was set at 0.1%. However, due to unregulated population growth, higher agricultural growth rates than the aforementioned rate may be needed to provide additional food. For agricultural demands, the gross cultivatable command areas of barrages and crop coefficients (kc) for crops under consideration were obtained from the provincial Irrigation Departments, the University of Agriculture Faisalabad, and Sindh Agriculture University Tandojam. To calculate agricultural irrigation water demands, the soil moisture method was used in the WEAP model.

4 RESULTS AND DISCUSSION

4.1 Central Data Repository and Web Portal

Central data repository implemented through this study is based on a relational database that is embedded on the webserver. The data repository is hosted on the data portal (www.beta.dsspak.org) in which the user can input the data. In this study, datasets required for modeling are incorporated in the repository; these datasets include the inflows and outflows from reservoirs/barrages, characteristic curves of reservoirs, canal command characteristics, climatic data, agriculture and population statistics, and crop coefficients (Table 3.1).

Fig. 4.1 shows the interface of the website. Index page shows the map available for display to the public user. The tabs “Data Portal” and “Maps” are available on the index page for registered users for input and downloading of the data. A user can register through the “Register” tab. Once user inputs the required details through the “Register” tab and requests to join the portal, administration will be notified to approve the user’s request to be a part of the portal. Once the request is approved, user will be able to enter the portal dashboard through the login page (Fig. 4.2). At the center of the portal dashboard, user can see his/her uploaded data values (Fig. 4.3). The user has options to view the data, download the data and plot the time series of the data. In the “View” tab, user will be directed to the tabular view of the data. In the “Download” tab, user can directly download the *.csv file on the standard format. In the “Graph” tab, user can download the graphic image of the time series data. On the left side of the dash board there are tabs to search the data inputted by other users.

The website is also interfaced to ArcGIS online, for map sharing. Presently, only “Admin” can control the map panel. Map generated in GIS can be displayed on the index page of the website. ArcGIS shape files (*.shp) can be uploaded directly to the ArcGIS online USPCAS-W map page, configured under DSSPAK. The generated map ID can be embedded in the map control panel of the website of DSSPAK (Fig. 4.4). Maps are only for display; however, the DSSPAK Admin can give access to registered users to download the maps through the ArcGIS online page.

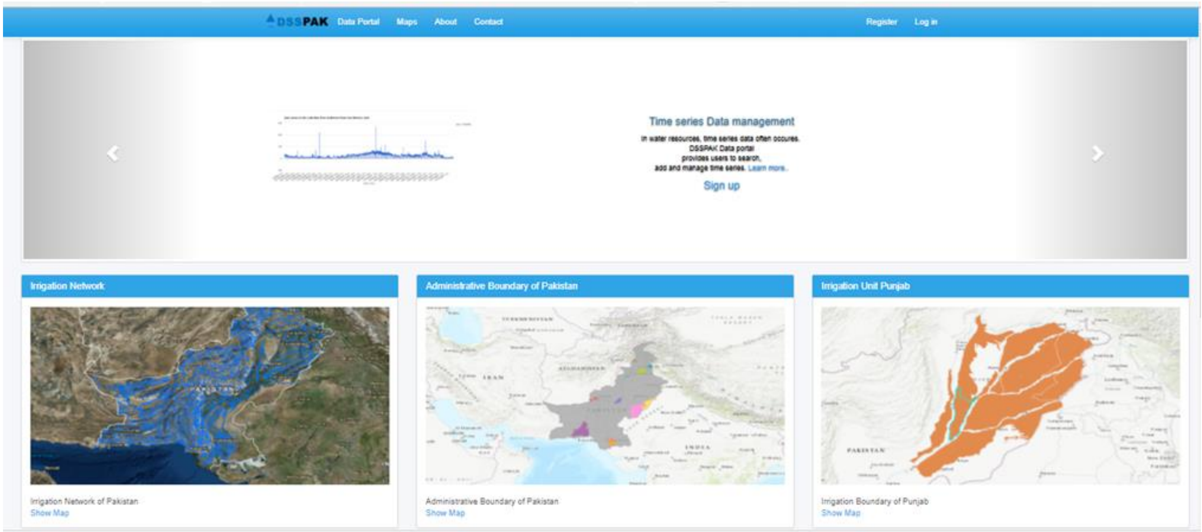


Fig. 4.1: Online portal hosting data repository

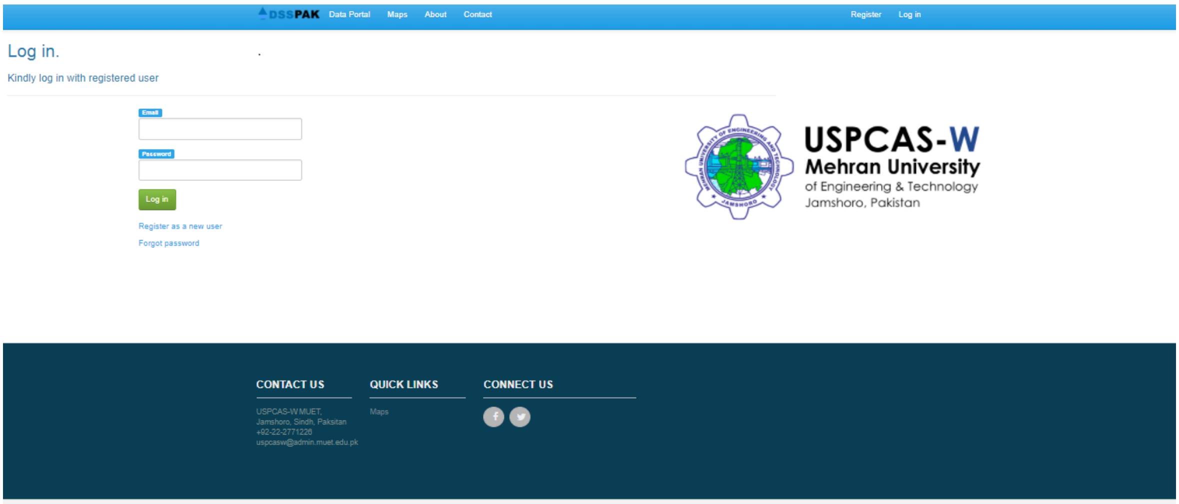


Fig. 4.2: Login page to data portal

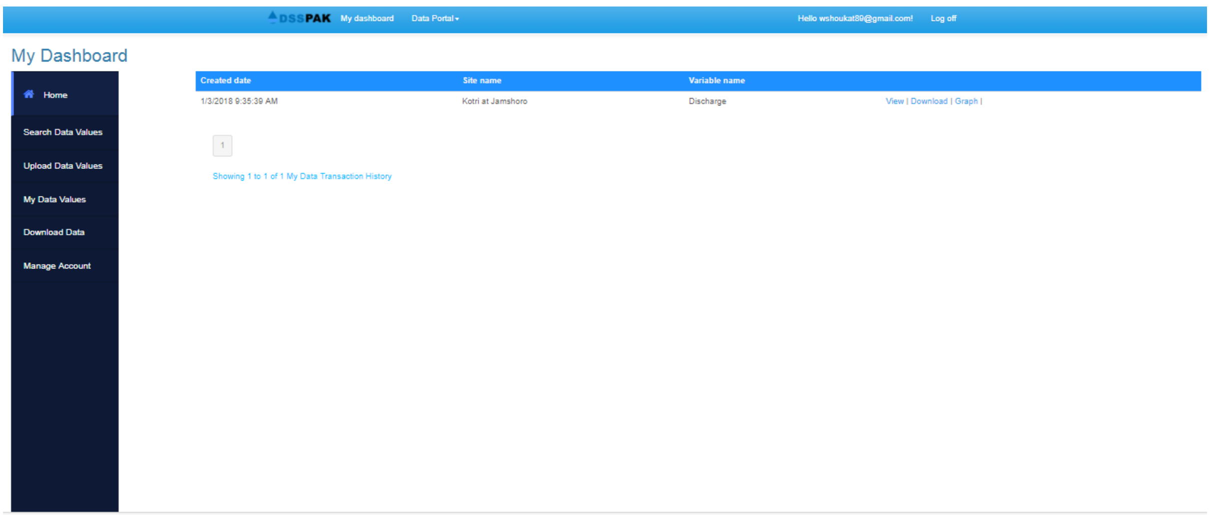


Fig. 4.3: Dashboard of the data portal

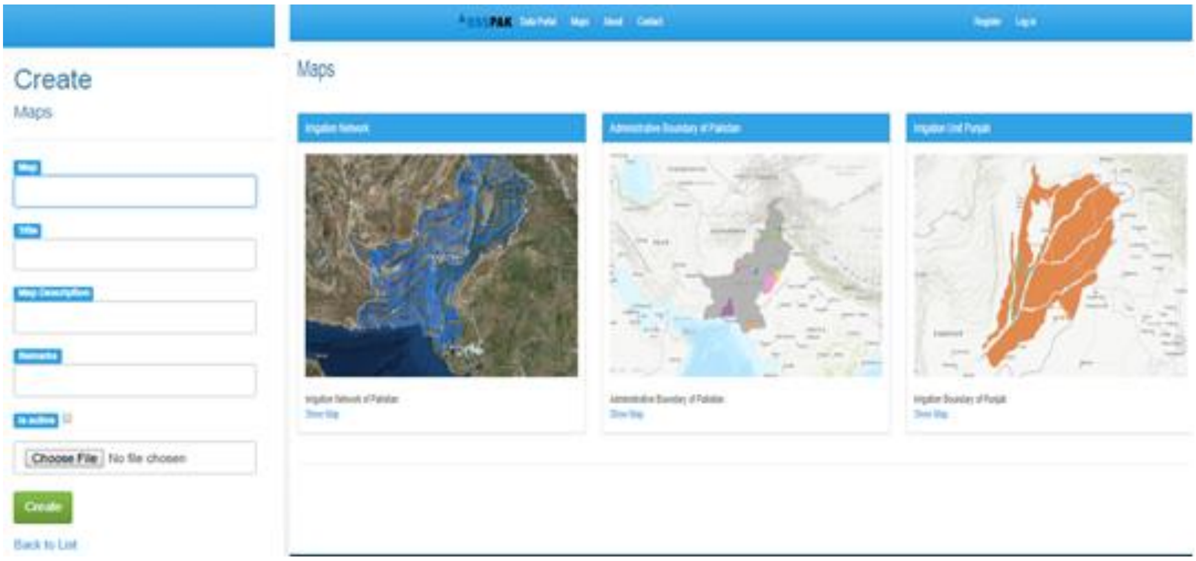


Fig. 4.4: GIS map panel

4.2 Evapotranspiration

Spatial variation in reference evapotranspiration is observed, ranging from 46 in/year at Upper Chenab area to 83 in/year at Guddu left command area. This spatial variation is mainly due to temperature and altitude of the area. The areas at lower altitudes experience higher temperatures, which boost the evapotranspiration process. Hence, a crop grown at lower altitude would require more water for completing its cycle to maturity. The seasonal analysis of reference evapotranspiration has revealed that this variation is not only spatial, but huge temporal variation also exists in reference evapotranspiration rates. There are two cropping seasons in Pakistan, namely Kharif (April to September) and Rabi (October to March). The spatial variation in Kharif is relatively more than that in Rabi season. The temporal and spatial variation in Kharif and Rabi seasons can be compared in a way, that highest reference evapotranspiration (ETo) for former is 57 in, whereas for latter it is 27 in, and the lowest values being 32 in and 13.56 in, respectively (Fig. 4.5). For all the weather recording stations, lowest values were observed in the month of December and highest in the month of June.

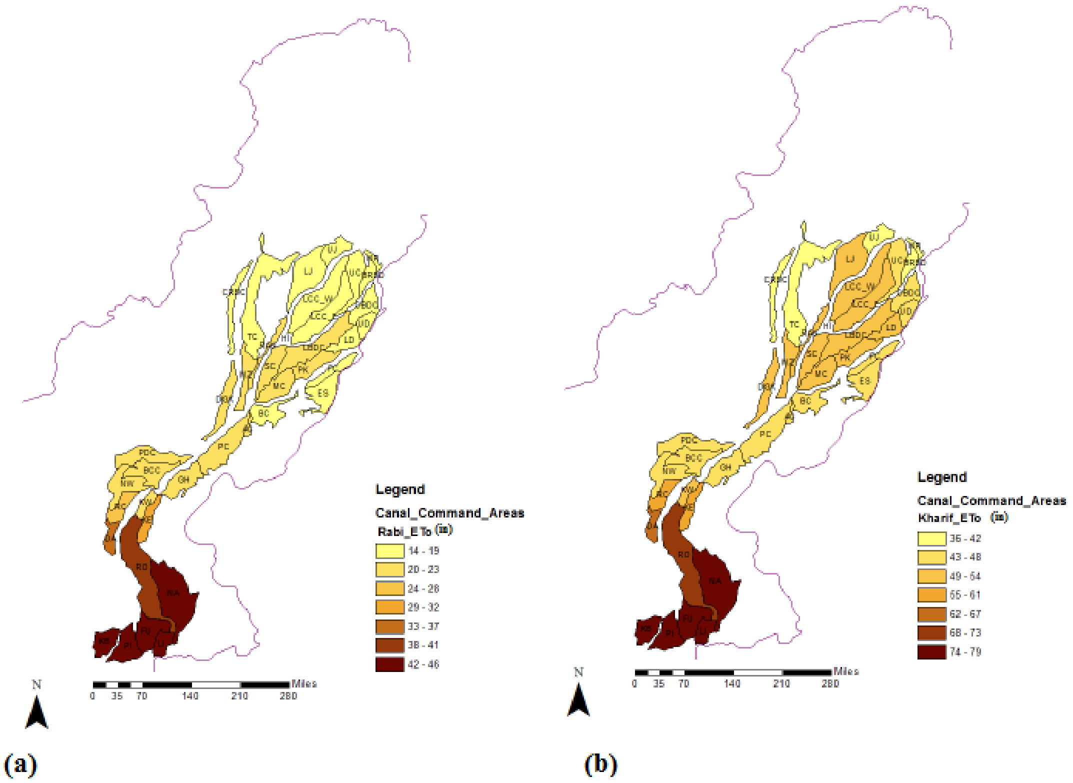


Fig. 4.5: Spatial variations in reference evapotranspiration. (a) Reference evapotranspiration for Rabi season; (b) Reference evapotranspiration for Kharif season.

Potential water consumption depends on the potential crop evapotranspiration, which varies based on crop type and climate of the region. It is the product of the crop coefficient and reference evapotranspiration, and plays a significant role in determining the necessary water supply. A monthly potential evapotranspiration (i.e. total water depth required for crops throughout its cropping period) of major crops was estimated for the canal command areas of Sindh (Table 4.1) and Punjab (Table 4.2).

Table 4.1: Potential crop evapotranspiration (inch) of major crops cultivated under the canal command areas of Sindh

Barrage	Canal	Code	Sugarcane	Rice	Cotton	Maize	Sorghum	Wheat	Oilseed	Pulses
Kotri	KB Feeder	KB	64.25	44.02	37.38	-	18.27	18.93	14.15	9.86
	Fuleli	FU	64.25	44.02	37.38	-	18.27	18.93	14.15	9.86
	Pinyari	PI	64.25	44.02	37.38	-	18.27	18.93	14.15	9.86
	Lined Canal	LI	64.25	44.02	37.38	-	18.27	18.93	14.15	9.86
Sukkur	Nara	NA	66.55	47.39	39.36	-	18.94	20.59	13.60	10.25
	Rohri	RO	67.44	48.72	40.35	-	19.15	19.98	13.08	9.85
	Khairpur East	KE	74.75	52.18	43.32	-	19.82	20.05	13.66	-
	Khairpur West	KW	73.99	51.90	43.06	-	19.59	19.23	13.03	-
	Dadu	DA	73.30	50.71	44.52	-	20.15	20.32	16.18	9.64
	Rice	RC	73.99	51.50	45.20	-	20.31	19.67	15.45	9.11
	North West	NW	75.75	52.73	46.27	-	20.76	20.08	15.68	9.28
Guddu	Pat & Desert	PDC	77.58	53.95	47.34	-	21.19	20.54	15.94	9.45
	Begari	BCC	75.75	52.73	46.27	-	20.76	20.08	15.68	9.28
	Ghotki	GH	71.71	50.49	41.87	-	19.21	18.56	12.52	-

Table 4.2: Potential crop evapotranspiration (inch) of major crops cultivated under the canal command areas of Punjab

Barrage	Canal	Code	Sugar-cane	Rice	Cotton	Maize	Sorghum	Wheat	Oilseed	Pulses
Jinnah	Thal	TC	62.22	29.24	31.19	13.19	18.05	11.53	11.42	-
Chashma	Chashma Right Bank	CRBC	59.93	28.34	29.98	12.75	17.45	11.50	11.35	-
Tunsa	DG Khan	DGK	62.88	30.08	31.76	13.53	18.56	11.72	11.51	-
	Muzaffargrah	MZ	62.88	30.08	31.76	13.53	18.56	11.72	11.51	-
Rasul	Lower Jehlum	LJ	62.85	26.33	30.27	13.57	16.55	13.08	11.89	-
Trimmu	Rangpur	RAN	64.05	30.26	32.25	13.54	18.59	11.84	11.70	-
Panjnad	Panjnad	PC	64.23	32.65	33.57	-	20.59	13.58	12.58	-
	Abbasia	AC	64.23	32.65	33.57	-	20.59	13.58	12.58	-
Khanki	Lower Chenab Canal _E	LCC_W	57.13	24.34	27.78	12.60	15.15	11.91	10.48	-
	Lower Chenab Canal _W	LCC_W	58.93	25.13	28.80	12.98	15.60	12.15	10.71	-
Balloki	Lower Bari Doad	LBDC	58.52	26.42	28.62	13.63	16.30	13.02	11.05	-
Sidhnai	Sidhnai	SC	61.36	30.13	30.37	13.54	17.25	13.67	11.57	-
Sulemanki	Fordwah	FC	70.38	34.84	36.55	-	21.92	14.36	13.43	-

	Eastern Sadiquia	ES	66.61	33.45	34.75	-	21.12	13.68	12.80	-
	Pakpattan	PK	61.26	30.08	30.33	13.53	17.24	13.57	11.51	-
Islam	Qaim	QI	65.32	32.99	34.24	-	20.74	13.21	12.42	-
	Bhawal	BC	62.78	32.06	32.93	-	20.34	12.98	12.15	-
Link Canals	Upper Jhelum	UJ	61.04	25.31	28.95	13.08	16.10	12.93	11.92	-
	Haveli	HI	62.40	30.26	30.72	13.54	17.28	13.70	11.70	-
	Mailsi	MC	61.26	30.08	30.33	13.53	17.24	13.57	11.51	-
	Marla Ravi	MR	50.85	23.54	25.07	11.55	14.81	12.45	9.78	-
	Upper Chenab	UC	52.34	24.36	25.85	11.96	15.34	12.73	10.11	-
	Bambanwala-Ravi-Bedian	BRBD	52.16	24.11	25.67	11.84	15.19	12.81	10.08	-
	Central Bari Doab	CBDC	45.65	21.25	22.53	10.46	13.42	11.18	8.90	-
	Upper Depalpur	UD	54.57	25.21	26.83	12.37	15.88	13.43	10.60	-
	Lower Depalpur	LD	57.82	25.93	28.12	13.40	16.02	12.98	11.00	-

4.3 Model Calibration

Model calibration was performed for Tarbela and Mangla reservoirs, and Jinnah, Taunsa, Rasul, Khanki, Baloki, Trimmu, Sulemanki, and Sukkur barrages. Table 4.3 shows the NSE, R^2, and PBIAS for each calibration point. The performance of the model was satisfactory as per the threshold limits defined by Moriasi *et al.* (2007).

Table 4.3: Model performance results and limits (Moriasi *et al.*, 2007)

Calibration Point	NSE	Limit NSE	R2	Limit R2	PBIAS (%)	Limit (PBIAS %)
D/S1 Tarbela	0.97	> 0.5	0.99	> 0.5	0.60	± 25%
D/S Jinnah	0.95		0.95		-11.43	
D/S Taunsa	0.98		0.90		5.93	
U/S2 Sukkur	0.97		0.97		-7.54	
D/S Mangla	0.99		0.99		5.14	
D/S Rasul	0.99		0.99		1.73	
D/S Khanki	0.95		0.91		-10.51	
D/S Balloki	0.98		0.99		8.07	
D/S Trimmu	0.99		0.99		-4.77	
D/S Sulemanki	0.96		0.99		9.54	

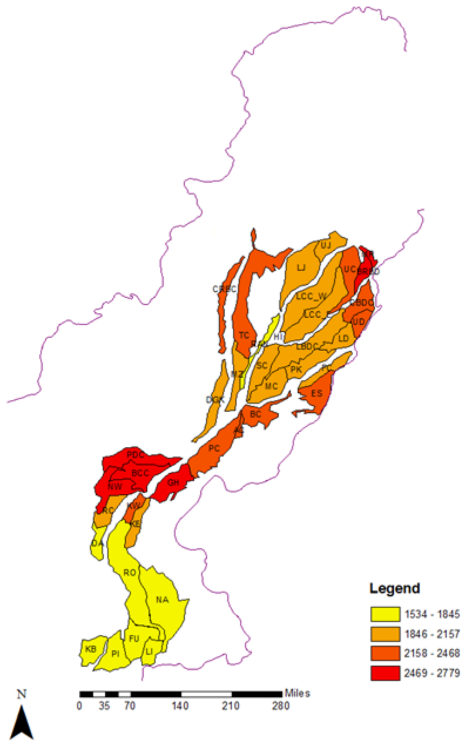
[1] D/S - Down-stream

[2] U/S - Up-stream

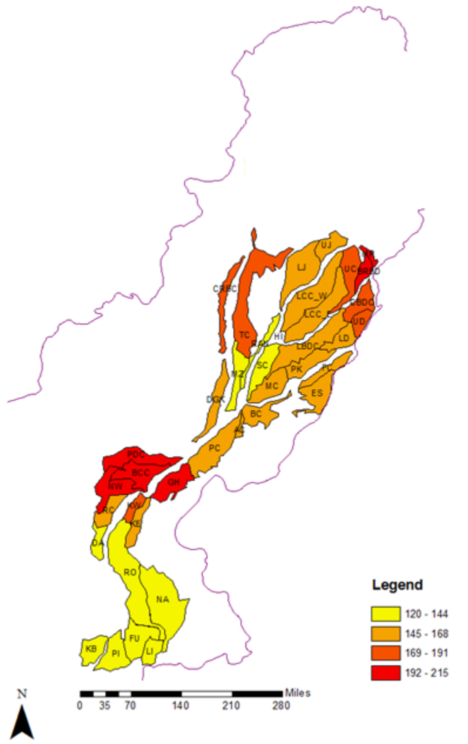
4.4 Base Line Scenario

4.4.1 Productivity potential of water at canal command level

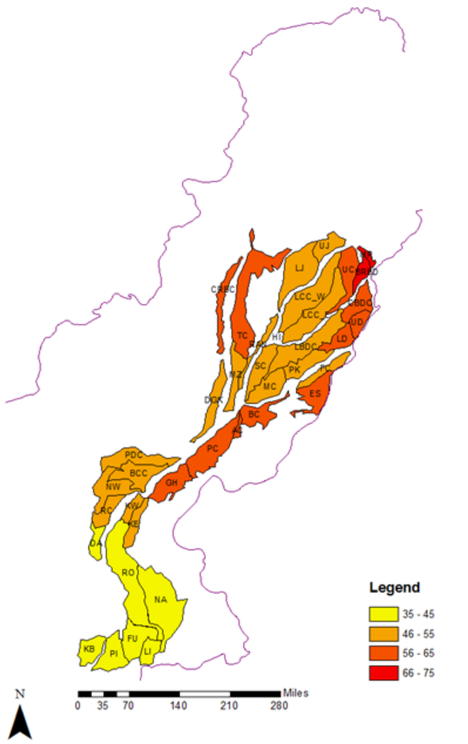
High rates of evapotranspiration have put some areas at risk due to high crop water requirement, hence less area is cultivated with the given amount of water. Nonetheless, analysis of historical data revealed that per acre crop yield of lower riparian was particularly higher than that of upper riparian. This can be attributed to several factors, some of these can be: favorable climatic conditions, early sowing, and excessive use of fertilizers in southern areas. Water productivity potential of all canal command areas for different crops is shown in Fig. 4.6. It can be seen that the Marla-Ravi link canal command area has highest water productivity potential and its surrounding canal commands have also shown plausible results. Kotri canal command area has the lowest water productivity potential. Guddu canal command area, despite lower water use potential, has shown high water productivity potential for sugarcane, rice and sorghum crops.



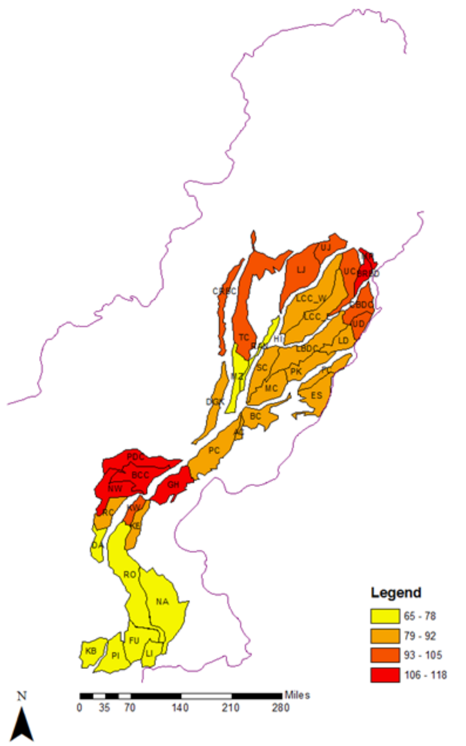
(a) Potential productivity of 1AF of water for sugarcane



(b) Potential productivity of 1AF of water for rice



(c) Potential productivity of 1AF of water for cotton



(d) Potential productivity of 1AF of water for sorghum

Fig. 4.6: Potential productivity for sugarcane, rice, cotton and sorghum in kg for 1 AF of water

4.4.2 Water demand and supply

The irrigation intensity at canal command level depends upon the supply and availability of water. As discussed earlier, besides surface water, the other sources of water supply are groundwater and rainfall in the IBIS. The contribution from alternate sources is not the matter of discussion for this study. The demand satisfied by surface water resource is estimated for each command by analysis of 23 years (1991-2013) of estimated demand and supply data. It can be deduced that the areas having high percentage of reliance on surface water resource have lower area under cultivation and vice versa. This is because of limited or no availability of alternate water supply sources. Specifically speaking, Sindh has low irrigation intensities because of lesser supply of surface water and poor quality of groundwater. The details of average water demand and supply situation for Kharif and Rabi seasons from 1991 till 2013 are shown in Table 4.4 for different canal command areas of Sindh and Punjab.

The surface water withdrawn by Sindh and Punjab provinces against their allocated share in 1991-2013 is shown in Fig. 4.7. In Kharif, the supply has never achieved the mark of allocation and deficiency is shared by both the provinces. The deficiency faced by Sindh was extreme especially for the years 1999 and 2002 when Sindh faced respective shortage of 69.47% and 77.23% of its allocated share (Fig. 4.8). The corresponding water deficit for Punjab for these two years was 17.92% and 19.20%. The most extreme deficiency faced by Punjab was 29.12% in the year of 2001 and in that year Sindh shared shortage of 32.91%.

4.5 Growth Scenario

Table 4.5 shows the water demand projections for different barrages of Punjab (Baoki, Islam, Jinnah, Khanki, Rasul, Sindhnai, Sulemanki, Taunsa, Trimmu, and Punjnad) and Sindh (Guddu, Sukkur and Kotri) based on population and agricultural growth rates. Projected demand till 2040 indicates that the command of Kotri will face drastic increase of 48% as of base year (i.e. 2015), followed by Taunsa (28%), Jinnah (23%) and Sukkur (23%), Khanki (17%), Rasul (16%), Sindhnai (15%), Baloki (12%), Trimmu (12%), Guddu (12%), Islam (11%), Sulemanki (7%), and Punjnad (7%).

Overall, the water demand of canal commands in Punjab Province, including the link commands i.e. upper Jhelum, upper Chenab, upper and lower Depalpur, BRBD, and CBDC agriculture systems was observed to be 42.3 MAF in the base year 2015. Accounting for agricultural and domestic growth rates, water demand is estimated to be 43 MAF in 2020, 43.8 MAF in 2025, 44.6 MAF in 2030, 45.7 MAF in 2035, and 46.9 MAF in 2040.

Table 4.4: Average water demand and supply situation in Kharif and Rabi seasons (1991-2013) in different canal command areas of Sindh and Punjab

Barrage	Canal command	Kharif			Rabi		
		Demand (MAF)	Supply (MAF)	Demand satisfied by canal water (%)	Demand (MAF)	Supply (MAF)	Demand satisfied by canal water (%)
Guddu	GH, BCC, PDC	8.27	5.62	67.9	2.18	1.69	77.5
Sukkur	Ro, NA, KE, KW, DA, NW, RC	15.34	12.56	81.9	9.22	6.96	75.5
Kotri	KB, FU, LI, PI	5.43	4.31	79.4	2.49	1.88	75.7
Baloki	LBDC	4.27	2.47	57.8	3.26	1.74	53.6
Sulemanki and Islam	PK, FC, ES, QI, BC, MC	10.95	7.18	65.5	6.83	4.08	59.7
Jinnah	TC	1.92	1.92	100	2.28	2.27	99
Khanki	LCC_E, LCC_W	5.99	4.26	71.2	5.34	3.53	66.2
Rasul	LJ	2.31	1.66	72	2.32	1.30	56
Sindhnai	SC	1.96	1.13	57.9	1.14	0.65	56.4
Taunsa	DGK, MZ	3.85	3.85	100	2.42	2.40	99
Trimmu	RAN	0.77	0.46	59.1	0.43	0.11	24.8
Panjnad	AC, PC	4.49	3.24	72.2	2.66	1.40	52.6
Chashma	CRBC	0.53	0.53	100	0.65	0.65	99
Link Canals	UC, BRBD, CBDC, UD	3.28	2.79	85.2	2.07	1.63	78.8
	LD	1.01	0.91	89.9	0.45	0.15	33.9
	UJ	1.12	0.79	69.9	0.95	0.92	97.1
	HI	2.54	0.35	13.9	1.65	0.22	13.5

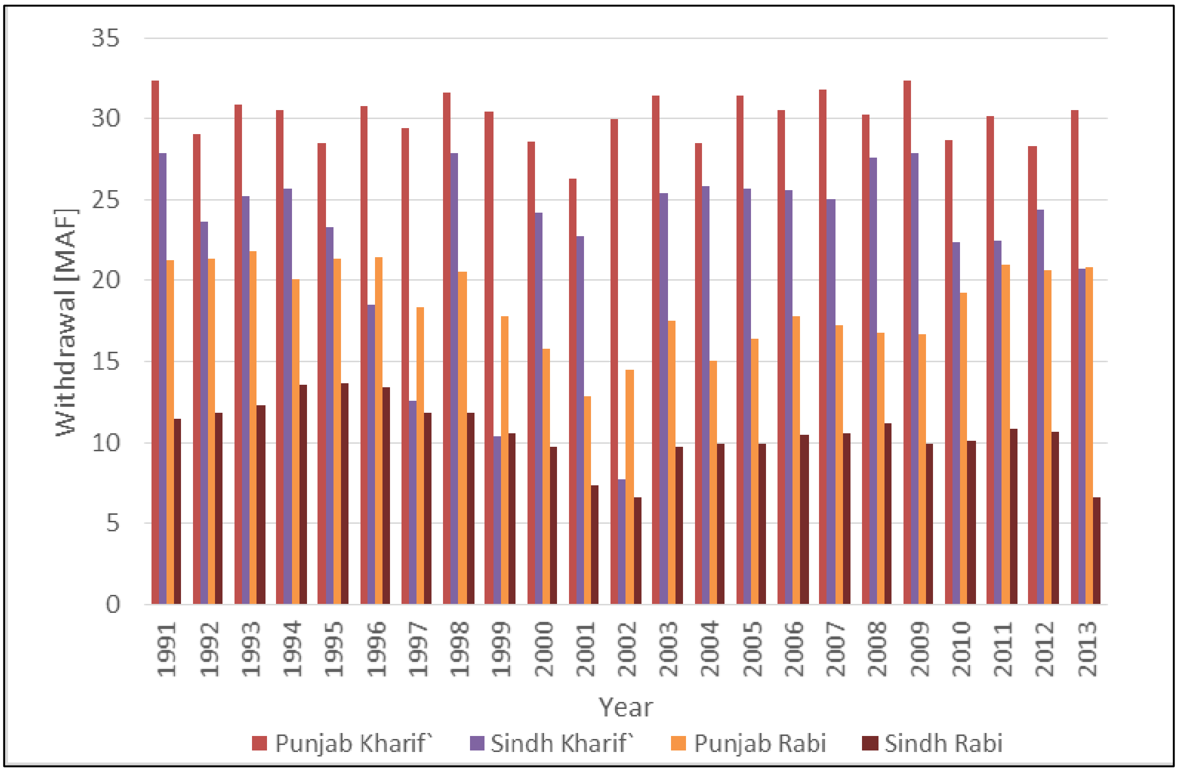


Fig. 4.7: **Water withdrawn by Sindh and Punjab provinces (1991-2013)**

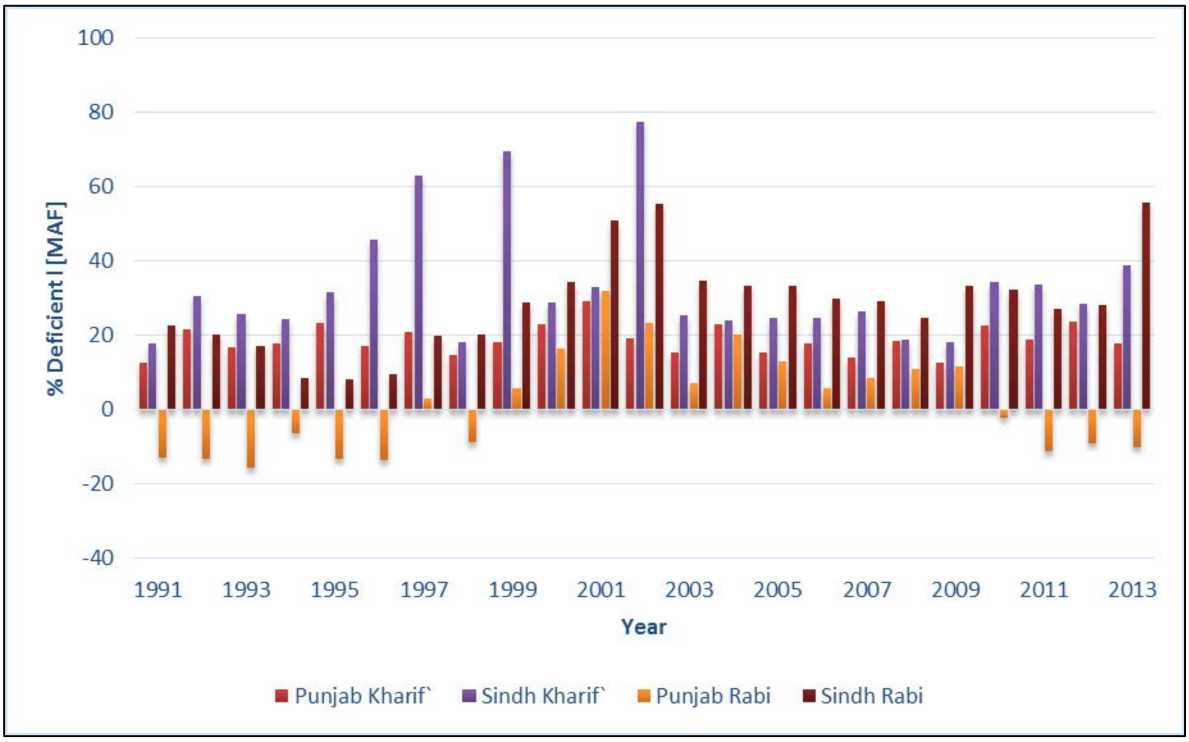


Fig. 4.8: **Deficit against the allocated share of water for the Sindh and Punjab Provinces (1991-2013)**

In 2040, the total water demand for the Guddu, Sukkur and Kotri barrages of Sindh will be 6.16, 15 and 8.76 MAF, respectively. In sum, if population and agricultural growth rates continue as such, Sindh water demand will rise to 30 MAF (i.e. 6.3 MAF more than that of the base year 2015) in the year 2040. During most years in the past, water availability has remained less than demand. Since Sindh province cannot augment its water supply, alternative water conservation strategies must be developed to combat future projected water supply demand deficits.

The combined water demand of canal command area in Sindh, Punjab, link canal commands, supply delivered to Baluchistan and Seawater requirements below Kotri was found to be 140.8 MAF in 2015, rising to 141.9 MAF in 2020, 143.5 MAF in 2025, 145.4 MAF in 2030, 147.6 MAF in 2035, and 150.1 MAF in 2040. To avoid sea intrusion, it is assumed that 10 MAF of water must escape to the sea below Kotri barrage now, as well as in the future.

Table 4.5: Future projected water demands in MAF at different barrages of Punjab and Sindh (2015 to 2040)

Barrages	2015	2020	2025	2030	2035	2040	Percent increase as of 2015
Baloki	4.05	4.13	4.22	4.3	4.46	4.54	12
Islam	2.19	2.19	2.27	2.27	2.35	2.43	11
Jinnah	2.51	2.59	2.68	2.84	2.92	3.08	23
Khanki	6.24	6.65	6.81	6.97	7.13	7.3	17
Rasul	2.59	2.68	2.76	2.84	2.92	3	16
Sindhnai	1.7	1.78	1.78	1.86	1.86	1.95	15
Sulemanki	7.22	7.3	7.38	7.54	7.62	7.7	7
Taunsa	3.81	3.97	4.13	4.38	4.54	4.86	28
Trimmu	0.65	0.65	0.73	0.73	0.73	0.73	12
Punjnad	3.57	3.65	3.65	3.73	3.73	3.81	7
Guddu	5.51	5.59	5.76	5.84	6	6.16	12
Sukkur	12.24	13.54	13.86	14.19	14.59	15	23
Kotri	5.92	6.32	6.81	7.38	8.03	8.76	48

Note: Values rounded to two significant digits

4.6 Dissemination of Research Results

The research results were disseminated by presenting articles in international conferences, publication in research journals and by organizing a National Workshop titled “Climate Change Projections and its Impact on Water System Performance” at the Center in August 2017. The main purpose of the workshop was to build capacity of government, policymakers, academicians and relevant stakeholders. Besides dissemination of the research results, it was also meant to build partnerships for catering the issue of data sharing and modeling water resources system in Pakistan. The workshop was attended by stakeholders from different government and non-government organizations. The concept note of the capacity building workshop and list of participating organizations is given in Appendix 1.

4.7 Research Output

The details of research output are given in Appendix 2 in terms of research papers accepted for publication in research journals (Appendix 2a), M.S. thesis completed by students as a part of this project (Appendix 2b), and the presentations made in international conferences (Appendix 2c).

Furthermore, data repository and web portal is hosted on http://www.beta.dsspak.org, and calibrated model is available for researchers on request.

4.8 Buildings Research Partnerships

This research project provided an opportunity to work in collaboration with Dr. Sajjad Ahmad, Professor and Chairman of Civil and Environmental Engineering and Construction Department at the University of Nevada, Las Vegas. He and his team worked as technical advisors for the present study. His graduate student Mr. Kazi Ali Tamaddun provided active research support in analyzing the data for the research study. He also presented the research work in Environmental & Water Resources Institute (EWRI) international conference for dissemination of the present study output. This partnership is sustained, and we (Mr. Tamaddun, Dr. Ahmad, and PI of this project) are now collaborating to extend the model for investigating the future scenarios for water system management in Pakistan.

This project also became driving force for building partnership with Dr. Steven. J. Burian, Project Director of the USAID-funded U.S.-Pakistan Center for Advanced Studies in Water at the University of Utah. His collaboration on the DSSPAK was extended, when he hired Mr. Daniyal Hassan (who worked in this project for his MS degree) as PhD student at the University of Utah. Mr. Daniyal Hassan extended the present study, and was able to formulate research paper based on the work he did in this study. Now, this common link of students between Dr. Burian and Dr. Ahmed is flourishing, and helping develop future research ideas based on the results of this study and the on-going works.

5 SUMMARY AND RECOMMENDATIONS

5.1 Data Management and Sharing

The water sector in Pakistan is well monitored but the data shared on the internet is rather limited in scope. Presently there are no protocols that define the standard information and management sharing mechanism for the water sector. Semantic and syntactic heterogeneity exists, which makes the data/information undiscoverable and hard to interpret.

In this project, we have demonstrated an implementation of a prototype platform for standard online sharing of the data. Data sharing platform is designed and implemented on the web based server that has standard protocols for data sharing and formats. We have demonstrated that how the time series and geo-spatial data (that occurs mostly in water resources) can be arranged in a standard format and can be shared among the registered users. The web portal has the capability to upload the data, so any registered organization can upload the relevant data which can be shared with other registered organizations. This sets up a standard sharing mechanism within and among the organizations. We have also implemented a work flow for associating targets and indicators for international monitoring. This will provide the organization to map the shared data with respect to the monitoring indicators.

Data management and sharing implemented in this project is to demonstrate that how the data in water sector can be managed. The portal is generic in terms of management of the data and it requires consistent update and input from different stakeholders in water sector to enhance, update, and modify the portal. The recommendation is to conduct outreach and capacity building of departments/ministries to keep the portal live. That have to include:

- Registration of the departments that intend to share their data and need technical help. Once departments are registered and start sharing the data, then it can be used as a demonstration case to attract other departments to manage and share their data in an efficient manner. Once the departments will come in the loop then it will be easy to standardize the data in one database.

- Build capacity of the registered departments to upload and share the data on the web based portal. Initially that can be done on the web portal implemented in this research project, and it can be further modified at the departmental level, considering the detailed needs of the departments in the water sector.

- Approval of the standard protocols for central data sharing.

- Approval of the control vocabulary of the variables that departments need to share nationally and internationally.
- Program to increase awareness about the importance of central data sharing in the water sector.

5.2 Water System Modeling

Baseline system model implemented in this project represents the major reservoirs, barrages and link canals of the irrigation system in Pakistan. Inflow estimates at the barrage level are satisfactory, and can be used to simulate scenario pertaining to the questions of water sharing and barrage/reservoir operations. Crop water requirement (for selected crops) and domestic water requirement at the canal command level are incorporated in the model. This model is baseline model that will further need improvement by water sector related departments in Pakistan to test relevant scenarios to support the decision making.

Baseline model requires continuous update to comprehensively describe the water system in Pakistan. Some of the recommendations for improvement of the model are given below:

- Model implemented is at the barrage command level, this aggregation unit should be scaled down to the canal command area to address the issues at the canal command level. For more detailed analysis this has to be scaled down to distributary level to answer the questions related to the management at that level and the associated issues concerning livelihood of people.
- This model is capable for solving scenarios for the interprovincial questions but is not capable of answering the questions at canal command level, both within and between the canal commands.
- Rule curves are used for reservoir regulation.
- Hydropower production node is not modeled. To answer the production question, it needs to include such details in the model.
- Model system boundaries do not include the upper Indus basin model that needs to be implemented to answer the question of climate change. Catchment modeling need to be performed to see the response on the hydrograph due to changing climate.
- Groundwater usage is not simulated in the present model. It only provides tools to test the surface water system. Being the second largest source of irrigation, it should be integrated in the system model.

5.3 Scenario Assessment

It was observed that the reference evapotranspiration rate showed great variability in canal command areas of Pakistan. Specifically, Guddu left, Khairpur East and Khairpur West command areas have the highest rate of evapotranspiration and they transpire 80 to 83 in/year of water for reference crop. High delta crops grown in these regions require more water depth. This makes Sindh at disadvantage to cope with the changing climate.

Analyzing the demand and supply situation of each canal command area, it was observed that in Kharif season, the canal command areas of Sindh and Punjab had not received the allocated share of water. Sindh faced extreme shortage in the year of 1999 and 2002, with respective shortage of 69.47 and 77.23% of its allocated share; while Punjab met with 17.92 and 19.20% shortage of its allocated share during the same years. The extreme deficiency faced by Punjab was 29.12% in the year 2001, while Sindh shared shortage of 32.91% in the same year. In future, if the population continues to grow at the same rate as observed in the 2017 Census; the water demand of canal command area in Sindh, Punjab, link canal commands, supply delivered to Baluchistan and Seawater requirements below Kotri will be 140.8 MAF in 2015, rising to 141.9 MAF in 2020, 143.5 MAF in 2025, 145.4 MAF in 2030, 147.6 MAF in 2035, and 150.1 MAF in 2040. To avoid sea intrusion, it is assumed that 10 MAF of water must escape to the sea below Kotri barrage now, as well as in the future.

Based on the scenario assessment using the implemented model, following recommendations are proposed:

- Promote the water conservation techniques to reduce water use because the water demand of Punjab and Sindh Provinces will increase to 150.1 MAF by 2040, which is more than the current entitlements and availability.
- In southern areas of Pakistan, the cropping pattern needs to be modified. For example, in Rabi season oilseeds and pulses may be preferred instead of wheat. They not only consume less water but also possess high economic value as compared to wheat. Therefore, these crops should be preferred for increasing the economic output and the area under cultivation from the water so saved.
- Special efforts be taken to implement water saving policies and practices to reduce its water use - as it is at disadvantage, for being a lower riparian, and highly dependent on the surface water. It also has canal command area that will have higher domestic demand in the future. Proper management policies should be implemented in Sindh to meet the domestic and agriculture demand in future.

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Yang, Y. E., Wi, S., Ray, P. A., Brown, C. M., and Khalil, A. F. (2016). The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. *Global Environmental Change*, 37: 16-30.

Appendix 1. Concept Note for the Capacity Building Workshop

Two Days Training Workshop on

Climate Change Projections and its Impact on Water System Performance

USPCAS-W, MUET, Jamshoro

From August 17-18, 2017

Resource Persons:

i. Ghulam Hussain Dars, USPCAS-W MUET

ii. Waqas Ahmed, USPCAS-W MUET

iii. Rakhshinda Bano, USPCAS-W MUET

Location: GIS Lab USPCAS-W MUET

Goal and Objectives:

The goal of this workshop is to advance engineers, scientists, water managers and experts' capacity related to climate change impacts on system performance. The workshop will stimulate innovation and build participants' training strength in the area of climate impact studies by using different tools such as R statistical language and WEAP decision support tool. Foundational concepts, tools and methods, and case studies will be covered. Participants will also be engaged in hands-on activities during the workshop.

The objectives of the workshop are to:

1. Explore large climate datasets in R.
2. Describe climate projections for different climate variables.
3. Explain climate vulnerability assessment techniques and tools.
4. Formulate and calculate water system performance measures and indicators using WEAP.
5. Apply data and computational tools for climate vulnerability assessment and adaptation planning.

a. Improved comprehension of climate projections and vulnerability assessment and techniques across a range of applications,

b. Increased knowledge of data sources and evaluation measures used in climate vulnerability studies,

c. Awareness of data analysis, programming, modelling, computational, and other tools for climate vulnerability assessment.

Participating Organizations:

- ☐ PMD/Research Center
- ☐ BUITEMS, Baluchistan
- ☐ PMAS Arid Agricultural University, Rawalpindi
- ☐ LUMS, Lahore
- ☐ Karakoram International University, Gilgit Baltistan
- ☐ PCRWR
- ☐ NED University
- ☐ SIDA,
- ☐ WAPDA
- ☐ Sindh Agriculture University, Tandojam
- ☐ QUEST, Nawabshah
- ☐ Civil Engineering Department, MUET
- ☐ Mechanical Engineering Department, MUET
- ☐ MUET Campus, Khairpur Mirs
- ☐ USPCAS-W, MUET

Workshop Program:

Day -1		
Time	Detailed Description	Instructor/Lead
9:00 – 9:05	Recitation of Holy Quran	
9:05 – 9:20	Welcome Remarks	Dr. B K Lashari, PD USPCASW
09:20 – 9:45	Overview of the USPCAS-W	Dr. R B Mahar, DD Academics and Research
9:45 – 10:15	Workshop Introduction	Waqas Ahmed
10:15 – 11:00	Participants' Presentations describing their/Institutes' research agenda	Waqas Ahmed, Rakhshanda, Ghulam H. Dars
11:00 – 11:30	Networking/Tea Break	
11:30 – 13:30	Participants' Presentations describing their/Institutes' research agenda (Continued)	Workshop participants
13:30 – 14:30	Lunch/Prayer Break	
14:30 – 15:00	Introduction to Climate Projections	G H Dars
15:00 – 16:00	Impact Lab-1 – Climate Change Projections – Use of web-based tools to analyze climate projections of various climate variables	G H Dars
18:00 – 21:00	Hyderabad Tour and Dinner at Hyderabad	Waqas, Rakhshinda and G H Dars

Day -2		
09:00 – 10:00	Impact Lab-2 – Exploring large climate datasets in R	G H Dars
10:00 – 10:30	Climate Vulnerability Assessment Concepts and Approaches	Miss R Bano
10:30 – 11:00	Climate Vulnerability Indicators and Performance Metrics	Waqas Ahmed/Miss R Bano
11:00 – 11:30	Networking/Tea Break	
11:30 – 13:00	Impact Lab-3: WEAP in one hour	Waqas Ahmed
13:00 – 14:00	Lunch/Prayer Break	
14:00 – 15:30	Impact Lab-4: System Analysis using WEAP	Waqas Ahmed and Miss R Bano
15:30 – 16:00	Group Discussion – Data and Modeling need assessment for the water system under climate uncertainties	Waqas Ahmed, R Bano and G H Dars
16:00 – 16:30	Concluding and Certificate award ceremony	G H Dars

Appendix 2 Research Output

Appendix 2a Journal Articles

i. Hassan, D., Rais, M. N., Ahmed, W., Bano, R., Burian, S. J., Ijaz, M. W., and Bhatti, F. A. Future water demand modeling using water evaluation and planning: a case study of the Indus Basin in Pakistan. *Sustainable Water Resources Management.* (Accepted)

ii. Hassan, D., Burian, S.J., Bano, R., Ahmed, W., Arfan, M., Naseer Rais, M., Rafique, A. and Ansari, K. An assessment of the Pakistan water apportionment accord of 1991. *Resources.* (Accepted)

Appendix 2b Masters Thesis

i. Muhammad Naseer Rais (2017). Decision support system for management and distribution of water resource in Pakistan.

ii. Daniyal Hassan (2017). Assessment of historical and future performance of the Pakistan Water Apportionment Accord-1991.

Appendix 2c Conference Proceedings

iii. Ahmed, W., Rais, M. N., Bano, R., Tamaddun, K., and Ahmad, S. (2018). Water sharing, governance, and management among the provinces in Pakistan using evidence-based decision support system. *In World Environmental and Water Resources Congress 2018: Watershed Management, Irrigation and Drainage, and Water Resources Planning and Management* (pp. 220-233). Reston, VA: American Society of Civil Engineers.

iv. Tamaddun, K. A., Ahmed, W., Burian, S., Kalra, A., and Ahmad, S. (2018). Reservoir Regulations of the Indus River Basin under Different Flow Conditions. *In World Environmental and Water Resources Congress 2018: Watershed Management, Irrigation and Drainage, and Water Resources Planning and Management* (pp. 207-219). Reston, VA: American Society of Civil Engineers.

v. Tamaddun, K. A., Kalra, A., Ahmed, W., Dars, G. H., Burian, S., and Ahmad, S. (2017). Precipitation and Indian Ocean Climate Variability—A Case Study on Pakistan. *In World Environmental and Water Resources Congress 2017* (pp. 526-535).

vi. Meghwar, S.L., Ahmed, W., Rakhshinda, B. and Ahmed, M.M. (2016). Analysis of missing data for river flow using statistical tool group method of data handling (GMDH). *In the 8th International Civil Engineering Congress 2016.*

About the Author

Waqas Ahmed is working as Assistant Professor in Hydraulics, Irrigation and Drainage (HID) Department at USPCAS-W, Mehran University of Engineering and Technology, Jamshoro. Earlier, he was working as a Research Assistant in the Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Germany. He worked as a modelling expert in European Union funded project "ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems."

Mr. Ahmed earned Master's degree in Water Resources Engineering and Management from University of Stuttgart, Germany and now pursuing his Ph.D at USPCAS-W. Mr. Ahmed teaches various subjects at the USPCAS-W including Hydro-informatics: Data Management and Analysis. Moreover, he has published a number of research articles in national and international journals. Mr. Ahmed's research develops new concepts, methods, and tools for application of informatics to studies in Water, Energy, and Food (WEF) and at the interface of WEF components. His WEF Informatics team creates databases, develops computer models, and conducts investigations using these products to inform planning, design, and policy governing WEF systems.

About the Technical Advisor

Dr. Sajjad Ahmad is serving as Chair and Professor at the Civil and Environmental Engineering and Construction Department, University of Nevada, Las Vegas, USA. Dr. Ahmad's research focuses on application of systems approach to understand and manage complex water and environmental systems. Goal of his work is to provide decision support to policy makers for sustainable management of water resources. He has published number of research articles in international journals, and has led several research projects in water resources systems planning.

Main thrust of Applied Research component of the Water Center is to stimulate an environment that promotes multi-disciplinary research within the broader context of water-development nexus to support evidence-based policy making in the water sector. This is pursued using the framework provided by the six targets of the Sustainable Development Goal on Water i.e. SDG-6.

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