Project Note on
Modeling for Indus Basin Water Management

With population approaching 200 million, Pakistan's food security and economy heavily relies on agriculture. Extensive agriculture is made possible by an elaborate irrigation infrastructure, referred to as the Indus Basin Irrigation System (IBIS). This is the largest contiguous irrigation system in the world. The Indus river system that feeds this irrigation system consists of the main Indus River and its major tributaries – the Kabul, Jhelum, Chenab, Ravi and Sutlej Rivers. These rivers flow through four provinces: Khyber Pakhtunkhwa (KPK), Punjab, Sindh and Balochistan.

Average annual river flows in Indus are about 146 million acre-feet (1 maf equals 1.234 km^3), of which about 106 maf are diverted from the river system to canals annually. The Indus river system has 2 major multi-purpose storage reservoirs (Mangla and Tarbela), 19 barrages, 12 inter-river link canals, and 45 major irrigation canal commands (Figure 1). The total length of the canals is about 60,000 km. More than 120,000 watercourses deliver water to farms. These canal waters are supplemented with extensive and growing groundwater extraction from private tube wells.

Irrigated agriculture covers 16.2 million hectare (74%) out of the total cultivated area of 22 million hectare. Irrigated agriculture is a lifeline of Pakistan's economy as it uses 94% of the available water, provides over 90% of agricultural produce, accounts for 25% of GDP, earns 70% of the export revenue and employs 50% of the workforce directly and another 20% indirectly.
The important characteristics of IBIS and major challenges include:

- Indus river system is trans-boundary. Significant portion of flow in Jhelum and Chenab rivers originates in upper riparian country India. Kabul river, originating in Afghanistan, is a tributary of Indus River. Flow in these rivers can reduce with future storage projects in India and Afghanistan.
- Main source of water in the Indus and Jhelum rivers is snow and glaciers melt in Himalayas, which will be impacted by future climate change.
- Entire provinces of Sind and Baluchistan and most of the Southern Punjab have arid or semi-arid climate - droughts are common.
- Majority of rainfall in Pakistan, with exception of upper Indus, results from monsoon system during the months of July and August. With flat topography in southern Punjab and Sind, and heavy rainfall during monsoon, Pakistan is very vulnerable to flooding. Most commonly deployed flood control option are structural i.e., dikes.
- In the irrigation system, conveyance losses are high and irrigation efficiency is low.
- Due to seepage from an extensive irrigation system and use of flood irrigation in fields – water logging and salinity are serious issues.
- Ground water is extensively used to supplement irrigation and is the main source for drinking water supply in urban areas. This has resulted in decline of water table in many aquifers. Ground water is brackish in some parts of the country.
- With growth in population, per capita water availability is declining rapidly (currently 1100 m^3 per person) – highlighting the need for better water and irrigation management.
- Due to extensive water withdrawls for irrigation from river system, in some years, sufficient flows do not pass the Kotri barrage to reach the Indus delta –resulting in sea water intrusion that now extends 50 plus miles upstream.
- Projected climate change is expected to significantly impact flows in the river system and crop water requirements.
- Planning and decision making is not informed by data-based analysis

Allocation of limited water resources between agricultural, municipal, industrial and environmental uses requires consideration and integration of supply, demand, water quality and ecological considerations. With interconnected nature of population growth, water availability, food security, climate change, extreme hydrologic events (floods and droughts) and environmental demands – there is a need to develop a simulation model that can provide support for planning and decision making.

Water and Power Development Authority (WAPDA) Pakistan with assistance from World Bank has developed the Indus Basin Model (IBM) as a decision support tool for investigating water-related projects and agricultural policies in the Indus Basin (Duloy and O'Mara, 1984). The original version of model was updated in 1988 by the World Bank's Development Research Center. The model uses the General Algebraic Modeling System (GAMS) to solve the water allocation for the Indus Basin Irrigation System (Ahmad et al., 1990). The World Bank and WAPDA updated the model again in 2002 by incorporating the Indus Water Allocation Accord. This accord, signed in 1991, governs the water apportionment among four provinces. The World Bank and WAPDA further updated the model in 2012 (Yang et al., 2013). The new update focused on analyzing the impact of climate change on agriculture production in Pakistan.

Existing Indus Basin Model is a very sophisticated optimization tool, and is the best mathematical representation available of the water, economy and agricultural sectors of Pakistan. However, IBM runs for a single-year at monthly time step. Current and any future year runs are compared to explore changes in agriculture production in response to external stressors. Because model only runs for one year, operation of storage reservoirs is not included in the model. Flooding is also not considered.

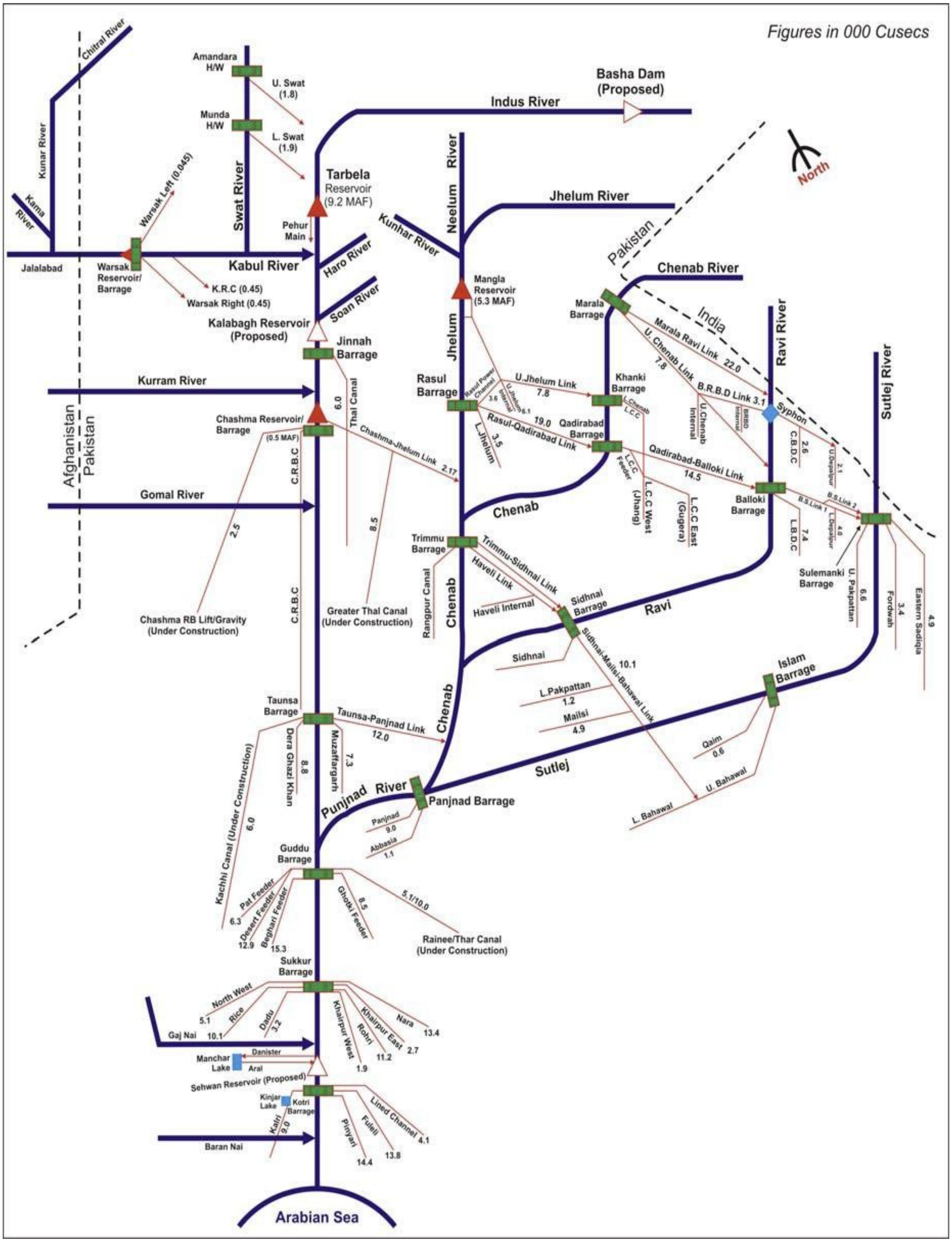

Figure 1. Line diagram of Indus Basin Irrigation System showing rivers, link canals, barrages, and major canals taking off from barrages.

We propose to develop a dynamic simulation model, a decision support system (DSS) that will be able to explore several "what-if" scenarios to support future water management and planning decisions in the basin. This DSS will be able to capture the inter-relationships among the climate, water, population and agriculture sectors. Model will be developed using software tool WEAP.
This will be a county level model, covering entire IBIS up to canal command area. Infrastructure shown in Figure 1 will serve as the basis for the model. A node-link system will be used to represent the entire river and canal network.

WEAP uses water demand and supply information to perform mass balance. It can calculate runoff, infiltration, crop requirements, stream flows, reservoir storage, pollution generation, water treatment, waste water discharge and instream water quality under varying hydrologic and policy scenarios. Using a dynamic link WEAP can be integrated with other models such as QUAL2K, MODFLOW, MODPATH, PEST, Excel and GAMS.

Spatial Resolution: Similar to existing IBM, we will divide Pakistan into 12 Agro-Climatic Zones (ACZ), each representing consistent climatic conditions, land characteristics and cropping pattern.

Temporal Resolution: Model will run monthly or by crop season (2 crop seasons per year).

Hydrology: For upper Indus, an empirical or regression method will be used to develop a relationship between snowfall, temperature, catchment area and flows. Similarly, in the lower Indus basin, a rainfall-runoff relationship will be developed. This is a limitation of WEAP model that detailed, physical base, hydrologic modeling is not possible. We may model the rainfall-runoff processes using a hydrologic model and then introduce runoff at appropriate nodes in the model.

Impact of climate variability and Change: Downscaled data from GCM's in CMIP5 will provide precipitation and temperature information to drive the model for future years. Climate change will impact the flows and the crop water requirement.

Reservoir Operation: Operation of two major storage reservoirs in the system i.e., Tarbela and Mangla will be modeled using depth-area-volume relationships and reservoir operating rules.

Irrigation system: Irrigation system will be modeled at the canal command level. Available data for canal commands will be aggregated to the level of the ACZ. Each ACZ may be under more than one canal command area.

Crop water requirements: using the area under cultivation for each crop, irrigation method used, and crop water requirements – irrigation water demand will be estimated. This demand will be withdrawn from one or more canal command areas for each ACZ. This will include setting-up the model with river system and diversion canals and estimating crop water requirements.

Flooding: This will be handled by providing flow capacity for river segment between 2 nodes. When flow capacity will be exceeded, excess volume will inundate floodplain. The flooded area will be estimated using relationships between flood volume and area flooded, developed from historic floods for each river segment. A hydraulic model may be used for estimation of floods and area inundated. Model results then can be used as relationships in WEAP model.

Groundwater: Different ground water aquifers will be defined by their extent and volume. Infiltration and well withdrawls will change the volume. A relationship between volume and water depth will provide the water levels in each aquifer throughout the simulation in response to change in volume. Linking with MODFLOW is also a possibility.

Model output: The main outputs will include water in reservoirs, agricultural production, and the flow to the sea. Model will also reports the surface-water and groundwater balances for each ACZ.

Some scenarios that model will be able to explore/evaluate:

- Impact of climate change on river flows and crop production
- Impact of alternate crop selection on water demand and agricultural productivity
- Impact of additional storage (adding reservoirs) on water availability, agricultural productivity, and flooding
- Impacts of using efficient irrigation methods on water use, agricultural production and waterlogging.
- vulnerability, reliability, and resilience of flood control infrastructure to climate variability and change
- Impact of water transfers on crop productivity
- Potential of water reuse in increasing water supply
- Use of pricing (abiana) and water markets for their potential to conserve water and improve agricultural productivity.
- Impact of climate change, alternate water management and reservoir operation scenarios on hydropower production
- Impact of changing irrigation methods and crop types on ground water level
- Ability to meet domestic food needs (food self-sufficiency) in future under base-case and improved water and agricultural management scenarios
- Impact of crop selection on revenues earned by farmers and virtual water trade

- The decision support system (DSS) can be used to explore the important questions, such as:

- What are the major short (by 2025) and long term (by 2050) changes in population growth, land use, water demand, and water availability that can be expected in the study area?
- How vulnerable is water infrastructure (irrigation and flood control systems) to climate variability and change?
- What is the most promising portfolio of water and agricultural management options in response to growth and climate change?

We envision that proposed DSS will be able to inform policy decisions for following SDG's.

SDG 2.4
Ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters

SDG 6.4
Substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity

SDG 6.5 Implement integrated water resources management at all levels
SDG 6.6 Protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
SDG 13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters
SDG 15.3 Combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods

References

Ahmad, M., Brooke, A., & Kutcher, G. (1990). *Guide to the Indus basin model revised*. Washington, DC: World Bank.

Duloy, J. H., & O'Mara, G. T. (1984). *Issues of efficiency and interdependence in water resource investments: Lessons from the Indus basin of Pakistan*. Washington, DC: World Bank.

Yang Y E, Brown C M, Yu W. H. and Savitsky A (2013) An introduction to the IBMR, a hydro-economic model for climate change impact assessment in Pakistan's Indus River basin, Water International, DOI: 10.1080/02508060.2013.830691