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Indus River System Model (IRSM) – a planning tool to explore water management options in Pakistan

Model conceptualisation, configuration and calibration

A project of the South Asia Sustainable Development Investment Portfolio (SDIP)

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Model ownership and distribution

MoWR-CSIRO Indus River System Model (IRSM) is a joint development of Australian scientists with Pakistan partners and has been constructed using the eWater Source modelling framework (Version 4.1.1.5345), saved as *IRSM_V4_1_1_5345_Baseline_V4.rsproj*.

As per Subsidiary Arrangements between the Government of Pakistan and the Government of Australia, distribution of IRSM and associated datasets to third parties is subject to written approval from the Ministry of Water Resources, Government of Pakistan.

This report designed and implemented by CSIRO contributes to the South Asia Sustainable Development Investment Portfolio and is supported by the Australian aid program. More details about the CSIRO SDIP projects are available from http://research.csiro.au/sdip.

SDIP's goal is increased water, food and energy security in South Asia to support climate resilient livelihoods and economic growth, benefiting the poor and vulnerable, particularly women and girls

SDIP end-of-strategy (2024) objective: Improve the integrated management of water, energy and food in the major Himalayan river basins – especially addressing climate change and the interest of women and girls.

SDIP end-of-investment (2020) objective: Key actors are using and sharing evidence, and facilitating private sector engagement, to improve the integrated management of water, energy and food across two or more countries - addressing gender and climate change.

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Executive summary

The 2012 report from the Water Sector Task Force (WSTF) of the Friends of Democratic Pakistan (FoDP) highlighted five solutions to the water resources challenges faced by Pakistan. One of these solutions was to build knowledge and capacity with a specific focus on Australian water management culture and software tools.

In response to the WSTF-FoDP Report, the Australian Government engaged the CSIRO to contribute to the task of building capacity and sharing the Australian water management culture with Pakistan. This task has primarily been undertaken through the development of a river system simulation model of the Indus River System.

The aspirational aim of this model is to provide a standalone tool for national and provincial water management agencies to simulate planning and seasonal operational decisions on the Indus River. Through this simulation tool, the consequences of decisions regarding river management, infrastructure investment, agricultural productivity and environmental sustainability may be investigated, enhancing the decision-making capacity of water management agencies in Pakistan.

This Report presents the MoWR-CSIRO Indus River System Model (IRSM) that is built using the eWater Source modelling framework. The IRSM represents the Pakistan Indus Basin Irrigation System (IBIS) by describing both the physical and water sharing systems on a daily time step. The physical system is described by a complex node-link network that commences at rim stations and includes 2 major supply reservoirs (Tarbela and Mangla), Ghazi-Botha scheme, 16 barrages (including Chashma), 14 main link canals and 73 irrigation supply canals and associated irrigation demands and ends below Kotri barrage. The model accounts for major supply reservoir sedimentation over time, flow routing and distribution losses. The model also considers energy generation at Tarbela, Mangla, Ghazi-Botha scheme and hydro capable barrages. The model simulates the water flow, use and operations of the Indus River system, including the mechanisms though which seasonal water allocations are planned, shared and delivered.

The model simulates the water allocation and distribution system in the same manner that it is currently undertaken in Pakistan. Seasonal flow forecasts are generated by the model which are used to generate seasonal operational rules for major infrastructure. Seasonal water allocation to the provinces is then undertaken in accordance with the 1991 Water Apportionment Accord.

The model also simulates the flow of water through all major rivers, dams, barrages and canals to distribute water to canal commands areas so that it can be used for irrigation. Crop demands are simulated in the model considering surface water delivery constraints and, where appropriate, a groundwater component is also considered in the model to supplement surface water supplies.

Model results for the period 2002–2012 match simulated seasonal inflow forecasts with historic forecasts resulting in provincial allocations that replicate historic water sharing and associated deliveries. The model replicates historic provincial entitlements reasonably well in terms of daily pattern of allocations and overall cumulative volume (2% volumetric error for combined Punjab and Sindh allocations vs withdrawals), the average annual maximum volume error as a proportion of mean annual inflow for Tarbela, Mangla and combined storage is respectively within 14, 7 and 4% and daily flow nash-sutcliffe efficiency (NSE) correlations at major barrages exceeds 0.7. Noting that Sukkur Barrage has an NSE of 0.6. Based on this performance, the model may now be used to investigate current and future water management decisions by Pakistan water management agencies. This could include investigating the potential impacts of climate change and infrastructure development on future water availability and the associated impacts on provincial sharing.

1 Introduction

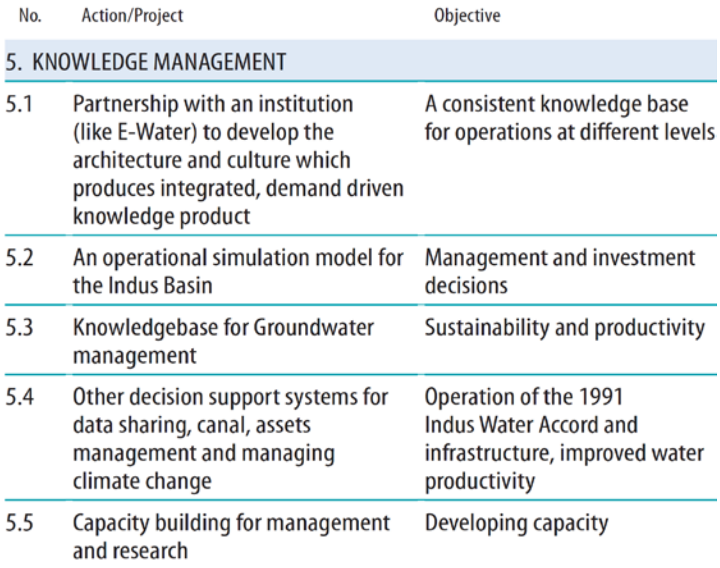
1.1 Background

This technical report is a product of the *Water Resources Management: Knowledge and Capacity Building in Pakistan for the Indus Basin* project (referred to as the Indus project), funded by the Government of Australia and supported by the Government of Pakistan. The project is part of Phases 1 and 2 of the Sustainable Development Investment Portfolio (SDIP), an Australian government initiative with the goal of increasing water, food and energy security in South Asia (https://research.csiro.au/sdip/projects/indus/). This work was undertaken in the context of a Subsidiary Arrangement between the Government of Australia and the Government of Pakistan, established in 2016.

In 2012, the Water Sector Task Force (WSTF) of the Friends of Democratic Pakistan, led by the Asian Development Bank, authored an influential Report: A Productive and Water-Secure Pakistan. This Report was endorsed by the Pakistan Government and identified 5 key solutions to the serious water resources challenges faced by Pakistan (WSTF-FODP, 2012):

1. building a platform of major infrastructure;
2. increasing water productivity in agriculture;
3. living better with floods;
4. improving institutions and infrastructure for productive and secure cities; and
5. building knowledge and capacity to manage one of the world's most complex water systems.

The WSTF report identified Australian expertise, software and approaches suitable to provide this solution and in response to the WSTF report, the Australian Government initiated a program to support Solution 5: Knowledge Management (Figure 1).



No.	Action/Project	Objective
5. KNOWLEDGE MANAGEMENT		
5.1	Partnership with an institution (like E-Water) to develop the architecture and culture which produces integrated, demand driven knowledge product	A consistent knowledge base for operations at different levels
5.2	An operational simulation model for the Indus Basin	Management and investment decisions
5.3	Knowledgebase for Groundwater management	Sustainability and productivity
5.4	Other decision support systems for data sharing, canal, assets management and managing climate change	Operation of the 1991 Indus Water Accord and infrastructure, improved water productivity
5.5	Capacity building for management and research	Developing capacity

Figure 1 Five priority actions from the Water Sector Task Force Report (Source: WSTF-FoDP, 2012)

Responding to the Australian Government contribution to Building Knowledge and Capacity, CSIRO undertook the task of building capacity and sharing the Australian water management culture with Pakistan through the development of a simulation model of the Indus River System.

1.2 Project context and objectives

The primary objective of the Indus project is to build capacity and knowledge in water resource management with a focus on integrated water resource management. Project activities include delivering a capacity building program and collaboratively building a standalone tool for national and provincial water management agencies to simulate planning and operational decisions on the Indus River System. The capacity building program has included formal training events, joint dialogues and technical visits to Australia. The river system simulation tool is developed to support an agreed and defensible understanding of the consequences of decisions regarding river management, water sharing, infrastructure investment, agricultural productivity and environmental sustainability, enhancing the decision-making capability and capacity of water management agencies in Pakistan.

The training workshops and subsequent ongoing collaborations have provided CSIRO with a deeper understanding of the Indus water resources and the subsequent sharing and management of these resources. This understanding has been incorporated into the Indus River System Model. As such, this model is a collaboration between CSIRO and all the key water management authorities in Pakistan and a point of reference for all of those who have undertaken training.

This work was done in collaboration with the Government of Pakistan from both federal and provincial agencies. The lead agency is the Ministry of Water Resources with departmental support from the Water and Power Development Authority (WAPDA), Indus River System Authority (IRSA), and provincial irrigation departments of Punjab, Sindh, Khyber Pakhtunkhwa (KP) and Balochistan.

1.3 Review of existing Indus River System models

River system models are analytical tools used to support river basin planning and water policy development. Typically, they are used to improve the understanding of the availability and sharing of water resources and how the resource may be affected by natural and anthropogenic interventions. Interventions of interest include changes in climate, water use, infrastructure and water management policies. The form and focus of the model depends on objectives of basin stakeholders as well as the available information that can be used to support its development. Interventions are typically assessed through the creation of river system model 'scenarios'.

Johnston and Smakhtin (2014) reviewed hydrology models of the Indus Basin, while Kirby and Ahmad (2015) reviewed hydrology–economic models. (Hydrology models include river system models, and also include models which may have no river modelling component, such as groundwater models.) What follows is a summary of those reviews.

There are few published river system models that deal with the whole Indus Basin. Eastham et al. (2010), developed a water accounting monthly model of the whole basin, with three components: rainfall – runoff, river flow, and irrigation demand and diversion. The Indus Basin within Pakistan excluding the upper catchments is modelled by the Indus Basin Model, IBM (O'Mara and Duloy, 1984) and its derivatives, the Indus Basin Model Revised, IBMR, (World Bank, 1990; Yu et al., 2013; Yang et al., 2013), and the Regional Water System Model, RWSM, (Robinson and Gueneau, 2014). The IBM and IBMR are hydrology–economic models designed to optimise water allocation economically, within the physical constraints determined by a hydrology model component. The RWSM is the hydrology-only component of the IBMR, embedded within a different economic model. Kirby and Ahmad (2015) review the hydrology–economic models in more detail. The Indus flood forecasting system, FEWS-Pakistan, models only the rainfall–runoff of the upper catchments, with hydrodynamic modelling of the main rivers below the upper catchment (Werner and van Dijk, 2005). There are also several published hydrology models for parts of the basin, including those reviewed in Johnston and Smakhtin (2014), and recent models such as Khan et al. (2014).

Groundwater is a crucial part of Pakistan's water resources (Ahmad et al., 2005), and Kirby and Ahmad (2015) reviewed groundwater models and groundwater–economics models. The IBM / IBMR has a simple water balance representation of groundwater of the irrigated parts of the Indus Basin (O'Mara and Duloy, 1984; World Bank, 1990; Yu et al., 2013; Yang et al., 2013). Several numerical groundwater models deal with waterlogging, salinity and declining water levels in selected parts of the Indus Basin: in the lower Indus (Garg and Ali,1998; Chandio and Lee, 2012; Chandio et al., 2012; Chandio et al., 2013; Kori et al., 2013); in the Rechna Doab (Khan et al., 2008); and in the Chaj Doab (Ahmad et al., 2011).

The currently available river system models do not address several water resource management issues that are important in the Indus of Pakistan (Kirby and Ahmad, 2015). These include modelling of seasonal water allocation and distribution to canal commands, river operations, flood forecasting (except by the FEWS-Pakistan Indus flood forecasting model), water quality (other than salinity), environmental protection, transboundary management, and urban water supply. The MoWP-CSIRO IRSM aims to address the capability gap in seasonal water allocation and distribution to canal commands.

The river and groundwater models reviewed above, especially the IBM / IBMR, have been used in many studies of the water resources of the Indus basin (Johnston and Smakhtin, 2014; Kirby and Ahmad, 2015). In the next section, we review the key water resource issues and policies in the Indus Basin in Pakistan, and then examine the need, if any, for an updated model.

1.4 Water issues and policies in Pakistan: the need for river system models

Kirby and Ahmad (2015) reviewed water resources issues in Pakistan and identified the gaps in current models regarding the issues and policies. They then discussed the need for further models in several areas: river system models, groundwater models, and hydrology–economic models. We summarise their review and discussion below, with emphasis on the river system models.

Pakistan's water economy faces great challenges (e.g. Briscoe and Qamar, 2005; Kugelman, 2009; WSTF-FoDP, 2012; Mustafa et al., 2013; Condon et al., 2014):

- Pakistan is one of the most water stressed countries in the world, with low per capita water availability which will decline further with population growth and with no new water sources to develop;
- fresh groundwater is over-exploited with falling groundwater tables in many places;
- there is widespread resource degradation due to salinity build-up in surface and groundwater, lack of sediment supply to the delta, and water pollution;
- flooding and drainage problems in the lower Indus basin will worsen due to the raised river bed level and thus the increased risk of channel breaches being disastrous;
- climate change may alter flows in the Indus disadvantageously, although Archer et al. (2010) suggest that the evidence is inconclusive, and they conclude that water resources are more threatened by socio-economic changes;
- transboundary and inter-provincial water sharing mistrusts and conflicts (Mustafa et al., 2013);
- lack of understanding on whole-of-the-basin water resources as well as linkages and dependencies between different uses leading to ineffective policies;
- land and water productivity in agriculture is low, indeed much lower than in neighbouring areas in India (e.g. Sharma et al., 2010); and,
- the knowledge base is poorly managed and inadequate.

Recognising these challenges, Pakistan has recently agreed on a National Water Policy, supported by a call to action and declaration of a water emergency in the form of a Water Charter signed by the Prime Minister and the Chief Ministers of the four provinces (MoWR, 2018). The preamble to the Policy describes the nature of the water crisis that confronts Pakistan and concludes that it has become a “national imperative to ensure water security for the people of Pakistan”, to be achieved by “an integrated water management strategy that can optimize the economic, social and environmental returns on water resources, ensure equitable allocation among its competing demands as well as its judicious use by consumers and safe disposal of post-use effluents”.

To address the concerns, the Policy aims to “lay down a broad policy framework and set of principles for water security on the basis of which the Provincial Governments can formulate their respective Master Plans and projects for water conservation, water development and water management”, and gives 33 detailed policy objectives.

As noted in the previous section, currently available Indus river models do not address several water resources issues, and those issues include some which are amongst the main challenges and policy goals in Pakistan. Kirby and Ahmad (2015) concluded that to satisfy Pakistan’s major national objectives of water supply for drinking, food security, hydropower, and flood management there is a clear need for a river model (or modelling system) that can assess the impact of climate variability and change, operations (such as flow forecasting, better description of river reach losses, water storage management and irrigation diversions) and floods. Such a model would address the major national need of water conservation, as optimal management of water storage and delivery helps maximise storage and minimise losses. The model would also assist greatly in the optimal siting, design, and operation of new infrastructure (e.g. of dams, irrigation, and urban supply). The conclusion of the need for a river model or modelling system is like that of the Water Sector Task Force (WSTF-FoDP, 2012).

There is also a clear need for a more comprehensive, basin-wide model (or models) of groundwater and salinity (or, at least, for those areas of the middle and lower basin where groundwater resources are an important component of the water resource) (Kirby and Ahmad, 2015).

1.5 Report overview

This report describes the conceptualisation, configuration and calibration of the Indus river system in the eWater Source modelling framework – Australia’s National Hydrological Modelling Platform. The objective of the report is to provide sufficient explanation of the model conceptualisation and its performance such that key stakeholders will accept that the model is suitable for its intended purpose. It will also provide sufficient detail that others could independently build a comparable model based on the available information. As part of this evidence and trust building process, the report presents details on how well the model represents:

- flows at barrages and canal commands;
- behaviour of major supply storages (levels, volumes and releases);
- seasonal forecasting of flows and implementation of the 1991 Water Apportionment Accord principles;
- seasonal and inter-seasonal water entitlements and delivery of water at the Provincial level; and
- system-wide water balance.

This report describes in detail how the Source modelling platform has been used to represent not only the water flows through the Indus River System, but also the water resource assessment and allocation system currently implemented in Pakistan. These two elements represent the physical distribution and movement of water within the Indus system, and the allocation and sharing of this resource between provinces and canal commands within provinces.

Modelling these two elements and their interactions in the same software system provides new opportunities to investigate future management scenarios that consider the combined physical and institutional constraints.

1.6 Report structure

This report is structured as follows:

Chapter 2: provides a description of the physical and management characteristics of the Indus basin, which forms the basis of the model conceptualisation.

Chapter 3: describes the sources of available data and the conceptualisation of the physical and management systems of the Indus River System Model (IRSM). This chapter also provides the setup data for barrages, the methods adopted for streamflow routing and the formulation of the seasonal forecasting and allocation system;

Chapter 4: describes the model calibration;

Chapter 5: reports on model performance and presents output results for key areas of forecasting, provincial allocation, river and canal flows;

Chapter 6: summarises the model development and provides conclusions, with recommendations for future development;

Appendix A provides key unit conversion factors;

Appendix B provides more details of gauging stations used for this project;

Appendix C contains storage level/volume/area tables adopted for Tarbela and Mangla reservoirs; and

Appendix D provides reach routing and loss parameters.

2 Description of the Indus Basin

2.1 Geography

The Indus Basin spans Pakistan, North Western India, Eastern Afghanistan and South Western China (Figure 2). The Indus Basin has a total area of approximately 1,125,000 km^2 and the Indus River is 3,180 km in length, making it one of the longest rivers in Asia. The physiography of the basin is defined by the Hindu-Kush in the north west, Karakoram in the far north east and Western Himalayan mountain ranges in the north and north east which all feed the Indus submarine fan, which is the second largest sediment body on the Earth which comprises around 5 million cubic kilometres of material eroded from these mountains.

The Indus comprises 7 major rivers (Figure 3); Indus, Chenab, Jhelum, Kabul, Sutlej, Ravi and Beas and at one time was named the Satnad River (meaning seven rivers). The origins of the Indus and Sutlej rivers are from Mt Kailash in the Tibetan plateau in China. The headwaters of the Chenab, Jhelum, Ravi and Beas rivers are in the Himalayas in India. The Jhelum and Ravi rivers flow into the Chenab River and the Beas flows into the Sutlej River. The Chenab and Sutlej combine at Punjnad Barrage prior to flowing into the Indus. The origins of the Kabul are in the Sanglakh range in the Hindu-Kush Mountains. The Chitral River flows from Pakistan into the Kunar River in Afghanistan which joins the Kabul River near Jalalabad. The Swat and Panjshir rivers are also major tributaries of the Kabul. The Kabul River joins the Indus in Pakistan near Attock. The Indus River flows into the Arabian Sea near Karachi.

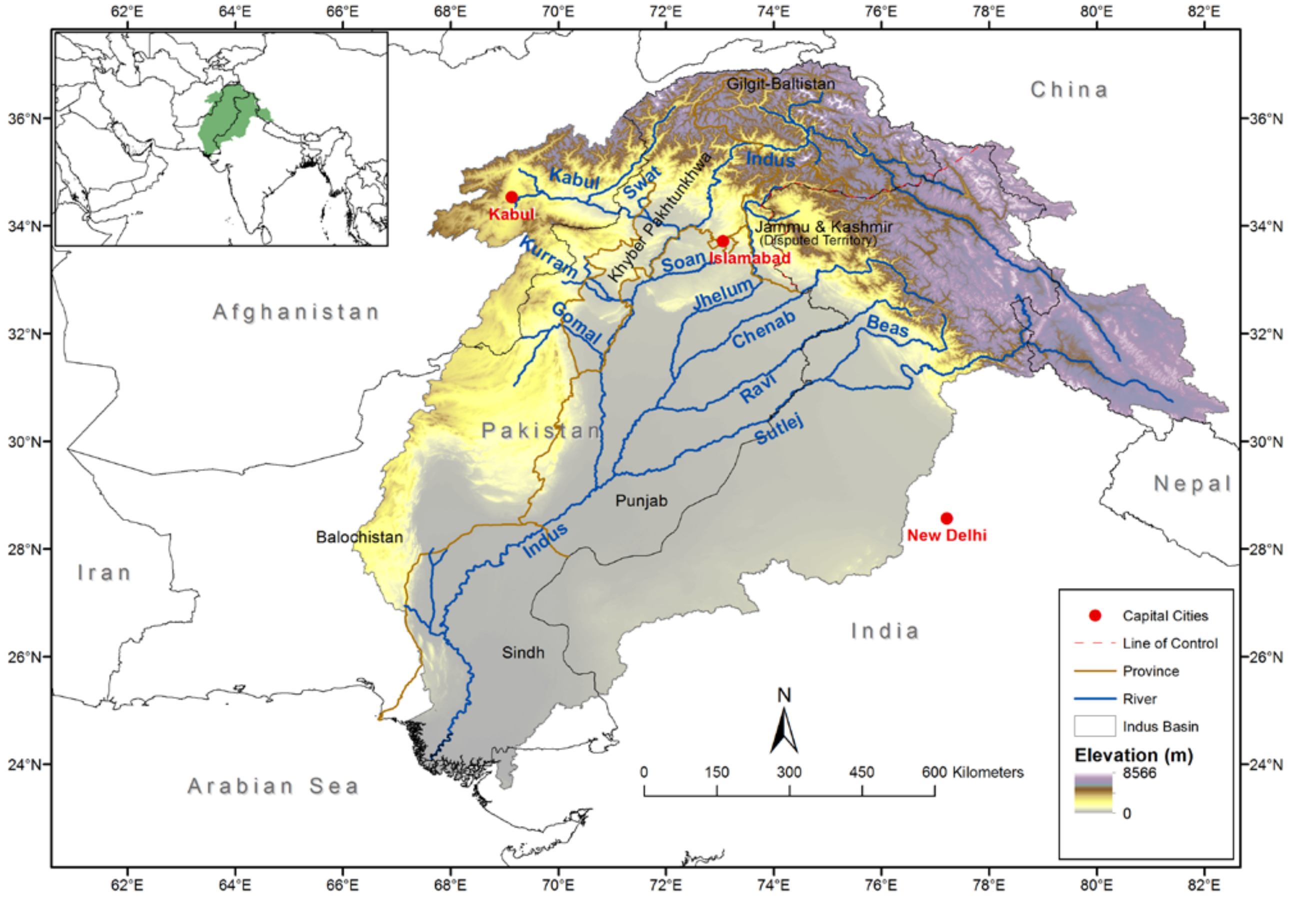


Figure 2 Indus Basin, showing major rivers within the basin

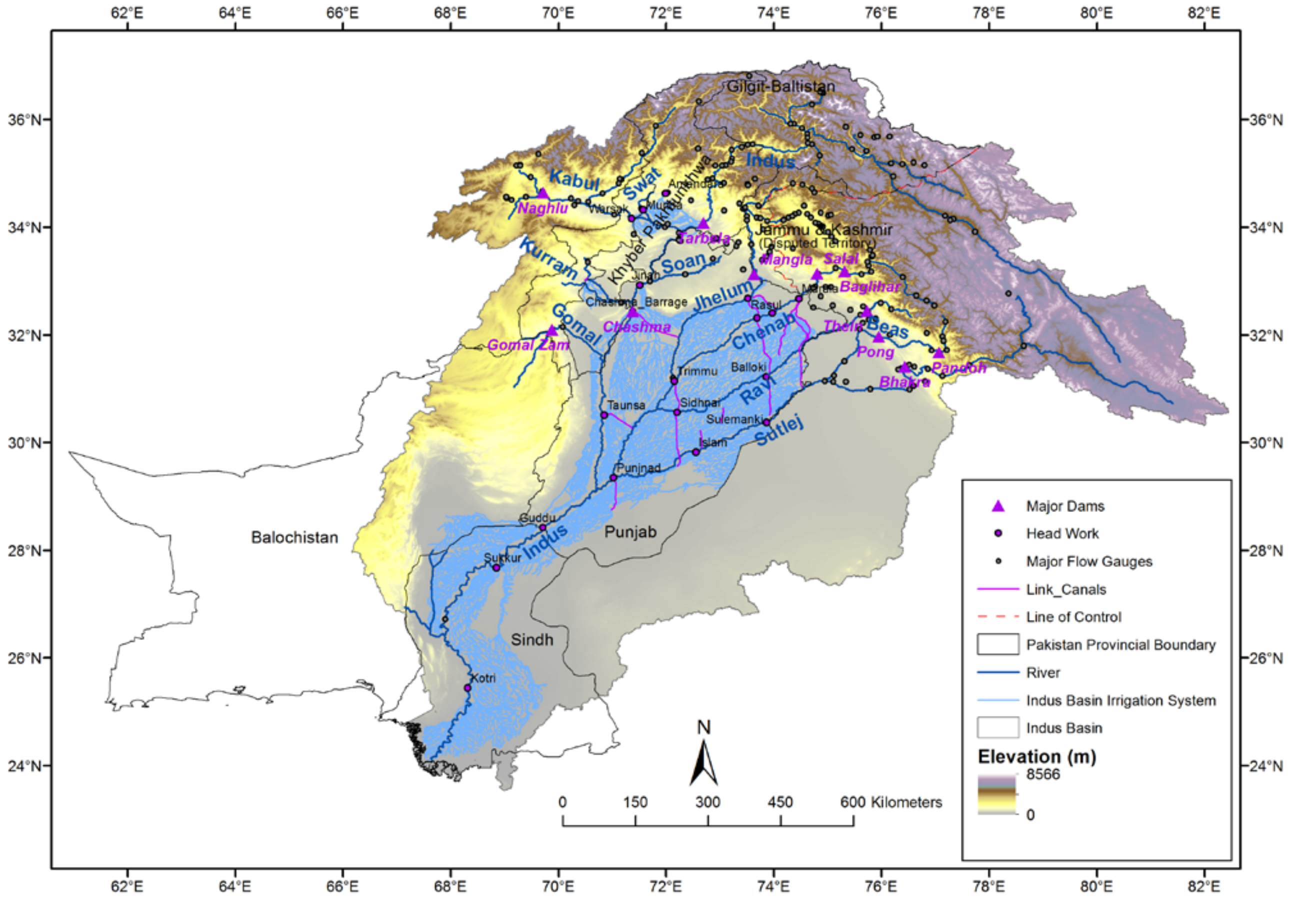


Figure 3 The Indus River system showing major dams, head works, flow gauging stations and Indus Basin Irrigation System (IBIS) in Pakistan

2.2 Climate

The monsoon (commonly referred to as the *South Asian monsoon* or the *Indian summer monsoon*) and western disturbances are the two major climate processes influencing precipitation magnitude, timing and variability across the Indus Basin).

The monsoon is the annual reversal of wind direction caused by excess heating over the South Asian land mass. It draws moisture from the Arabian Sea and Bay of Bengal into South Asia, across Pakistan and into the southern Upper Indus Basin during June to September. It is the predominate source of precipitation for Pakistan and the Indus Basin during the June to September period, and as it is the period of maximum insolation it coincides with the period of maximum snow and glacier melt contribution to flow in the Upper Indus Basin.

Western disturbances are mid-latitude low-pressure systems originating in the Mediterranean Sea, or even the eastern Atlantic Ocean, together with secondary sources from the Persian Gulf and Arabian Sea. They propagate from west to east across Iran, Iraq, Afghanistan, Pakistan and northern India during the October to March period. They interact with the steep orography to be the dominant source of heavy winter snowfalls across the Hindu Kush, Karakoram and western Himalayas.

The ANUSPLIN (Hutchinson, 1998a and b) thin plate smoothing spline package used daily climate observations to develop monthly rainfall and daily temperature surfaces for the entire Indus Basin. Based on this analysis it was determined that the mean annual precipitation varies from less than 200 mm in the south east to 1800 mm in the Himalayas (Figure 4). There is a rain shadow region in the Karakoram where precipitation is less than 300 mm.

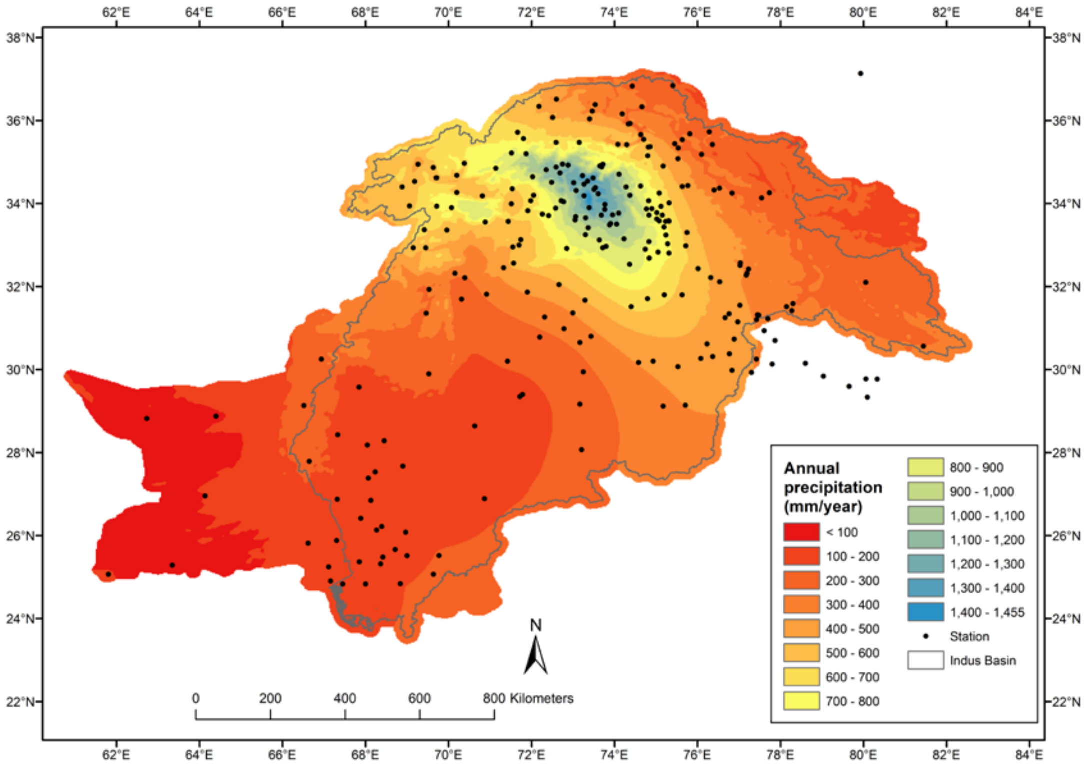


Figure 4 ANUSPLIN mean annual precipitation for 1990 to 2013

The Indus Basin has a continental type of climate characterized by extreme variations of temperature, both seasonally and daily. Very high altitudes modify the climate in the cold, snow-covered northern mountains; K2 peak (8611 m) can have minimum temperatures in December-January below -40°C. Along the coastal strip, the climate is modified by sea breezes. In the rest of the country, temperatures reach great heights in the summer; the mean temperature during June is 30°C in the plains, and the highest temperatures can exceed 47°C (Figure 5). Pakistan recorded one of the highest temperatures in the world, 53.5°C on 26 May 2010 at Mohenjo-Daro, Sindh.

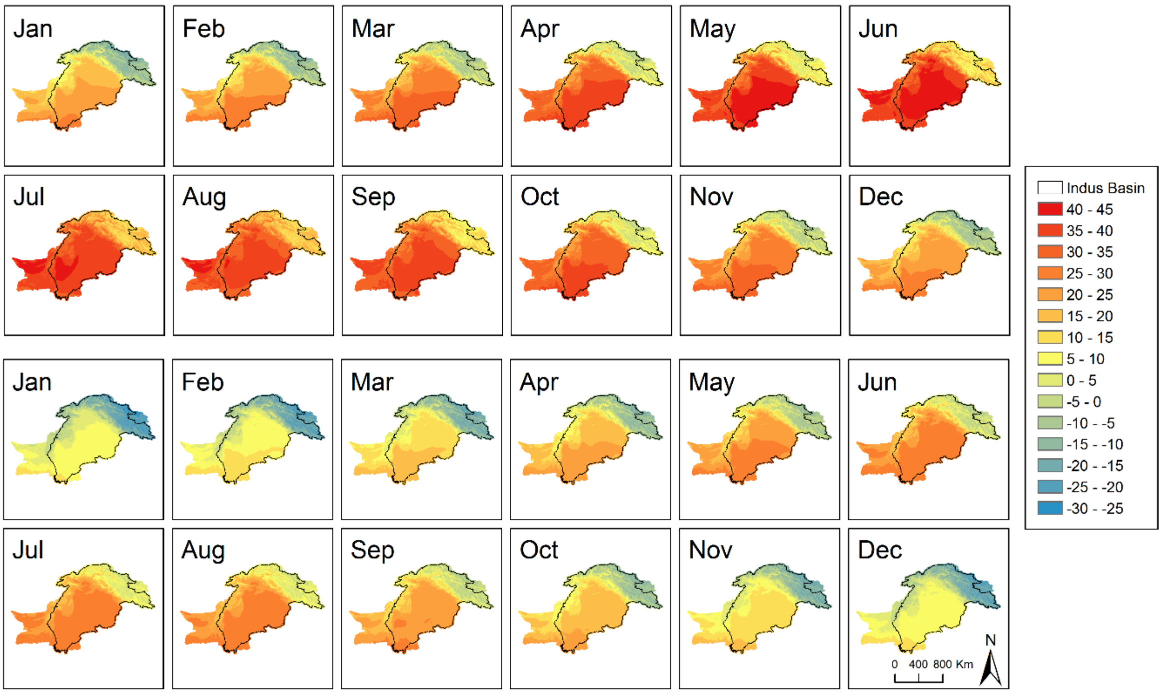


Figure 5 ANUSPLIN (top) 2013 mean maximum monthly temperature (°C) across the region, (bottom) 2013 mean minimum monthly temperature (°C)

2.3 Water resources in Pakistan

The Indus and its tributaries have a mean annual flow of about 175 km^3 (Archer et al., 2010), much of which derives from snow and glacier melting.

Pakistan has been described as 'the gift of the Indus', a phrase which derives from the description by Herodotus in the 5th century BC of Egypt as 'the gift of the Nile' (Griffiths, 1966). Archer et al. (2010) suggest that the remarks could apply to the relationship between the Indus and Pakistan, and Mustafa (2010) and others use the phrase 'the gift of the Indus'. The phrase aptly captures the very heavy reliance of Pakistan on the Indus for its water. The Indus Basin Irrigation System, developed originally by the British, is the largest contiguous irrigation system in the world (Condon et al., 2014).

- Of the mean annual flow of the river (175 km^3) approximately 75% (131 km^3) is diverted to agriculture producing 90% of the food for Pakistan.
- Irrigated agriculture accounts for about 85 % of cereal production, all sugar production and nearly all cotton production. Agriculture employs approximately 45% of the workforce, while textiles and food account for 75% of Pakistan's exports (Archer et al., 2011).
- The Indus supplied about 32 % of the nation's electricity from hydropower between 2010-11 and 2013-14 (Ministry of Finance, 2015).
- The Indus and its tributaries supply about 60% of the water used for irrigation (Archer et al., 2010). Much of the rest is groundwater. The groundwater is recharged partly by natural recharge, and partly by seepage from the rivers and the leaky canal network. Groundwater is more heavily used in the Pakistani Punjab (and the Indian Punjab) than in Sindh, primarily because much the groundwater in Sindh is too saline for use. It is generally agreed that the groundwater is over-used in the Punjab, with extractions exceeding recharge in many places, resulting in falling water tables. The future use and sustainability of groundwater is a crucial issue for future food security in Pakistan (Kirby et al., 2017).

The 1947 partition of India and Pakistan gave about 90% of the Indus Basin Irrigation System to Pakistan. As much as two-thirds of the overall surface water resource originates outside Pakistan. Thus, after partition, Pakistan relied greatly on water much of which it has no control over. The Indus Waters Treaty of 1960 gave Pakistan the water of three western tributaries (the Indus, Jhelum and Chenab) with 75% of the water of the basin, while India was given the water of three eastern rivers (the Ravi, Beas and Sutlej) (Condon et al., 2014). There is no treaty between Pakistan and Afghanistan governing the Kabul or other rivers shared by the two countries, nor between India and China.

2.4 Basin land use

Much of the land in the northern mountainous parts of the basin is under permanent snow and ice or seasonal snow (Figure 6). Much of the remainder is under mountain forests, shrublands and pastures. There are small areas of cropping, sometimes irrigated, in the valleys of this part of the basin.

To the south of the mountains, the flat plains of the Indus and its tributaries are largely used for cropping, much of it irrigated from the irrigation canals and groundwater. The most important crops in terms of area and water use are wheat, cotton, fodder (for dairy production), rice, maize and other summer grains, pulses, and sugarcane.

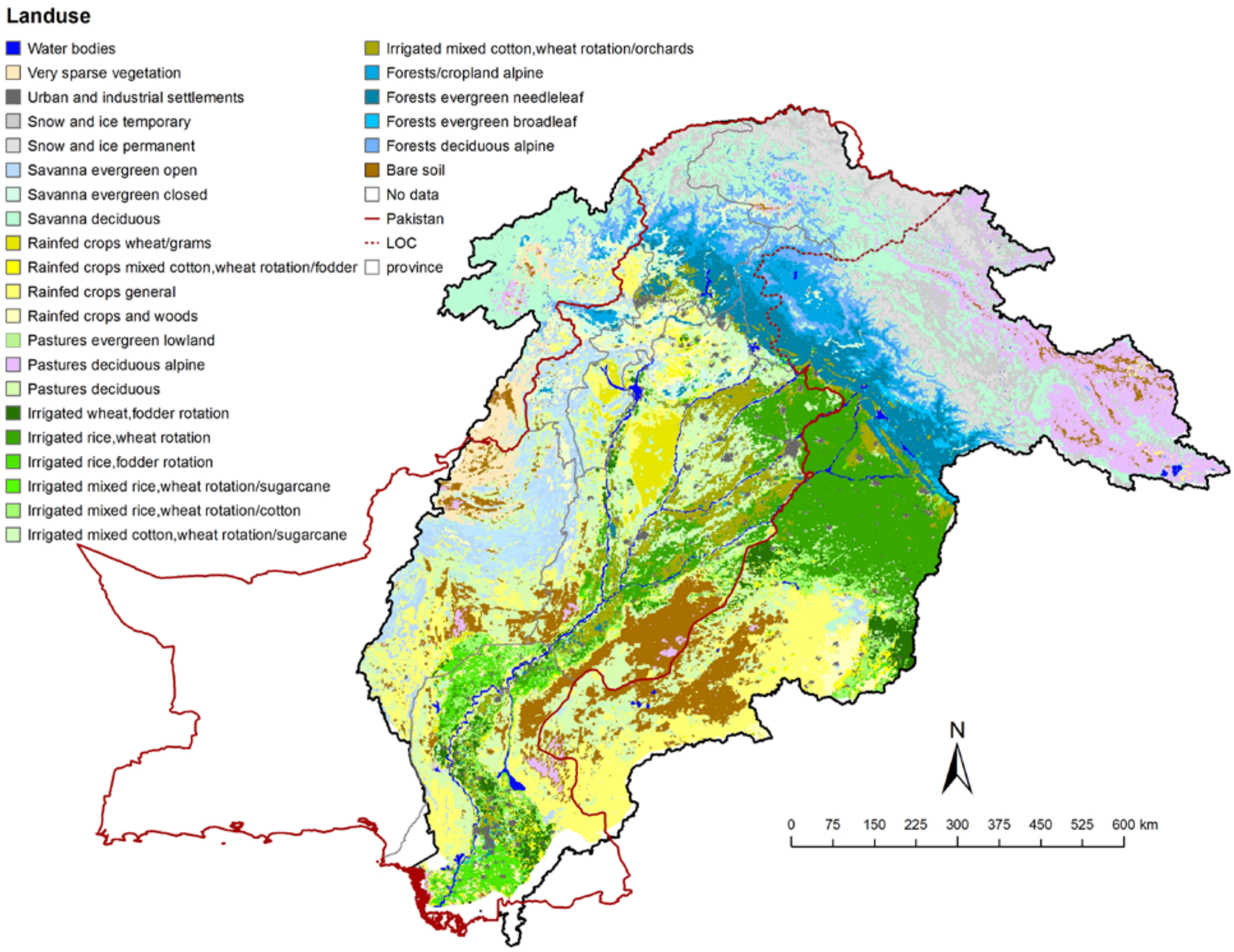


Figure 6 Land use Indus Basin based on 36 SPOT- Vegetation based NDVI values in 2007 (after Cheema, 2012)

According to agricultural surveys, the total area of crops in 2011-12 was about 230,000 km^2 (calculated from the figures in Kirby and Ahmad, 2016), but this figure includes crops that may be planted in the same fields in different seasons; for example, wheat in the Rabi season (grown over the dry winter) is often sown in rotation with cotton or rice in the Kharif season (grown over the wet summer). The Ministry of Environment (2009) gives the area of land used for agriculture as about 166,000 km^2 for the whole country (including areas outside the Indus Basin, though the area outside is very small), a figure that does not include double cropping. The crops are mostly irrigated, though a small part of the wheat crop and some other crops like bajra (millet) are rain-fed and grow partly outside the main river plains areas.

Most of the land outside the main river plains is rangeland, though some land is too arid even for pastures. According to the Ministry of Environment (2009), the total area of rangeland in Pakistan (in the mountainous north and the rest of the country combined, including areas outside the Indus Basin) is about 225,000 km^2 (about 27 % of the area of the country).

2.5 Water infrastructure in Pakistan: the Indus Basin Irrigation System

As noted in Section 2.3, the Indus Waters Treaty gave Pakistan the water of three western tributaries (the Indus, Jhelum and Chenab) with almost two-thirds of the water of the basin, while India was given the water of three eastern rivers (the Ravi, Beas and Sutlej). However, most of the historic irrigation development was on eastern rivers whereas western rivers were untapped due to steep terrain in the upstream areas. Consequently, the division of the waters necessitated the building of dams and link canals in Pakistan to supply water from the western rivers to the irrigation districts that had previously been supplied from the eastern rivers (Briscoe and Qamar, 2005). The water thus conveyed along the link canals feeds a massive canal system (Figure 7) that distributes water down to the farm and field using a time-based roster allocation known as warabandi, which means turns (wahr) which are fixed (bandi).

The link canals and distribution canals are designed to maximise the use of run-of-river diversions (Briscoe and Qamar, 2005). That is, it is a supply-based system where whatever is available in the river is supplied to irrigators. This contrasts with a demand-based system such as that in the Murray-Darling Basin in Australia, the general principle of which is for irrigators to receive an allocation of water at the start of the season, and then to request (‘demand’) water in response to crop requirements; large volumes of water storage ensure that demands are predominantly met.

The operation of the supply-based system of the Indus does, however, rely on two large dams, Tarbela and Mangla (Figure 8), as well as several barrages on the rivers from which the water is diverted along the link and distribution canals (Figure 3).

Mangla Reservoir is located on the upper Jhelum River. Capacity of the reservoir was increased in 2009 to 9.24 km^3 (7.49 Million Acre Ft (MAF)) (2011 survey) which is drawn upon for irrigation via a hydroelectric power generation plant. Surveys from 1993-2011 made available for this study suggest that sedimentation is occurring in the dam resulting in up to 0.02 MAF/year average loss in storage capacity.

Tarbela Reservoir is located on the Indus River. Active storage capacity of the reservoir is 6.849 MAF which provides irrigation water and hydroelectric power generation. Like Mangla Reservoir, surveys from 1998-2013 made available for this study suggest that sedimentation is also occurring in Tarbela reservoir, but at a much higher rate than Mangla, resulting in up to 0.1MAF/year average loss in storage capacity.

Chashma Reservoir is considered as a balance reservoir as it has significantly less capacity at approximately 0.5 MAF. Chashma is located on the Indus River downstream of Tarbela and just downstream of the Kabul confluence with the Indus.

Mangla, Tarbela and Chashma are the first major pieces of water management infrastructure used to regulate irrigation waters and provide hydroelectric power generation to Pakistan. The combined storage off all three main reservoirs on the Indus River is 14.84 MAF and this active storage volume is reducing on average by approximately 0.8% per year due to sedimentation.

From these three reservoirs, 15 additional barrages are located along the Indus and tributaries. These barrages divert waters to irrigation command areas through *Command Canals* and facilitate inter-basin transfers through *Link Canals*. The location of this major infrastructure is often displayed schematically as in Figure 7.

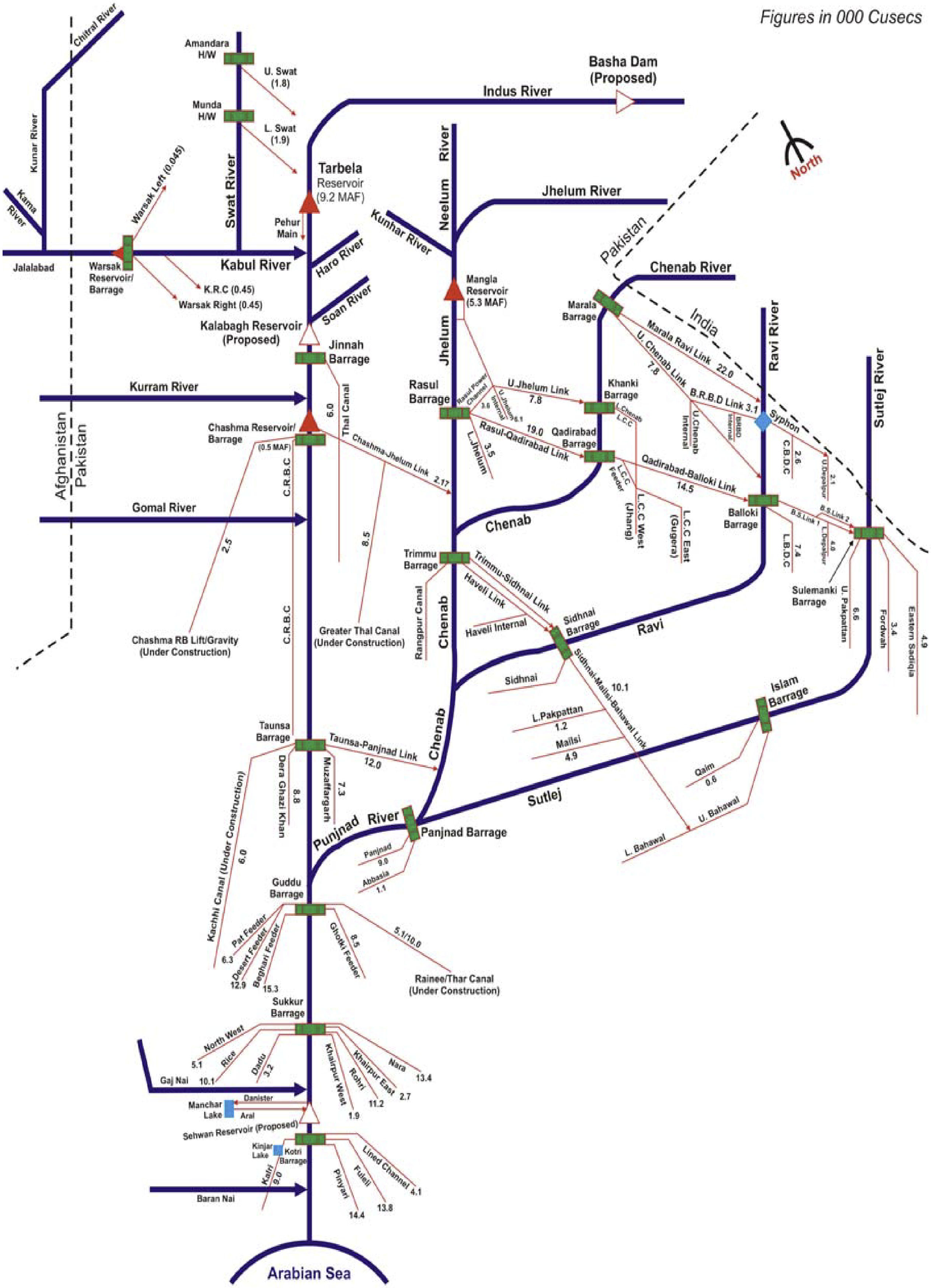


Figure 7 Indus River infrastructure schematic (sourced from http://water.utah.edu/uspcasw/research/indus-basin-model/ in 2017 – no longer available at this location)

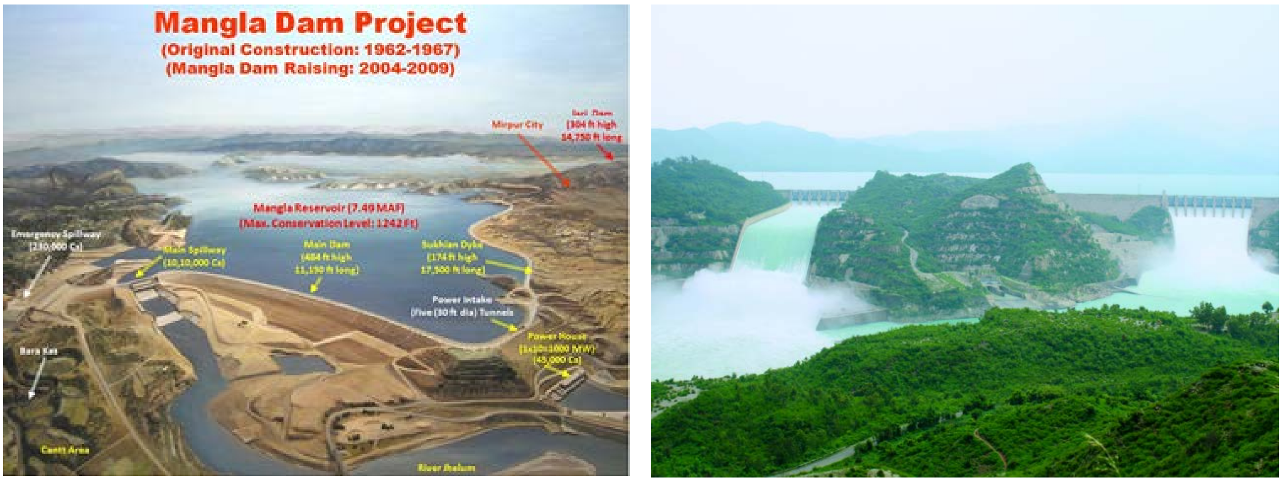


Figure 8 Mangla (left) and Tarbela (right) reservoirs (provided by WAPDA)

2.6 Water allocation in Pakistan

The 15 barrages and associated canals, in conjunction with the 3 reservoirs Tarbela and Mangla and Chashma form the key operational infrastructure of the Indus used to manage the distribution of water. Making this distribution equitable and ensuring that seasonal variability is managed is the role of the forecasting and allocation system.

As the volume of storage in the Tarbela, Mangla and Chashma is small relative to the mean annual flow in the Indus (approximately 10% of mean annual flows which can ensure up to 30 days of supply), considerable seasonal planning takes place to equitably maximise the future use of water. The way in which this is currently achieved is a result of:

- seasonal forecasting of flow quantities and flow patterns at *Rim Stations* which are the flow gauges on the largest rivers upstream of all major Pakistan infrastructure;
- forecasting major storage operations,
- water sharing between Provinces using the Water Apportionment Accord (1991); and
- water distribution within the command canals in provinces.

The Water Apportionment Accord (1991) is the cornerstone of agreed distribution of the water resources of the Indus between the four Provinces of Balochistan, Khyber Pakhtunkhwa, Punjab and Sindh. It sets out in 14 paragraphs how the waters of the Indus are to be shared and the relative seasonal patterns of those shares (http://www.pakirsa.gov.pk/WAA.aspx). However, how these paragraphs are interpreted and operationalized is not document and consequently capturing this within a model requires extensive discussion with river operators within the Indus River System Authority (IRSA).

Being able to understand and simulate the seasonal forecasting, allocation and distribution of Indus waters is a key water resource planning and operational requirement in Pakistan. Implementation of the Water Apportionment Accord principles is essential to the planning and operational procedures.

Model conceptualisation

2.7 Overview

An integrated modelling approach has been adopted by CSIRO to simulate the baseline Indus River system with the objective of being able to support planning and operational decisions and studies on the Indus River at an irrigation system scale.

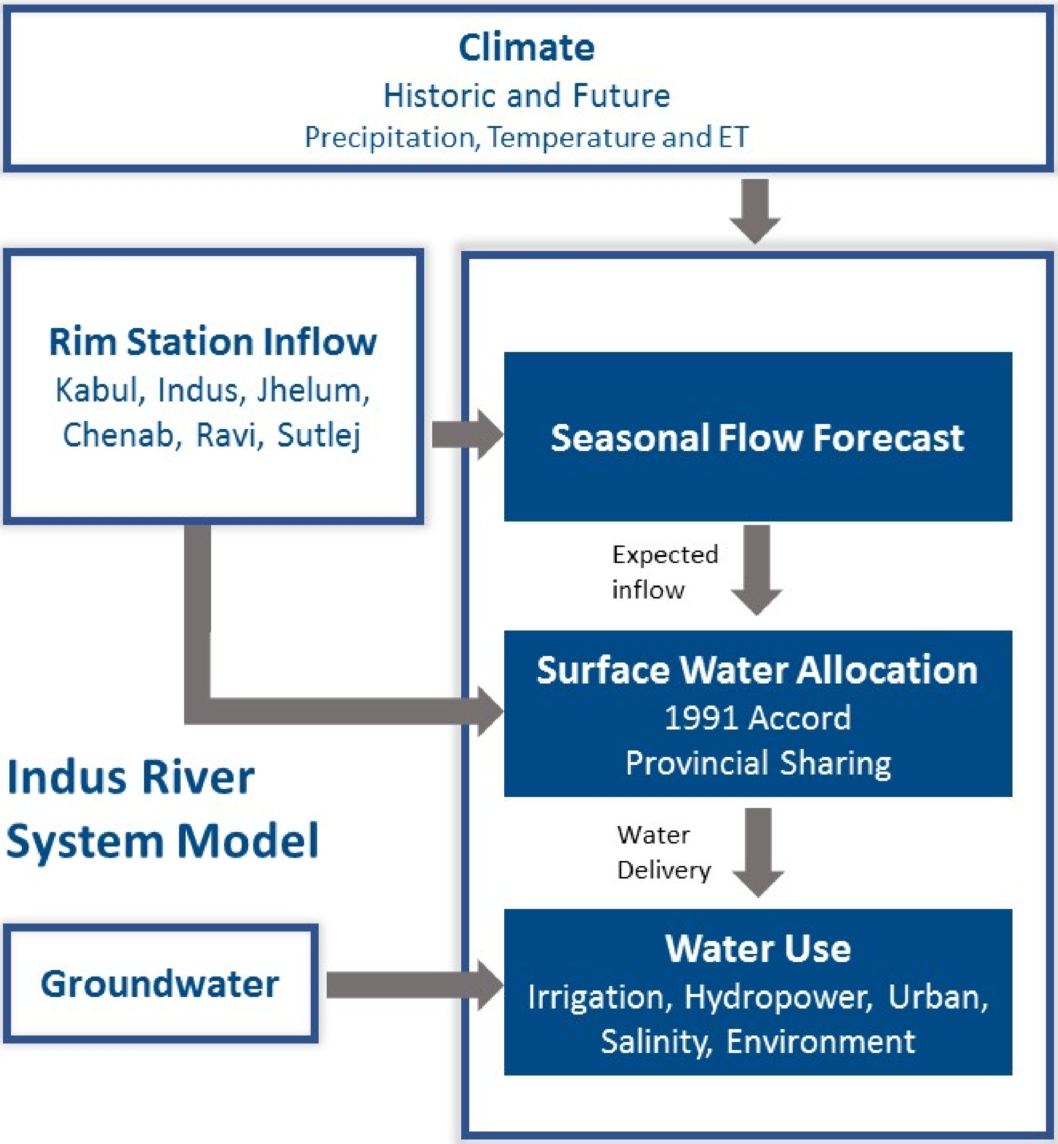


Figure 9 Core components of the Indus River System Model

The Indus River System Model (IRSM) has been constructed using the eWater Source modelling framework (Version 4.1.1.5345), which was recommended in section 5.1 of the Water Sector Task Force Report. The model uses climate and time series flow inputs (Figure 9). The rim station flow inputs are used in seasonal forecasts as well as physical input to the model. The climate inputs are used for modelling net evapotranspiration on water surfaces and crop demand. The model provides hydrological flux outputs such as time series of flows, storage volumes and levels throughout the system. It also estimates hydropower energy and crop production.

The eWater Source software (http://ewater.org.au/products/ewater-source/) is Australia's National Hydrological Modelling Platform. It is designed to simulate all aspects of water resource systems, and to support integrated planning, operations and governance from urban, catchment to river basin scales including human and ecological influences. Source accommodates diverse climatic, geographic, water policy, and governance settings for both Australian and international conditions.

The Source modelling framework supports both rainfall-runoff and snow and glacial melt modelling as well as complex river operations through the simulation of water flows through natural or constructed channels, barrage operations, storage operations and water demands. Source also provides the capability to model water allocation systems that control or influence distribution of water within a river system. Source also supports various levels of customisation with functions and plugins, making it one of the most versatile river simulation modelling environments available.

The IRSM was first constructed using available data and information to define the Indus River irrigation system. A baseline model (*IRSM_V4_1_1_5345_Baseline_V4.rsproj*) was developed that represents current water availability and water apportionment accord sharing rules and IRSA implementation of these rules in the Basin, with current infrastructure and historic climate and inflows.

The following sections describe the input data, model conceptualisation and calibration of the baseline IRSM.

2.8 Sources and overview of input data

Numerous agencies monitor and manage the water resources of the Indus River system and an understanding of the available data provides insight to the limitations of spatial and temporal resolution of a river system model. River system data have been provided to the project from:

- (former) Ministry of Water and Power and (now) Ministry of Water Resources;
- Indus River System Authority;
- Punjab Irrigation Department;
- Sindh Irrigation Department;
- Water and Power Development Authority; and
- Pakistan Meteorology Department.

The data include:

- observed daily and monthly climate data;
- water levels and flows for all major barrages and storages on a daily time step;
- water released from barrages to Canal Commands and Link Canals on a daily time step;
- water entitlements and deliveries to Canal Commands on a 10 daily time step;
- seasonal forecast inflow volumes;
- example water forecasting calculation spreadsheets and distribution planning sheets;
- major storage characteristics;
  - dimensions
  - outlet capacities
  - hydropower generation characteristics
  - level, volume area relationships over time (typically annually)
- Link and Command Canal capacities;
- selected canal discharge/rating tables;
- gauged flow time series for headwater Rim Stations on a daily time step;
- gauged flow time series for internal rivers daily time step;
- groundwater data;
- power plant water requirements;
- irrigation areas and cropping patterns; and
- the Water Apportionment Accord 1991.

The data listed above represents the major datasets available in Pakistan to undertake river system modelling and constrain the conceptualisation of a river system model to:

1. daily time step resolution utilising 10 daily flow pattern data;
2. flow calibration and verification at barrages and canal heads; and
3. spatial extents limited to operational infrastructure and rim stations.

A summary of the data used in developing the IRSM is presented in Table 1.

Table 1 Data used to develop the Indus river system model

Dataset	Description	Reference / source of the data
Canal Command Areas	With some modifications from CSIRO	IRSA, CSIRO
Catchment boundaries	SRTM 90m DEM with corrections for isolated areas. Broken at key gauging stations and points of interest	CSIRO
Rainfall surface	ANUSPLIN 1979 – 2013 2.5km resolution Indus and Pakistan	CSIRO
Minimum temperature surface	ANUSPLIN 1979-2013 2.5km resolution Indus and Pakistan	CSIRO-ANU
Maximum temperature surface	ANUSPLIN 1979-2013 2.5km resolution Indus and Pakistan	CSIRO-ANU
PET surface	Generated from temperature surfaces based on Hargreaves method 1979-2013, 2.5km resolution Indus and Pakistan	CSIRO
Observed streamflow	Available records from: Barrages, Gauges. Observed data gaps filled with flow derived from mass balance calculations at barrages	WAPDA, PID, SID, PCIW
Sub-catchment runoff	Observed data with gaps filled with rainfall runoff modelling	WAPDA, PID
Crop types and area	Consolidated dataset of district crop areas remapped to canal command areas. The district datasets based on several publicly available official Pakistan datasets (see reference for sources)	Kirby and Ahmad (2016)
Crop production	Same source as crop types and area	Kirby and Ahmad (2016)
Irrigation water use	Based on 1. the crop area data listed above and 2. two remotely sensed estimates of actual evapotranspiration by Ahmad et al. (2009) and Cheema (2012)	Ahmad et al. (in review)
Storages	Salient features	WAPDA, IRSA
Canals	Salient features	WAPDA, PID, SID, PCIW
Entitlements and deliveries	Canal command flows	PID, SID
Water allocations	Kharif and Rabi seasonal and 10-day water allocations to provinces	IRSA
1991 Water Apportionment Accord	Rules for sharing surface water resources	IRSA

The time series for streamflow gauge data extended over the period 1990-2012 or longer, but not all gauges had this duration of data. Key model datasets generated from the above data are outlined in the following sections including catchment boundaries, climate, irrigation demands, barrage setup and water resources allocations.

2.8.1 Catchment boundaries

The catchment boundaries are essential to define the basin area and domain for hydrological investigations. As consistent boundaries for the Indus and its sub-basins were not available, CSIRO has developed these boundaries using the Shuttle Radar Topography Mission (SRTM) 90m DEM (Jarvis et al., 2008) and the key flow gauging stations in the Indus.

A subset of required tiles of SRTM 90m DEM were downloaded from http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1 and combined into a single raster file covering the entire Indus basin. Although STRM 90m available at CGIAR Consortium for Spatial Information (CSI) is processed to fill data voids, it was further processed using the standard fill tool within ArcGIS to address the localised imperfections (sinks) for stream network and catchment delineations. The generated catchment boundaries were checked against remotely sensed images. Manual adjustments were conducted to reinforce hydrological connectivity of the stream network and associated watersheds.

The key streamflow gauge coordinates in the upper Indus was obtained from PCIW, WAPDA and other publicly available sources. These were then verified with Google Earth and corrected in consultation with PCIW and WAPDA. In addition to actual flow gauges, arbitrary gauges at major streams crossing national and provincial jurisdictions were added to enable transboundary investigations.

2.8.2 Climatic and streamflow data

Climate

Gridded rainfall, temperature and evapotranspiration data were developed for the entire Indus basin by CSIRO and ANU using ANUSPLIN and observed daily climate records (Figure 5). These data were converted to Source-compatible time series for the purposes of the model development.

Streamflow data

Gauged flow time series have been provided by WAPDA and Punjab and Sindh Irrigation Departments. The time series for streamflow gauge data extended over the period 1990-2012 or longer, but not all gauges had this duration of data. Some quality checking, primarily using double mass plots, was conducted for these data and showed no unexpected behaviour between flows at neighbouring gauges.

River system model inflows

The gauged rim station flow time series define the upper limit of the river system model and have been provided by WAPDA, IRSA and PID for the following rim stations:

- Kabul River at Nowshera 1990-2013
- Indus River Tarbela inflows 1990-2012
- Jhelum River Mangla inflows 1990-2012
- Chenab River Marala inflows 1990-2012
- Ravi at Border (Jassar Gauge) 2007-2012 (incomplete)
- Sutlej at Border (Ganda Singh Wala) 1990-2012.

These flows are used in the calculation of inflow forecasting and actual inflows to the model. Only observed catchment inflows are used in the model, however these input time series can be substituted at any time with modelled time series of other model generated inflows as deemed appropriate for scenario modelling.

Water flows across barrages and associated water levels have been provided by WAPDA, Sindh and Punjab Irrigation Departments. These data have been used to provide calibration/verification datasets for the IRSM. Water level data have been used to formulate operational water level targets on some barrages.

The approach of using observed time series at the rim stations as input to the model means that to run the model for alternate or extended periods of time, ***all*** inflow time series must be updated and correspond to the model period being simulated.

Extending the Ravi at Border (Jassar) gauge time series

Ideally, model time series extension and/or infill is facilitated through catchment modelling. However, in the case of Ravi at Border (Jassar) gauge, the following method has been adopted to extend or infill gauge data. This method has been adapted from mass balance methods used in Pakistan, whereby ungauged inflows into barrages (such as Sutlej at Border) are estimated by adding canal and barrage main river discharges:

- The 2007-2012 Jassar gauge flows are compared with the corresponding Ravi at Balloki Barrage upstream flow data, revealing that flow above approximately 900m^3/s correspond with the upstream Jassar gauge flows plus Deg Nala flows;
- Therefore, for the purposes of extending the model period, an **estimate** of the Jassar gauge flows plus Deg Nala flows time series is the flow upstream of Balloki Barrage that exceed 900 m^3/s. The cumulative discharge plot (Figure 10) representing this derived discharge series and is compared against actual Jassar gauge flows and shows seasonal and overall flow volume agrees using this simple method; and
- To extend the model period, the estimated Jassar gauge time series is used for the period prior to 2007, and actual gauged flows are used thereafter.

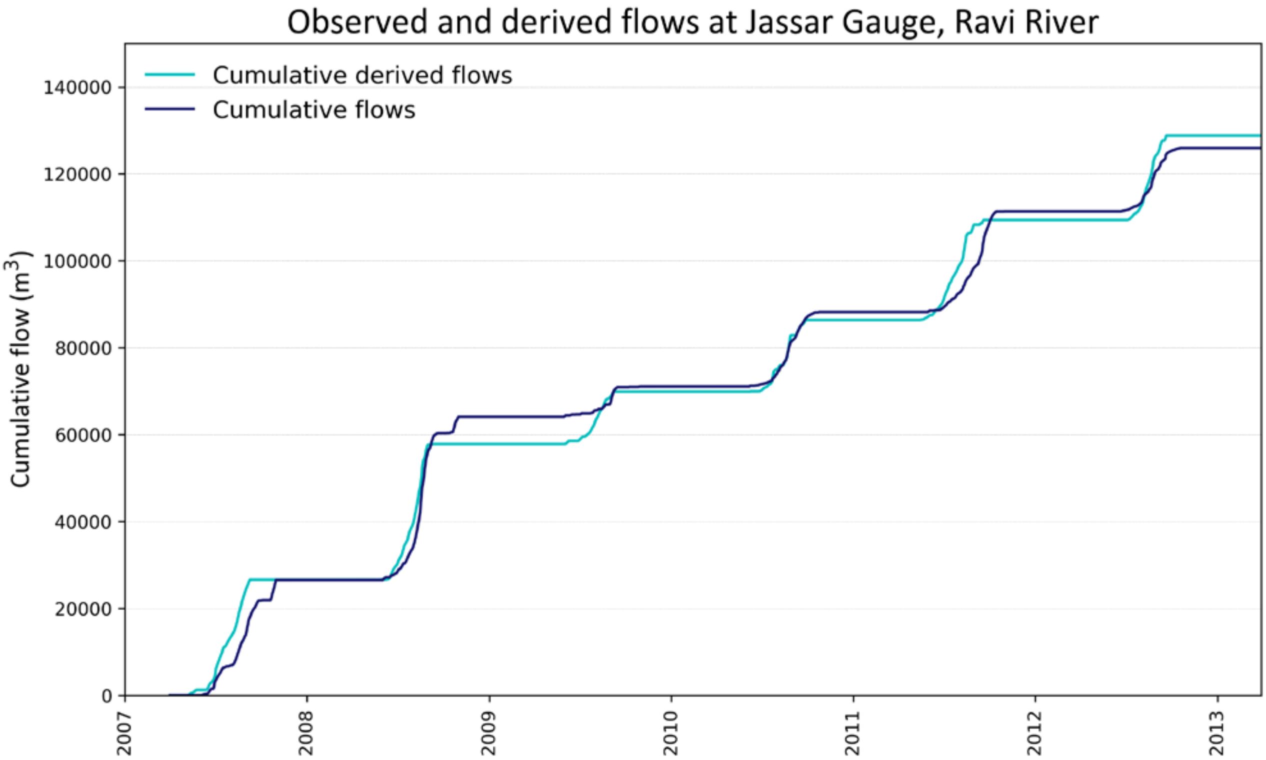


Figure 10 Comparison of observed and derived Ravi inflows at Jassar gauge 1990-2012

Model extended flow time series

The extended model flow time series from 1990-2012 (inclusive) for all rim stations are shown in Figure 11 and the accompanying Table 2 shows mean seasonal and annual flows for the same period. Note in Figure 11(f) the period of no flow is assumed to be missing values.

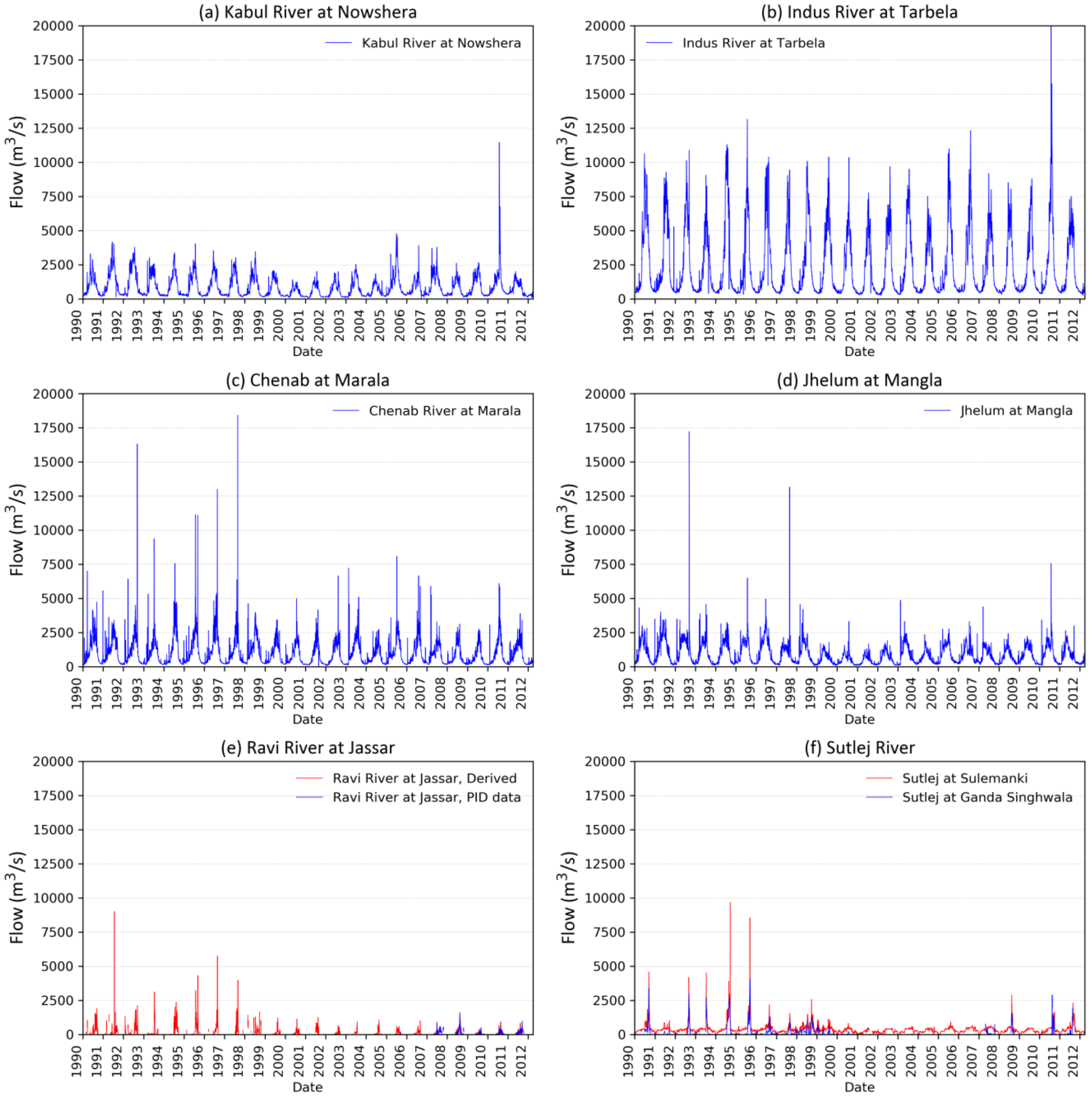


Figure 11 Rim station gauge flow data used for extended model (1990-2012) showing (a) Kabul River at Nowshera, (b) Indus River at Tarbela, (c) Chenab River at Marala, (d) Jhelum River at Mangla, (e) Ravi River at Jassar (f) Sutlej River at Ganda Singhwala

Table 2 Rim station mean seasonal and annual flow 1990-2012 (GL)

Rim Station	Mean Rabi flow (GL)	Mean Kharif flow (GL)	Mean annual flow (GL) (Rabi + Kharif)	Percentage contribution
Kabul River at Nowshera	5000	21414	26414	16.1%
Indus at Tarbela	10812	64176	74988	45.6%
Chenab at Marala	5609	24900	30508	18.6%
Jhelum at Mangla	6250	20896	27146	16.5%
Ravi at Jassar	117	2389	2506	1.5%
Sutlej at Ganda Singhwala	432	2315	2748	1.7%
Total (GL)	**28220**	**136089**	**164309**	**100.0%**

Other inflows incorporated in the model include:

- Soan at Chirah
- Kurram River at Thal
- Gomal at Kot Mutaza
- Haro at Gariala
- Selected nalas and residual reach inflows:
    - Deg Nala (U/S Balloki), extra Marala inflows (U/S Khanki), U/S Trimmu inflows, U/S Sidhnai inflows, U/S Chashma inflows, U/S Taunsa inflows, U/S Punjnad inflows, U/S Guddu inflows, U/S Sukkur inflows, U/S Kotri inflows.

Where available, gauge data have been used (e.g. Haro River has a complete time series for 1990-2013). In most cases, inflows from these tributaries and nalas are either derived using mass balance methods as described above, routing methods as described in the model calibration section, or included as zero inflow time series so that flows can be added when modelling results become available.

2.8.3 Irrigation demands

Irrigation areas (Table 3) were developed from mapped Command Areas, overlapped with land use to identify areas of irrigated crops. Crop categories represented in the baseline IRSM are basmati rice, seeds, rice, cotton, summer grains, pulses, sugar cane, wheat, other, fodder rabi, fodder kharif, evergreen orchard and deciduous orchard.

The crop categories and the areas of each are those described in Kirby and Ahmad (2016). The irrigation demands are calculated in the river system model using a crop coefficient approach (Allen et al., 1998).

It has been assumed that there are no return flows from irrigation command areas and that all locally generated runoff is used within these areas. Saline and non-saline areas are split based on the IBMR model. In non-saline areas it is assumed that surface water is used as a priority and any shortfall is met by groundwater.

Groundwater data include water level and quality and have been supplied by WAPDA. Groundwater quality data are indicative of how much groundwater may be used in a canal command area to supplement surface water use.

The demands for irrigation use the window of seasonal planting and information on crop water requirements.

Table 3 Command areas and maximum irrigated areas (in hectares, and acres) included in the IRSM baseline model

Water user*	Ground water	Maximum irrigated area (ha)	Maximum irrigated area (acre)	Water user*	Ground water	Maximum irrigated area (ha)	Maximum irrigated area (acre)
Kalri Beghar	Saline	136570	337471	Chashma_RB_KP_KPMW	Fresh	207230	512076
Pinyari	Saline	191910	474219	Chashma_RB_Punjab_KPMW	Fresh	107230	264971
Fuleli_SRWS	Saline	224690	555220	Greater_Thal_PMW	Fresh	586570	1449444
Lined Channel	Saline	117400	290101	Greater_Thal_PMW	Saline	95490	235961
NW	Saline	256560	633973	Havali	Saline	73500	181622
Rice	Saline	128530	317604	Upper Rangpur	Fresh	100580	248538
Dadu_SRWN	Saline	204180	504539	Thal	Fresh	616360	1523056
Khairpur West	Saline	99680	246314	Thal	Saline	331890	820117
Rohri South	Fresh	161920	400112	Upper Swat PHLC	Fresh	132330	326994

Water user*	Ground water	Maximum irrigated area (ha)	Maximum irrigated area (acre)	Water user*	Ground water	Maximum irrigated area (ha)	Maximum irrigated area (acre)
Rohri South	Saline	253030	625250	Pehur	Fresh	20500	50657
Rohri North	Fresh	353180	872725	Tarbela LB	Fresh	26440	65335
Rohri North	Saline	181100	447507	Lower Jhelum	Saline	204050	504218
Khairpur East	Saline	171890	424749	Lower Jhelum	Fresh	362730	896324
Nara	Saline	697140	1722668	Upper Jhelum	Fresh	260810	644475
Upper Nara	Saline	164060	405400	Upper Chenab	Fresh	428160	1058005
Pate Feeder	Fresh	433080	1070162	Marala Ravi	Fresh	93900	232032
Desert_BRW	Fresh	115850	286271	BRBD	Fresh	210640	520502
Begari_SRWN	Saline	162660	401941	Central_Bari_Doab_PRW	Fresh	335910	830050
Begari_SRWN	Fresh	162660	401941	Upper Dipalpur	Fresh	154610	382049
Ghotki_SCWN	Fresh	143620	354892	Gugera RW	Fresh	308050	761207
Ghotki_SCWN	Saline	143620	354892	Gugera SW	Saline	140120	346244
Raini	Saline	27250	67336	Gugera SW	Fresh	353630	873837
Kachhi	Fresh	33580	82978	LBDC	Fresh	737290	1821880
Dera_Ghazi_Khan_PCWW	Fresh	477640	1180272	Lower Dipalpur	Fresh	260600	643956
Muzaffargarh	Fresh	92820	229363	Fordwah_PCWE	Fresh	182770	451634
Muzaffargarh	Saline	278530	688262	Sadiqia_PCWE	Saline	460630	1138240
Rangpur Lower	Fresh	45440	112285	Upper Pakpattan	Fresh	408870	1010338
Punjnad	Fresh	377440	932673	Jhang RW	Fresh	113760	281107
Punjnad	Saline	161760	399717	Jhang SW	Saline	137320	339325
Abbasia_PCWW	Fresh	125730	310685	Jhang SW	Fresh	320440	791823
Karanga	Saline	16050	39660	Fordwah	Saline	460630	1138240

* Water users are split into fresh and saline zones reflecting groundwater quality. Only irrigation areas in the fresh zones can access and pump groundwater to supplement surface water supplies.

2.8.4 Other water demands

Power plant water requirements are supplied by WAPDA. Selected power plant water needs are included in the model at minimum flow requirement nodes to create an additional water flow requirement at Rasul Power Canal, Mangla and Tarbela. Additional nodes have also been incorporated for power station demand offtakes from CJ Link canal and Guddu Barrage – these are yet to be fully parameterised and return water to the main stem of the Indus and thereby do not impact on the overall mass balance of the system.

Smaller water demands not yet configured in the model include:

- water use for domestic demand for rural populations noting that most water use is from groundwater
- water use for domestic demand for urban centres
- industrial demands
- mining.

Typically, these demands are either small, too numerous to obtain reliable data for, or are accounted for in a modelling context as part of the provincial water share. Three exceptions to this general rule, listed below, are incorporated in the baseline model for testing and assessment purposes and are yet to be fully parameterised:

- Muzaffargarh drinking water supply (Punjab province)

- DG Khan drinking water offtake (Punjab province)
- Karachi water supply (Sindh province).

2.8.5 Water regulation infrastructure

Key infrastructure considered in the baseline model includes major supply and distribution storages, barrages (Table 4) and canals.

Storage infrastructure

The modelling approach adopted for storages is as follows:

- Storage dimensions over the modelling period (volume vs. water depth) for Tarbela and Mangla have been provided by WAPDA and IRSA.
- Storage dimensions are used in the model to generate level-volume-area tables so that the model can calculate how much water is stored as the level changes.
- The level-volume-area relationships are used directly in the model and are progressively changed when new hydrographical survey information is obtained to account for the loss of storage volume due to sedimentation.
- The model linearly interpolates between level-volume-area tables according to when the surveys were undertaken, thus the storages are progressively in-filled, consistent with survey data.
- The area of the storage associated with different level-volume-area tables is assumed to not change as new survey data becomes available because the in-filling of the storage occurs at the bottom of the storage. Also, this data is only used to calculate net evaporation from the storage - typically a small component of the mass balance relative to the through-put of water.

Table 4 Major storages and barrages included in the Indus model

Name	Full supply-level (m)	Full supply-volume (km³)	Full supply-surface area (km²)	Initial storage-level (m)	Initial storage-volume (km³)	Dead storage level (m)	Dead storage-volume (km³)
Tarbela Dam (1976)	76.544	10104.866	233.3	44.14	3751.000	21.00	1529.518
Mangla Reservoir (1968)	64.671	9137.696	431.3	56.00	6626.628	3.50	162.820
Chashma Barrage (1971)	9.144	189.861	41.5	9.14	189.861	0.74	0.028
Taunsa Barrage	5.334	50.000	26.0	2.67	25.000	0.00	0.000
Rasul Barrage	7.500	54.334	14.5	2.36	5.490	1.06	1.091
Khanki Barrage	5.486	64.685	23.6	1.52	5.009	1.52	5.009
Qadirabad Headworks	8.230	109.413	26.6	1.83	1.060	1.83	1.060
Trimmu Barrage	7.772	42.076	10.8	1.22	1.035	1.22	1.035
Sidhnai Barrage	6.681	25.891	7.7	1.22	2.582	1.22	2.582
Balloki Barrage	4.115	15.343	7.4	4.12	15.346	1.07	1.022
Sulemanki Barrage	6.706	21.759	6.5	0.91	0.405	0.91	0.405
Islam Barrage	6.248	50.930	16.3	1.68	2.540	0.00	0.000
Punjnad Barrage	6.828	73.419	21.5	1.52	4.214	1.52	4.214
Guddu Barrage	8.382	266.847	63.7	8.38	266.847	2.29	26.586
Sukkur Barrage	7.163	93.116	26.0	7.16	93.116	1.52	4.191
Kotri Barrage	9.845	139.265	28.3	9.85	139.265	3.05	13.594
Jinah Barrage	3.169	52.222	32.3	2.39	31.875	0.05	0.051
Marala	7.620	20.305	5.3	2.44	2.079	2.44	2.079
Chotiari balancing storage	26.82	1267.400	182	26.82	1267.400	19.66	48.700

Barrage infrastructure

In the case of barrages, detailed hydrographical survey data are often not available to facilitate the derivation of level-volume-area relationships. The model still requires level-volume-area tables to determine discharge from barrages through gates and out to canal command areas, which are typically a function of water surface elevation. An appropriate level-volume-area table for each barrage was derived by adopting the following modelling principles:

- The volume retained by the operational volume in a barrage should be approximately equivalent or greater than 2 days' supply to the offtake canals. This concept is a Source modelling 'rule of thumb' and ensures that when the model is undertaking a mass balance at a barrage daily, the water supplied to the offtake canals does not take all the water available, reducing the head available and thus cutting off supply within that daily time step. In practice, upstream river flows arrive in time to replace the water that is let out to canals, but to ensure model stability, good modelling practice dictates that enough water should be retained in the barrage for 2 days of supply;
- Barrage cross sections describing gate height, gate sill level, under-sluice sill level and upstream bed level were used where available to describe the operational space for water depth available at each barrage;
- An appropriate water surface area for the barrage was derived such that the 'rule of thumb' storage volume was available at the barrage for typical operational head levels that allowed for sufficient water to be supplied to canals;
- Where available, the gate sill levels, width of gate openings and the number of gates for each barrage outlet (main barrage for downstream flow, navigational gates, offtake canals) were used with typical weir equations and coefficients to derive relationships describing the maximum outlet capacities for all barrage outlets for given head levels;
- Priorities were given to link and irrigation canal outlets when water supplies were limited before water was released downstream as a default operational condition. In some cases, discussions with Punjab Irrigation and Sindh Irrigation Departments provided general operational rules for outlet priorities at individual barrages; and lastly
- Barrages that showed distinctive operational levels (applied at times of the year e.g. cleaning) were assigned target operational water levels according to the average observed closing time of year.

Canal infrastructure

Barrages in the river system model supply water to link canals and command canals. As the barrages have gates than can be either fully open or closed, the release of water to these canals must be triggered by an event. In the IRSM, this event is the water entitlement request of the irrigation command area (or aggregate downstream command areas). Actual link and command canal capacities have been provided by Sindh and Punjab Irrigation Departments. Link and command canal capacities are used in the IRSM as a constraint on meeting requests so that the canal capacity is not exceeded down that branch of the irrigation network. The modelling approach to releasing water at barrages is as follows:

- barrage gate configurations and water levels determine the maximum amount of water that can be released to a link canal or irrigation canal;
- water entitlements determine when water is released, with the water released potentially being constrained by the gate configuration (water head); and
- canal maximum capacities cannot be exceeded.

Flows through canals have been described through canal discharge rating tables provided by IRSA, where data exists. These data are used to generate flow routing parameters for selected canals that relate discharge to head and velocity, allowing the calculation of travel time in a reach. Where these data are unavailable, average canal width combined with average canal slope and canal length have been used with Manning's formula to estimate a canal discharge rating table and thus derive routing parameters.

Irrigation supply

For the actual irrigation areas receiving the water entitlement, surface water irrigation extractions were limited to the surface water entitlement that could be delivered through the barrage and canal infrastructure. This reflects a supply-based system.

For some irrigation areas the shortfall in irrigation demand can be made up from groundwater extracted from underground aquifers that are known to have fresh water supply. For this reason, irrigation areas (command areas) have been split into those that have fresh underlying aquifers and those that have saline groundwater. Irrigation areas overlaying saline aquifers are not provided with groundwater extraction nodes to supplement supply.

2.8.6 Water resource allocation

Water entitlements and delivery datasets are a very important part of the IRSM. Water entitlements have been provided by Sindh and Punjab Irrigation Departments. The data has been used as a minimum flow constraint time series imposed on canal commands and link canals to request water, thereby creating the flow and distribution of water from major storages to the canal commands.

Seasonal forecast inflow volumes were provided by IRSA to allow the comparison of model generated forecast volumes with actual historic forecast volumes.

Seasonal forecast and distribution planning sheets were provided by IRSA to show the calculation steps and outcomes of the typical seasonal planning process. The historic seasonal forecast and distribution planning outcomes have been compared against model generated equivalents.

The Water Apportionment Accord 1991 contains the provincial water sharing rules that are used in the IRSM to distribute the seasonal water forecast. Paragraph 2, 4 and 14 are particularly important for the IRSM and include the provincial share breakup as well as seasonal 10 daily patterns for canal commands.

Full details of how the water resource allocation system works within the IRSM are provided in Section 2.10.

2.8.7 Environmental flow demands

Environmental flows remain the subject of ongoing debate for the Indus River system. The 1991 Water Apportionment Accord recognised that some flows below Kotri barrage to counter the impact of seawater intrusion to the estuary are required, however an agreement on the actual amount of water required could not be made without further study.

While no legislated provision in the 1991 Water Apportionment Accord was been made for a specific water entitlement for the environment, we note that Sindh Province argues for a 10 MAF allocation below Kotri and that IRSA calculates the anticipated below Kotri water availability as part of anticipated water availability calculations.

At this stage, the baseline IRSM reflects the 1991 Water Apportionment Accord in not containing a specific allocation for environmental flows but has provision to test proposed environmental flow provisions through future scenario modelling.

2.9 Baseline IRSM conceptualisation

River systems can be defined by a network of nodes connected by links. Nodes represent locations where water is measured, input, combined, split, stored, demanded, extracted, regulated or shared. Links represent the movement of water between nodes.

Key feature types used to model characteristics of the Indus River system are:

Links – represent the movement of water through rivers and canals. Where routing is included in a reach, lag and attenuation of flow can be incorporated into the model, thus modifying the shape of the downstream hydrograph. Routed links may optionally include net evaporation, extractions/diversions and losses and gains.

Gauge nodes – are typically locations where river or canal flow is measured or may be used as points of interest for modelled flow. They provide points for calibration of the model where observed and modelled flows can be compared.

Inflow nodes – represent inflows into the river system either as headwaters or as gauged or ungauged tributaries within the river system.

Confluence nodes – represent locations where rivers or canals join. In regulated systems they provide a decision point for determining how to distribute orders up each path or to forecast and account for contributions from an unregulated branch.

Splitter nodes – represent locations where rivers of canals split. The split may be a fixed proportion of upstream flow (mostly the case in the IRSM) or may be controlled within bounds to meet downstream orders or operational rules.

Storage nodes – are used to represent locations where water is stored in the system, typically dams, weirs and barrages, and may also be used for floodplains, wetlands or groundwater. They are used to hold and optionally regulate water at a point in the river system. Storages use a mass balance approach where a static or dynamic level-volume-area relationship is used in conjunction with multiple outlet configurations, inflow, water surface net evaporation, seepage and demands and operational rules to calculate discharge for each outlet path. In regulated systems storages may order from upstream storages to maintain operational targets e.g. Chashma reservoir.

Supply points – represent locations where water is optionally extracted to meet water user demands. The supply may extract water from the river or from an unlimited groundwater source. The extraction is constrained by a share of the available flow and may optionally be constrained by diversion thresholds or extraction capacity all of which are configurable by rules. It may also be configured for overbank diversions/extractions which are also rule configurable. The supply point may be configured to pass orders to a regulated river system. It can also include a delivery loss. Note in the Indus system groundwater supply points are included for irrigation areas that have access to fresh groundwater supplies and surface water supply points are unregulated.

Water users –represent locations where water is demanded from the system. Note this may not necessarily be extracted depending on how the associated supply points are configured. The demand may be a fixed number, demand pattern, time series, user specified functions or irrigation demand. The node may optionally include an on-farm storage and may return water to the on-farm storage or the river system via a confluence node. The water user may be supplied by multiple supply points with a distribution hierarchy. In the Indus models some irrigation water users are configured with both a surface and groundwater supply with priority given to the surface water supply and the shortfall being met from the groundwater supply.

Irrigation demand model – represents irrigation districts or command areas and takes into consideration supply escapes and losses, on-farm escapes and losses to groundwater, fallow and multiple cropped areas throughout a year using a FAO56 soil moisture water balance method. In the IRSM a standard set of 13 crops are considered at each irrigation water user node. These crops generate a demand that is met subject to water availability at the supply points. They do not generate orders i.e. they effectively have an unregulated supply.

Loss nodes –represent the amount of water that is lost from the system as a function of flow. These have not been used in the IRSM as in-stream and canal losses have been included in the routed links (see above).

Maximum Order Constraint nodes - are used to constrain the amount of regulated flow in a river or canal system, as such they constrain orders within a system. Noting that unregulated flow may exceed this constraint. In the IRSMl these nodes have been used to constrain canal orders to physical canal capacity limits.

Minimum Flow Requirement nodes - are provided to ensure flows are maintained at a location in the river system by regulated releases. In the IRSM these nodes have been used to reflect water sharing within a province, subject to the provincial share under the 1991 Water Apportionment Accord.

Figure 12 shows the node-link schematic layout of the baseline IRSM. The baseline IRSM l is comprised of 27 sections (Table 5), where a section is one or more river reaches or canals. Sections were defined using the location of the gauges (typically barrages). Each section includes:

- inflows (from upstream and the residual catchment area)
- current infrastructure for medium and major irrigation districts
- irrigation demands for Command Areas
- lumped demands for stock/domestic and industry purposes.

For each irrigation Command Area, the irrigator demand model within the Source software[1] has been used to represent the irrigation requirements of 13 basin crop types. This also allows modelling of scenarios that consider the impact of changes in crop area and crop type on water demands and the ability of the current infrastructure to meet demands.

Table 5 Indus River System Model (IRSM) sections

Section Name	Section Name	Section Name
Tarbela Dam to Kabul River	Rasul to Trimmu	Qadribad to Balloki
Kabul River to Jinah Barrage	Rasul to Qadribad	Qadribad to Trimmu
Jinah Barrage to Chashma Barrage	Trimmu to Punjnad	Ravi rim station to Balloki
Chashma to Taunsa Barrage	Trimmu to Sidhnai	Balloki to Sidhnai
Taunsa to Guddu	Sidhnai to Punjnad	Balloki to Islam
Guddu to Sukkur	Punjnad to Guddu	Sutlej rim station to Sulemanki
Sukkur to Kotri	Marala to Khanki	Balloki to Sulemanki
Mangla Reservoir to Rasul Barrage	Marala to Ravi	Sulemanki to Islam
Mangla to Khanki	Khanki to Qadribad	Islam to Punjnad

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[1] Details relating to the irrigator demand model can be found at <https://wiki.ewater.org.au/display/SD41/Irrigator+Demand+Model>

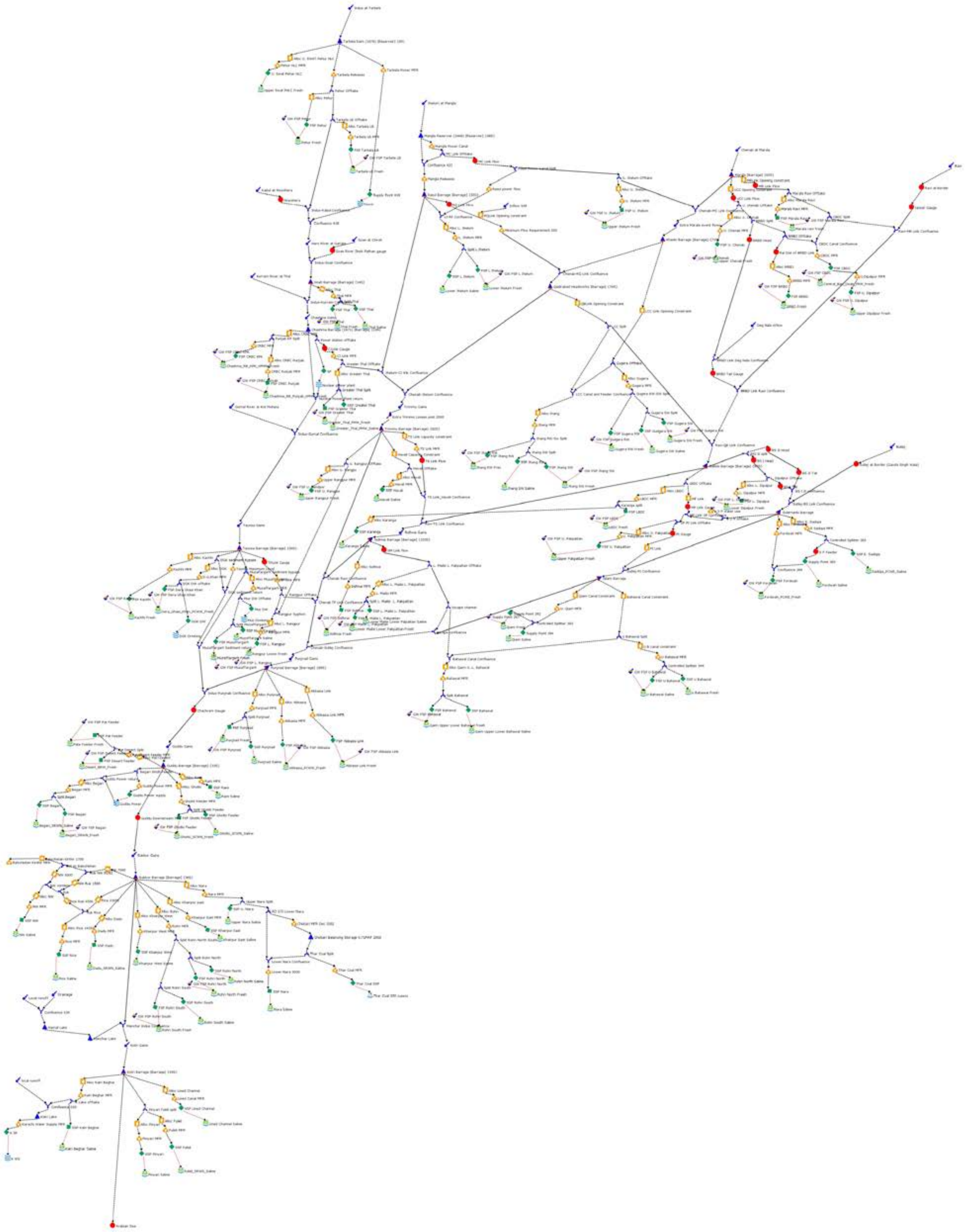


Figure 12 Indus River System Model (IRSM) schematic layout

2.9.1 IRSM structure

The IRSM structure is shown in Figure 12 and resembles a typical line diagram of the system. Some key features are:

- The upper extents of the model are the Rim Station inflows;
- Tarbela, Mangla and Chashma reservoirs are included, as is Kalri Lake and Manchar Lake and Chotiari Reservoir in the Sindh province, however the remaining smaller reservoirs and dams are not yet included (e.g. Rawal Lake, Khanpur Dam, Simly Dam and Ghazi Botha);
- All barrages are included;
- All Canal Commands are included in addition to major link canals;
- The IRSM repeats the irrigation command areas for crop production and allows water to be drawn from groundwater as well as surface waters to meet crop demands.

2.9.2 Tarbela, Mangla and Chashma Reservoirs

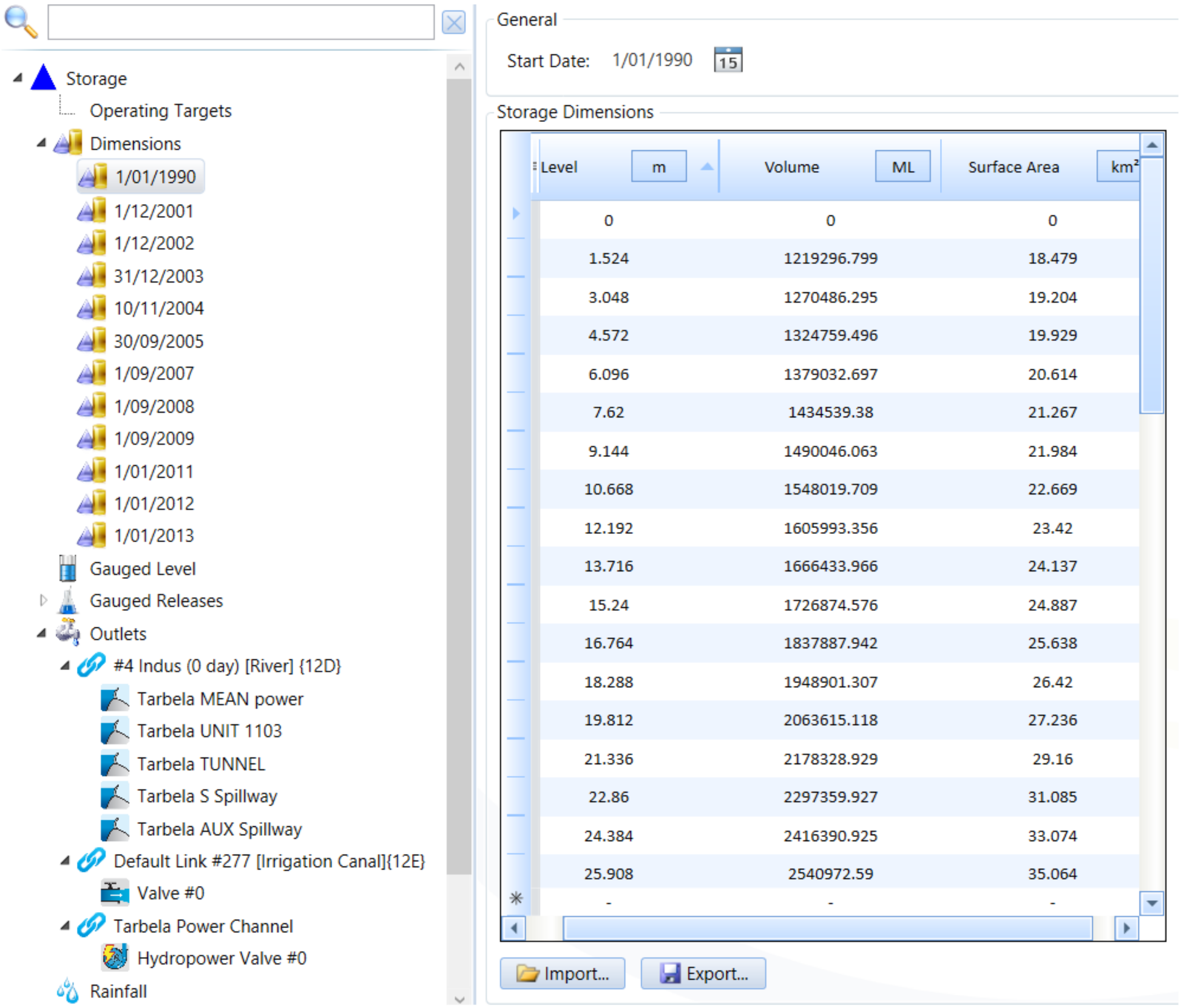
This section describes the configuration of Tarbela, Mangla and Chashma Reservoirs within the IRSM and the techniques used to facilitate emptying and filling of these storages in a way that resembles observed water levels. The operation of Tarbela and Mangla Reservoirs is critical to the correct simulation of flows through the Lower Indus.

The key water management elements of reservoir operations in Source are the level-volume-area relationships, physical outlet capacities and the water releases as determined by balancing the demands of downstream entitlements and target water levels. The level-volume-area relationships and outlet capacities are physical characteristics of the reservoirs. The downstream entitlements and target water levels interact with the reservoirs through *Ordering* and *Functions.*

Physical reservoir characteristics

Tarbela Reservoir

Tarbela Reservoir is set up in the IRSM with multiple (13) level-volume-area (LVA) curves representing the different years that survey has been taken of the reservoir, accounting for sedimentation. Source linearly interpolates the dimensions between years and lineally interpolates intermediate LVA points (Figure 13). All LVAs for Tarbela and Mangla in the IRSM are provided in Appendix C .



Start Date: 1/01/1990

Level m	Volume ML	Surface Area km²
0	0	0
1.524	1219296.799	18.479
3.048	1270486.295	19.204
4.572	1324759.496	19.929
6.096	1379032.697	20.614
7.62	1434539.38	21.267
9.144	1490046.063	21.984
10.668	1548019.709	22.669
12.192	1605993.356	23.42
13.716	1666433.966	24.137
15.24	1726874.576	24.887
16.764	1837887.942	25.638
18.288	1948901.307	26.42
19.812	2063615.118	27.236
21.336	2178328.929	29.16
22.86	2297359.927	31.085
24.384	2416390.925	33.074
25.908	2540972.59	35.064
-	-	-

Figure 13 Tarbela Reservoir dimensions (level-volume-area) and model setup

Six outlets on Tarbela are modelled as gated spillways and valves which have a minimum and maximum release volume associated with each outlet. Maximum release volumes are generally limited by the specific outlet configuration (pipe, valve or spillway gate) and head of water in the reservoir. Minimum release volumes may be set to zero for valves and gates that can be fully closed, or spillway capacity, when specific head requirements are met. Therefore, for any head level in the reservoir, there is a minimum and maximum release rate that (allowing multiple release pathways) that Source operated within.

The configuration relating the maximum and minimum release rates for a given head level for each of the six outlets was undertaken systematically using outlet flow and accompanying head data. Discharge for outlets was plotted against reservoir head (Figure 14) to determine the operational space and the minimum and maximum discharges for the full range of head conditions. Maximum and minimum discharges for given head levels were then transferred to a table for import to Source.

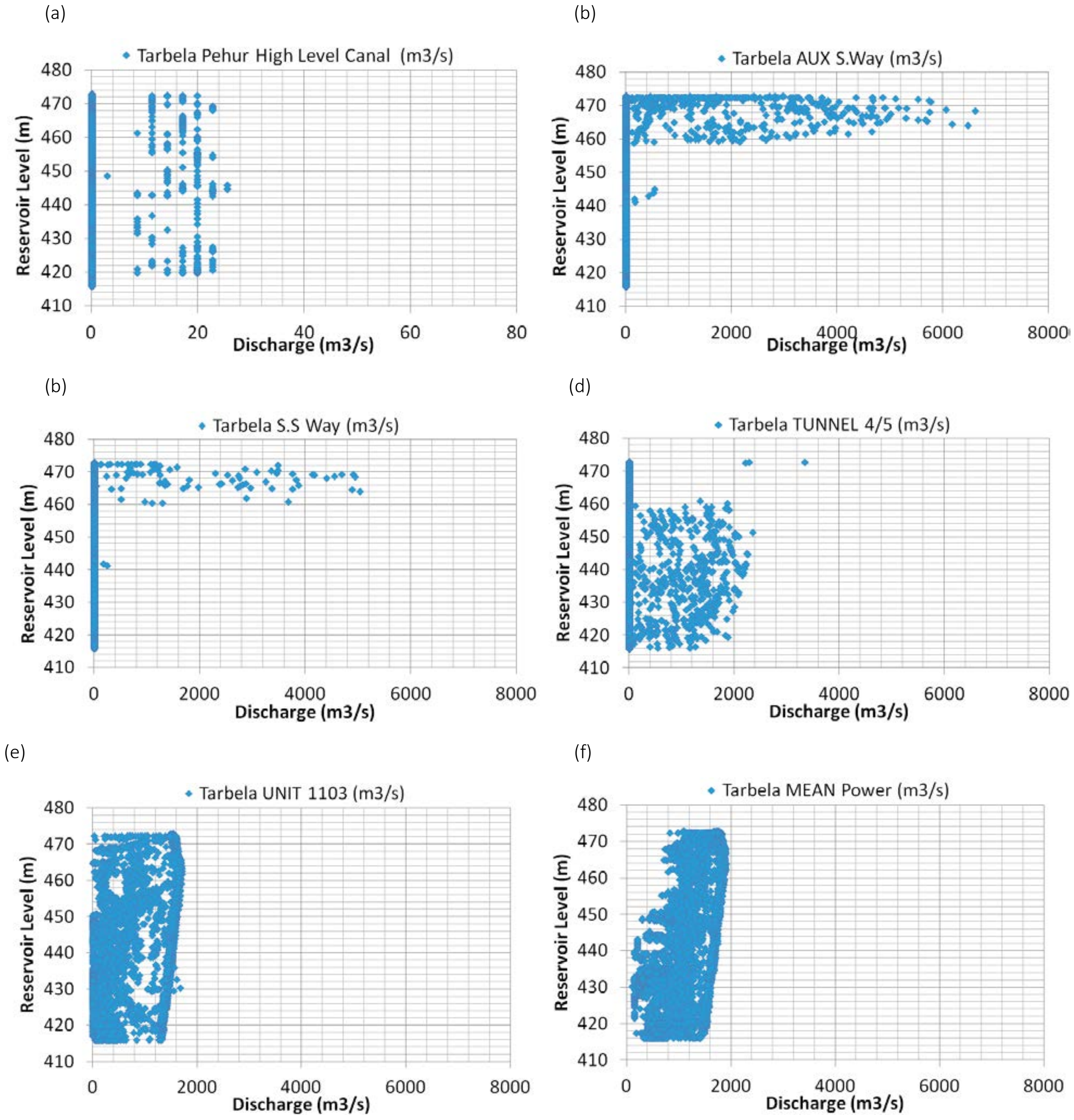


Figure 14 Tarbela Reservoir outlet flows and head (2001-2012) showing (a) Pehur high level canal (b) Tarbela Auxiliary spillway (c) Tarbela S.S spillway (d) Tarbela Tunnel 4/5 (e) Tarbela Unit 1103 (f) Tarbela mean power

Currently, there are no priorities set on which outlets from Tarbela Reservoir have preference over others, however the model structure is in place to implement this option if required. Similarly, hydropower has not yet been implemented on the power outlets. This has been calculated outside of the IRSM in spreadsheets. It is planned to include this within the IRSM as the need arises.

The combined minimum and maximum outlet curves for Tarbela Reservoir, representing all outlets is provided in Figure 15.

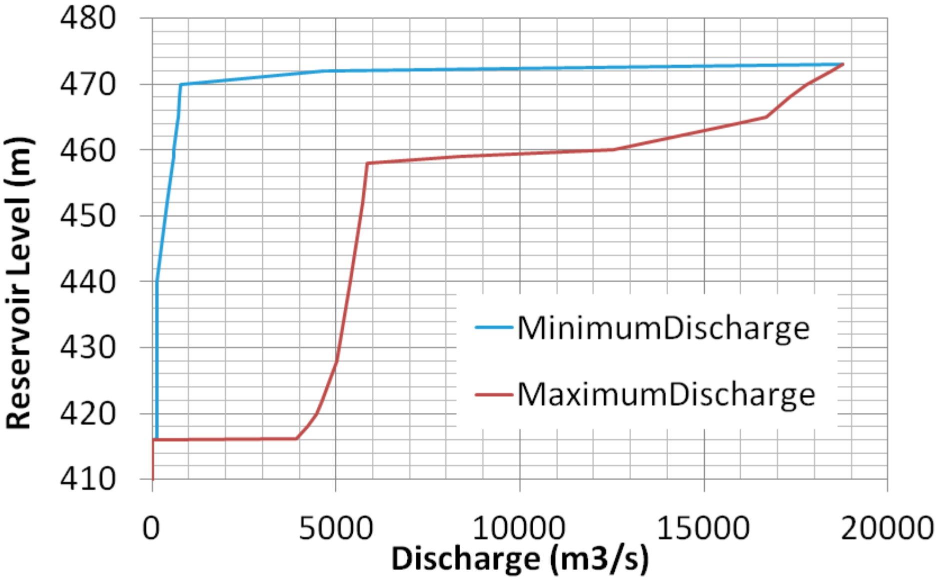


Figure 15 Tarbela Reservoir minimum and maximum outlet capacity

Tarbela operating targets

Tarbela Reservoir is only subject to a small number of direct water orders. Water orders for the Indus Zone are sent to Chashma Barrage and are not passed up to Tarbela. Nevertheless, Tarbela is subject to reservoir filling targets that govern the retention and release of water.

The modelled maximum and minimum rule curve operating targets are shown in Table 6 and Table 7 respectively.

Table 6 Tarbela maximum rule curve operating targets

Season	Target type	Section name	Target
Early Kharif	Filling	1st April to 9th March	30% volume
Late Kharif	Filling	10th March to 31st July	100% volume
Late Kharif	Filling rate	10th June to 31st July	1 foot /day
Late Kharif	Retention	1st August to 31st August	100% volume
Late Kharif	Depletion	1st September to 30th September	13% volume by 30th September
Rabi	Depletion	1st October to 30th March	1% volume by 30th March

Table 7 Tarbela minimum rule curve operating targets

Season	Target type	Section name	Target
Early Kharif	Filling	1st April to 9th March	30% volume
Late Kharif	Filling	10th March to 9th August	100% volume
Late Kharif	Filling rate	10th June to 9th August	1 foot /day
Late Kharif	Retention	10th August to 31st August	100% volume
Late Kharif	Depletion	1st September to 30th September	13% volume by 30th September
Rabi	Depletion	1st October to 30th March	0% volume by 30th March

Chashma Reservoir

Chashma Reservoir is set up in the IRSM with a static level-volume-area curve. Outlets on Chashma are modelled as gated spillways and a hydropower valve. Chashma has two canals that offtake from the barrage (Chashma Jhelum Link (CJ Link) and Chashma Right Bank Canal (CRBC)).

Figure 16 Chashma Barrage showing main barrage, hydropower and offtake canals

Data provided by ISRA (2015) indicate that:

- the crest level of the under-sluice bays is at Chashma is 188.1 m above mean sea level(617 ft);
- the upstream floor level is 186.5 m above mean sea level(612 ft);
- the capacity of the storage was surveyed in 2012 to be 429,500 ML (0.3482 MAF);
- there are 41 standard bays on the main weir 18.288 m across (60 ft);
- there are 11 under-sluice bays 18.288 m across (60 ft); and
- the maximum observed discharge for the barrage was 32,052 m^3/s (1,131,905 ft^3/s) at level 197.815 m (649 ft).

Estimating stage discharge curves for barrages and offtakes

Barrages are typically broken into several sections with the main weir component forming the central part of the barrage and a section on either bank forming the area where canal offtakes, hydropower and the under-sluice gates are located.

The flows over the main weir structures are estimated using a weir equation of the form shown in equation 3

Equation 3: $Q = \frac{2}{3} L C_d \sqrt{2g} H^{\frac{3}{2}}$

Where:

Q = discharge (m^3/s), L = weir opening length (m), Cd = discharge coefficient, g = acceleration due to gravity (assumed 9.81 m/s^2) and H = water height above the weir crest (m).

Weir opening length (L) is calculated as being the number of bays along the main weir barrage multiplied by the bay width. The choice of discharge coefficient has an impact on the calculated discharge. Typically, the value of Cd may be given in reports, or derived from known head/discharge combinations associated with high flows.

The discharge for the under-sluice components of the barrages are modelled differently to the main weir discharge and use the modified form of Bernoulli's equation (Equation 4). This equation is used for canals and under-sluice gates as it is considered more appropriate. For the main river, under sluices will likely be somewhere between free outflow (Equation 3) and submerged orifice (Equation 4).

Equation 4: $Q = LC_d b\sqrt{2gh}$

Where:

Q = discharge (m^3/s), L = weir opening length (m), Cd = discharge coefficient, g = acceleration due to gravity (assumed 9.81 m/s^2) and h = upstream water depth (above the weir crest) and b is the gate opening.

Weir opening length (L) is calculated as being the number of bays along the main weir barrage multiplied by the bay width. For maximum flow, the value b (gate opening) is equivalent to h (the water depth above the spillway crest). The choice of weir discharge coefficient is different to that for the main barrage weir as described above.

For many barrages, peak or flood flow discharges have been measured or estimated and typically correspond to the maximum barrage design level. In such cases, this data point can be used to adjust the total calculated barrage discharge (the main weir discharge + the under-sluice discharge). For barrages where flows have been estimated for the barrage design maximum level, the calculated discharge curve will be adjusted using a correction factor such that the calculated maximum barrage discharge will match the measured data.

For the hydropower station on Chashma Barrage, the following assumptions were incorporated into the IRSM:

- the operating head is 8.4 m, meaning that at normal operating level of 195.682m (642 ft), the crest level is 187.282 m (614.5 ft)
- the number of bays is 8 at an approximate opening width of 40 ft
- a turbine efficiency of 89% is estimated based on each unit at 23 MW output capacity at 250 m^3/s discharge at a rated head 8.4 m.

For the Chashma Jhelum Link Canal, the following assumptions were incorporated into the IRSM:

- the crest level is 193.876 m (636 ft) to pass design flows at design head
- the number of bays is 8 at an approximate opening width of 35 ft.

For the Chashma Right Bank Canal, the following assumptions were incorporated into the IRSM:

- The crest level is approximately 191.765 m (629.15 ft) to pass design flows at design head; and
- The number of bays is 2 at an approximate opening width of 35 ft.

Table 8 Chashma Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km³	Surface area (estimate) ha	Under-sluice discharge m³/s	Main weir discharge m³/s	Hydro discharge m³/s	Combined maximum Main Weir discharge m³/s
Zero point, no water	186.538	0	0	0	0	0	0	0
Hydropower offtake	187.282	0.744	0.028	8	0	0	0	0
Under-sluice level	188.062	1.524	0.350	46	0	0	199.4	199.4
Main weir level	189.586	3.048	4.018	264	676.6	0	1,012.3	1,688.9
Intermediate point	190.500	3.962	10.121	511	1,369.4	781.4	1,671.3	3,822.0
Chashma Right Bank Canal	191.765	5.227	26.843	1,027	2,562.9	2,874.8	2,747.7	8,185.4
CJ Link Canal	193.876	7.338	88.634	2,416	5,042.2	7,941.7	4,901.8	17,885.8
Normal Operating Level	195.682	9.144	189.861	4,153	7,564.7	13,450.1	7,047.1	28,061.8
Intermediate point	196.596	10.058	263.593	5,241	8,966.4	16,587.1	8,228.5	33,782.0
Maximum Barrage Level	197.815	11.278	429.498	7,617	10,954.8	21,097.2	9,895.9	41,947.9

Table 9 Chashma Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft³/s	Main weir discharge ft³/s	Hydro discharge ft³/s	Combined maximum Main Weir discharge ft³/s
Zero point, no water	612.0	0.0	0.0000	0	0	0	0	0
Hydropower offtake	614.4	2.4	0.0000	19	0	0	0	0
Under-sluice level	617.0	5.0	0.0003	114	0	0	7,042	7,042
Main weir level	622.0	10.0	0.0033	652	23,894	0	35,749	59,643
Intermediate point	625.0	13.0	0.0082	1,262	48,358	27,594	59,021	134,973
Chashma Right Bank Canal	629.1	17.1	0.0218	2,538	90,507	101,523	97,036	289,066
CJ Link Canal	636.1	24.1	0.0719	5,969	178,064	280,459	173,107	631,630
Normal Operating Level	642.0	30.0	0.1539	10,262	267,143	474,984	248,865	990,992
Intermediate point	645.0	33.0	0.2137	12,951	316,644	585,768	290,587	1,193,000
Maximum Barrage Level	649.0	37.0	0.3482	18,822	386,865	745,040	349,470	1,481,375

Table 10 Chashma Barrage offtake summary model data

Level description	Level		Depth		CJ Link discharge*		CRBC discharge*	
	m	ft	m	ft	m³/s	ft³/s	m³/s	ft³/s
Zero point, no water	186.5	612.0	0.000	0.0	0	0	0	0
Hydropower offtake	187.3	614.4	0.744	2.4	0	0	0	0
Under-sluice level	188.1	617.0	1.524	5.0	0	0	0	0
main weir level	189.6	622.0	3.048	10.0	0	0	0	0
Intermediate point	190.5	625.0	3.962	13.0	0	0	0	0
Chashma Right Bank Canal	191.8	629.1	5.227	17.1	0	0	0	0
CJ Link Canal	193.9	636.1	7.338	24.1	0	0	21.3	753.0
Normal Operating Level	195.7	642.0	9.144	30.0	614.5	21,700.0	141.6	5,000.0
intermediate point	196.6	645.0	10.058	33.0	1,136.1	40,123.0	268.0	9,465.0
Maximum Barrage Level	197.8	649.0	11.278	37.0	1,980.2	69,928.0	530.5	18,734.0

* Discharge refers to maximum theoretical discharge applying equation 4 (submerged orifice) with coefficient of discharge = 0.67. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Source requires maximum and minimum release volumes for barrages and offtake canals. Minimum release volumes are generally set to zero for gates that can be fully closed, and maximum release volumes are calculated as a function of head and gate opening dimensions as per the equations above.

For Chashma Barrage, the combined maximum and minimum discharge capacity curves, including hydropower and canal discharges, are provided in Figure 17.

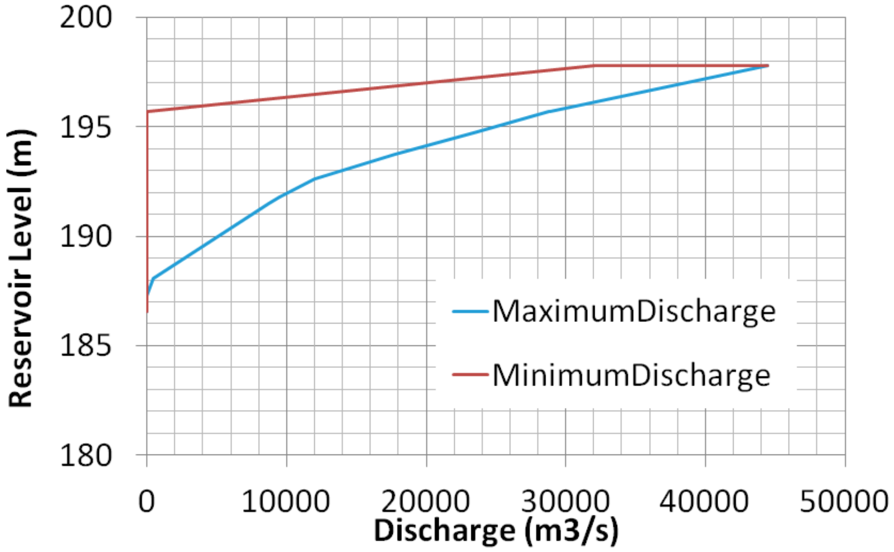
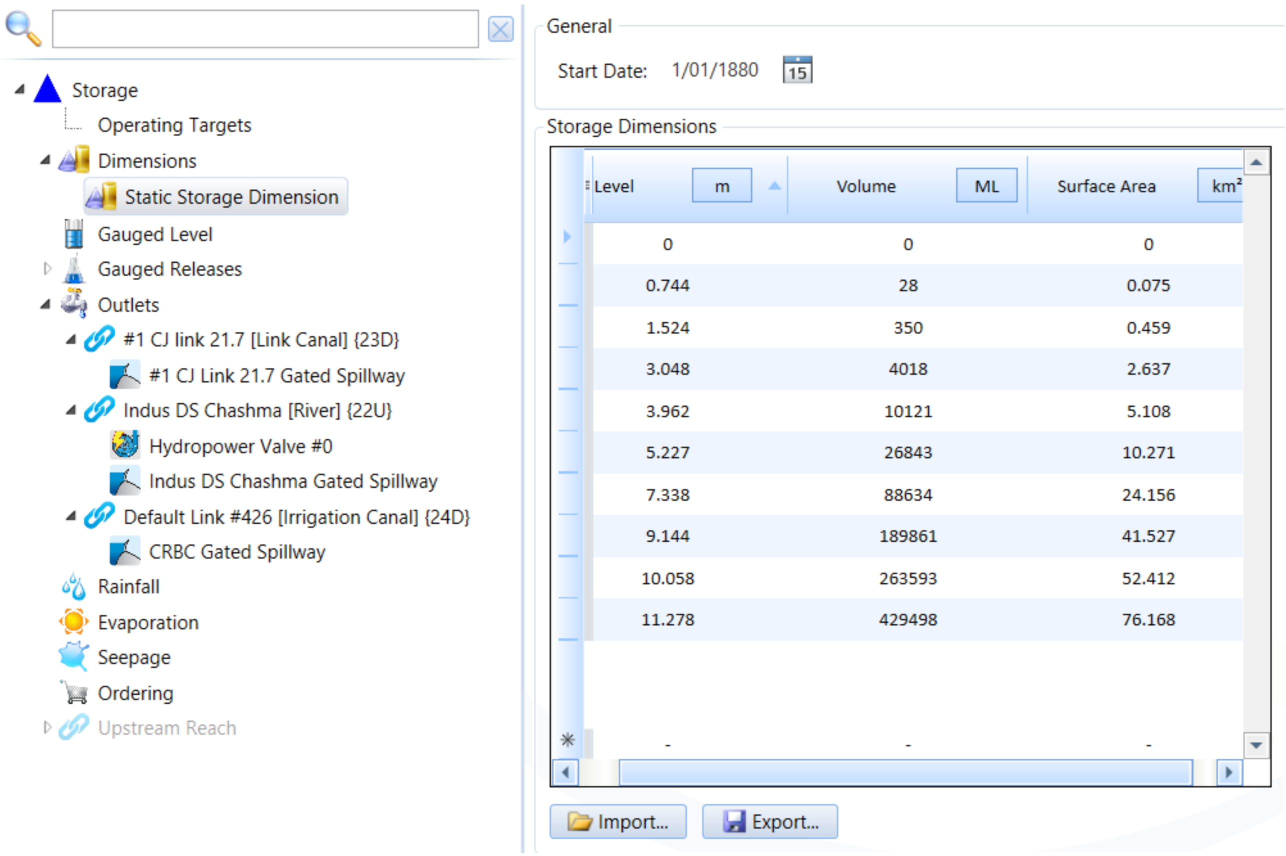


Figure 17 Chashma Reservoir combined minimum and maximum outlet capacity

The storage dimensions for Chashma Barrage (level-volume relationship) were provided by IRSA (2015). To obtain an estimate of area associated with the volume, the water impounded behind the reservoir was assumed to take the form of a triangular prism and surface area calculated from the volume and head. The resultant level-volume-area relationship for Chashma Barrage is shown in Figure 18.



Start Date: 1/01/1880

Level (m)	Volume (ML)	Surface Area (km²)
0	0	0
0.744	28	0.075
1.524	350	0.459
3.048	4018	2.637
3.962	10121	5.108
5.227	26843	10.271
7.338	88634	24.156
9.144	189861	41.527
10.058	263593	52.412
11.278	429498	76.168
-	-	-

Figure 18 Chashma Reservoir dimensions (level-volume-area) and model setup

Mangla Reservoir

Mangla Reservoir is set up in the IRSM with five level-volume-area curves representing the different survey years and accounting for sedimentation. Like Tarbela, Source linearly interpolates the dimensions between years. Mangla LVAs are provided in Appendix C.

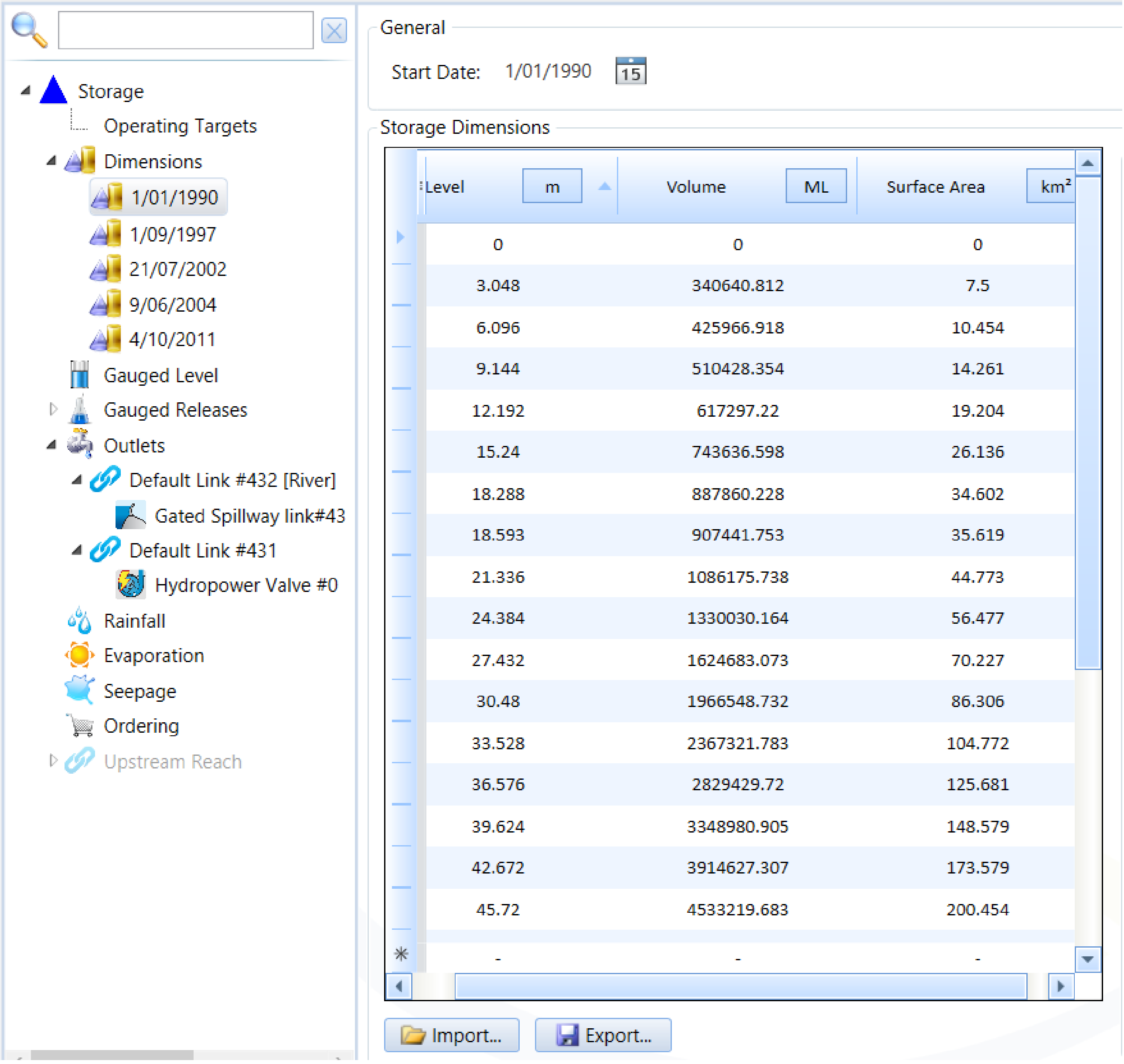
At the time of the initial construction of Mangla Dam, provision was made to raise the dam by 40 ft. Since commissioning in 1967 sedimentation reduced the capacity from 5.88 MAF to 4.674 MAF in 2005. In 2004 work commenced on raising the dam level by 30ft and work was completed in 2009 providing an extra 2.8 MAF of capacity and on average 644 GWh of power generation as well as further flood alleviation (Table 11). As the modelling period spans the enlargement of Mangla this is taken into consideration in the model configuration.

Table 11 Mangla dam enlargement characteristics

Characteristic	1967	Post enlargement
Normal maximum conservation level	1202 ft. (366.5 m)	1242 ft. (378.7 m)
Minimum operation level	1040 ft. (317.1 m)	1040 ft. (317.1 m)
Storage capacity	5.88 MAF	7.475 MAF
Crest length	84,00 ft	11,000 ft
Crest length	10,300 ft. (3,350 m)	11,150 ft. (3,400 m)

Like Tarbela, outlets on Mangla are modelled as gated spillways and valves which have a minimum and maximum release volume associated with each outlet.

The configuration relating the maximum and minimum release rates for a given head level for each of the outlets was undertaken systematically using outlet flow and accompanying head data. Discharge for outlets was plotted against reservoir head (Figure 20) to determine the operational space and the minimum and maximum discharges for the full range of head conditions. Maximum and minimum discharges for given head levels were then transferred to a table for import to Source.



Start Date: 1/01/1990

Level m	Volume ML	Surface Area km²
0	0	0
3.048	340640.812	7.5
6.096	425966.918	10.454
9.144	510428.354	14.261
12.192	617297.22	19.204
15.24	743636.598	26.136
18.288	887860.228	34.602
18.593	907441.753	35.619
21.336	1086175.738	44.773
24.384	1330030.164	56.477
27.432	1624683.073	70.227
30.48	1966548.732	86.306
33.528	2367321.783	104.772
36.576	2829429.72	125.681
39.624	3348980.905	148.579
42.672	3914627.307	173.579
45.72	4533219.683	200.454
-	-	-

Figure 19 Example Mangla Reservoir dimensions (level-volume-area) and model setup

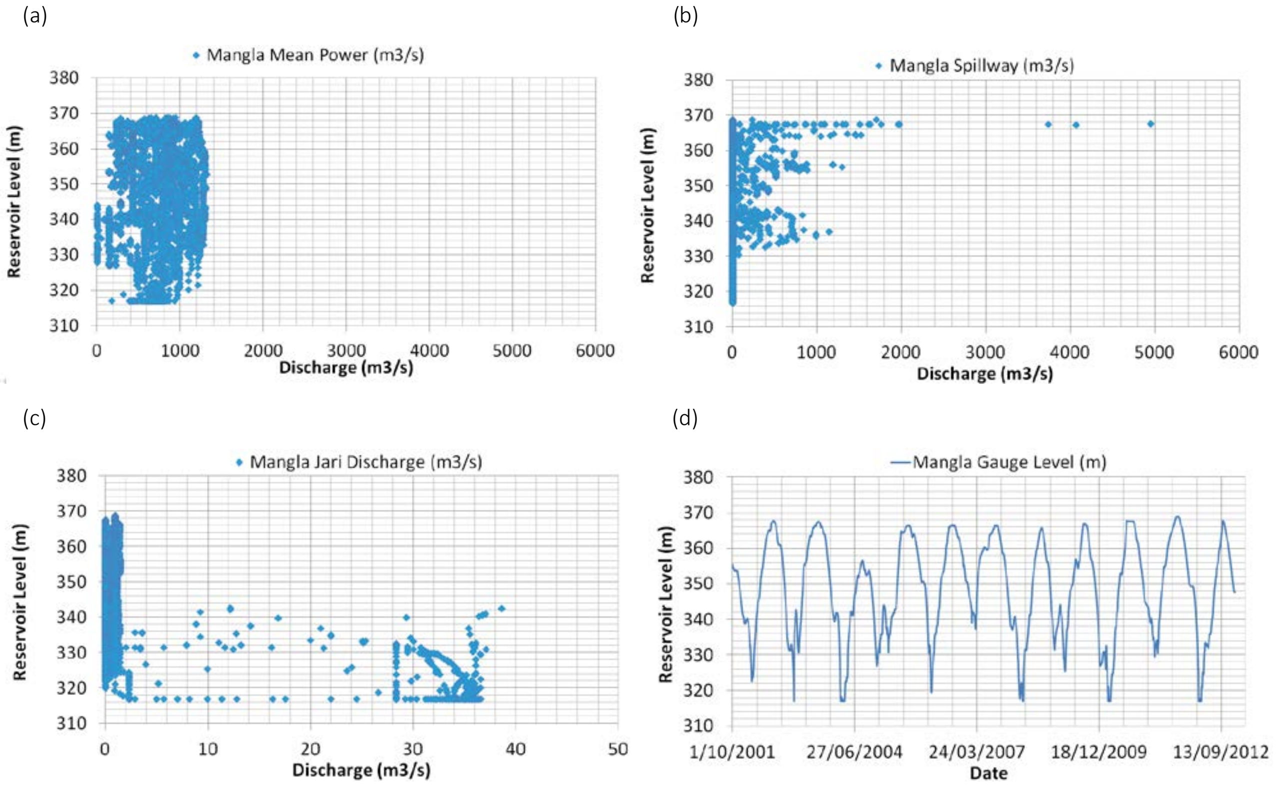


Figure 20 Mangla Reservoir outlet flows and head (2001-2012) showing (a) power outlet (b) spillway release (c) Jari release and (d) water level

Currently, there are no priorities set on outlets from Mangla Reservoir, however typically, the power outlet is the default pathway for water release. Hydropower production has not yet been implemented on the power outlet but can be configured in the future.

The combined minimum and maximum outlet curves for Mangla Reservoir, representing all outlets is provided in Figure 21.

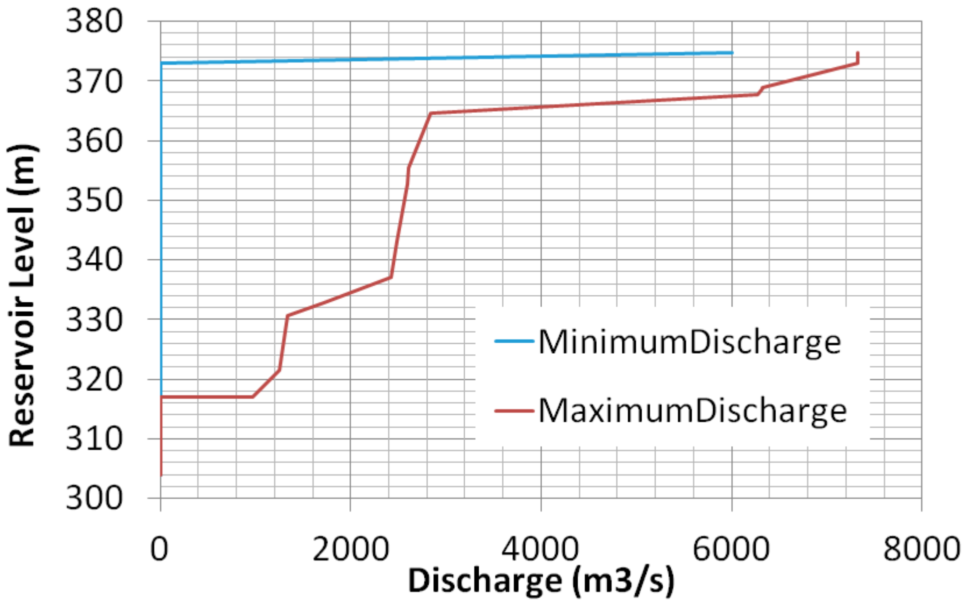


Figure 21 Mangla Reservoir combined minimum and maximum outlet capacity

Mangla operating targets

Mangla Reservoir is subject to water orders that trigger the release of water from the reservoir to downstream canal commands. These orders are generally constrained by the following operating targets.

The modelled maximum and minimum rule curve operating targets are shown in Table 12 and Table 13 respectively.

Table 12 Mangla maximum rule curve operating targets

Season	Target type	Section name	Target
Early Kharif	Filling	1st April to 9th March	50% volume
Late Kharif	Filling	10th March to 31st July	100% volume
Late Kharif	Retention	1st August to 31st August	100% volume
Late Kharif	Depletion	1st September to 30th September	13% volume
Rabi	Depletion	1st October to 30th March	0% volume

Table 13 Mangla minimum rule curve operating targets

Season	Target type	Section name	Target
Early Kharif	Filling	1st April to 9th March	50% volume
Late Kharif	Filling	10th March to 19th August	100% volume
Late Kharif	Retention	20th August to 31st August	100% volume
Late Kharif	Depletion	1st September to 30th September	13% volume
Rabi	Depletion	1st October to 30th March	0% volume

Water ordering from reservoirs

Water ordering in Source governs releases from reservoirs and barrages. Water orders are created at the *Minimum Flow Requirement* node at the canal commands and are 'directed' towards the appropriate reservoir in the IRSM by using *priority settings* in the confluence nodes used to link the river network. Note irrigators in canal commands do not place orders but are supply based on the water that enters the canal. The canals are demand based on water allocation and sharing between provinces and within provinces.

Water orders are passed up the branch with the highest priority setting, provided the branch is regulated. Unregulated branches cannot pass water orders upstream, however the water arriving down an unregulated branch can still be used to fulfil orders. River and canal reaches that are treated as regulated are shown in Figure 22 in addition to the priority settings associated with reached upstream of confluences.

Water orders accumulate as they are passed up the system and consider water travel time, the capacity of the river or canal branch they are directed towards, anticipated instream losses and any additional inflows from other branches that may be used to fill the water requirement. Under this system, a water order placed at a canal command some distance from a reservoir is placed early enough and with sufficient water so that the order will arrive on time and in the right quantity.

Water ordering pathways and branch priorities were configured based on consultation with Punjab Irrigation Department and may be subject to further review. Generally, orders are directed toward Chashma and Mangla, however some orders for Eastern Canal Commands must be sent toward Marala. If water orders cannot be met by the highest priority path, orders will be directed to the next priority path. Orders passed to T-P link and C-J Link currently operate by assessing the storage levels in Tarbela and Mangla. If more water is in Mangla, the orders are not passed up the link canals. If more water is available in Tarbela and the provincial shares can be met, then water orders can be passed up the link canals to transfer water between basins. Water arriving from unregulated tributaries or canal branches is not wasted. This water is also utilised to fulfil water orders at the canal command level if it is available at the time that it is required.

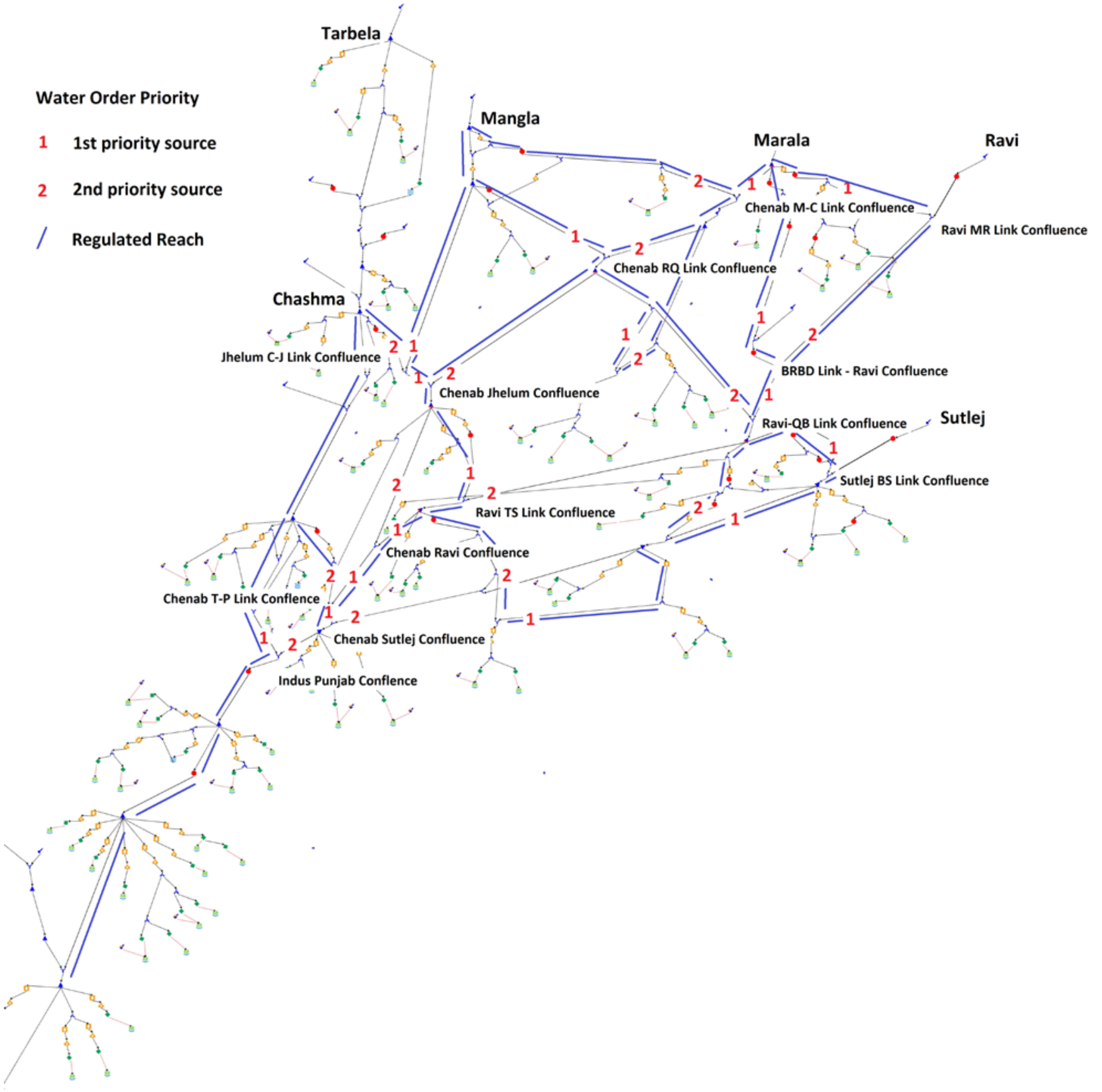


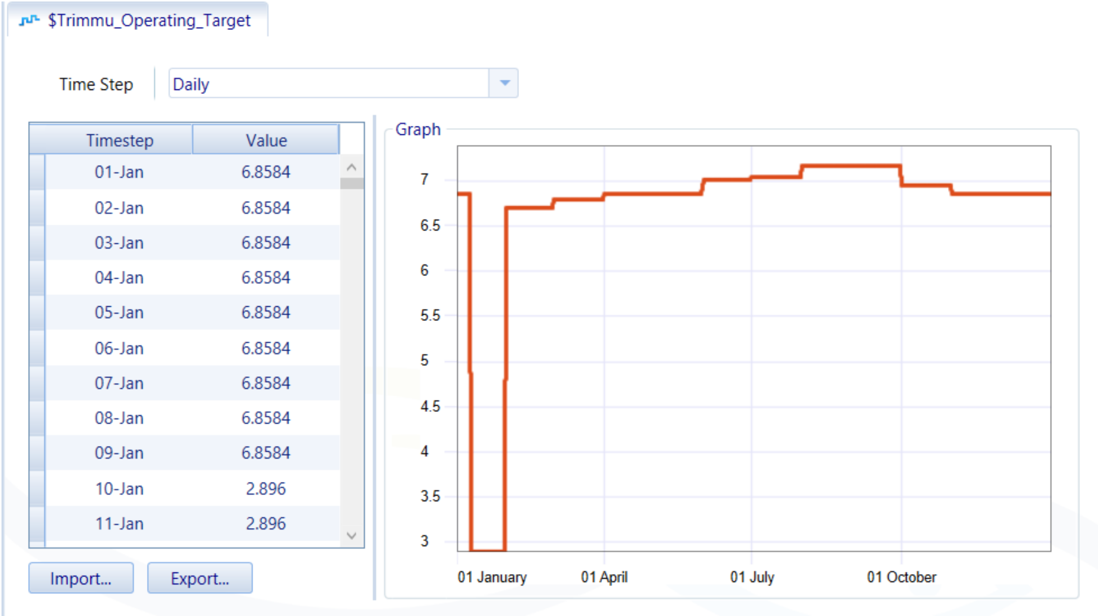
Figure 22 Priority ordering pathways upstream of major confluence nodes

2.9.3 Barrage and canal operations

Barrages

Except for Chashma Barrage, the barrages of the Indus River system are not intended as storage reservoirs, but rather as head regulators to allow the waters to be diverted to the irrigation canals and link canals. As such, the specific water volume retained behind barrages is less critical from a modelling perspective but needs to reflect a volume of at least 1–2 days' supply to the offtake canals to avoid modelling mass balance issues. In all cases, the barrage must have an associated level-volume-area curve to operate in Source and these have been generated from survey data when available. Storage area was estimated from Google Earth at low flow and high flow conditions and points were linearly interpolated between.

In terms of barrage operation, barrage water levels are generally allowed to fluctuate throughout the season depending on inflows, such as the Sindh barrages. Selected barrages in the Punjab province tend to be operated according to specific seasonal, or inter-seasonal head requirements, with the head at the barrage enabling greater flows to the link canals and irrigation command canals. An example of this is Trimmu Barrage where a weekly water level operation target has been used to guide seasonal barrage water levels (Figure 23).


$Trimmu_Operating_Target

Time Step: Daily

Timestep	Value
01-Jan	6.8584
02-Jan	6.8584
03-Jan	6.8584
04-Jan	6.8584
05-Jan	6.8584
06-Jan	6.8584
07-Jan	6.8584
08-Jan	6.8584
09-Jan	6.8584
10-Jan	2.896
11-Jan	2.896

Figure 23 Trimmu Barrage operating target function

Canal regulators that allow water to be drawn from the barrage operate as gated spillways, where the gate opening (under-sluice) is adjusted according to the head in the barrages to achieve the required downstream flow. Under this typical configuration, it is the *water demand pattern* from downstream (the water entitlement) that determines the outflow though the canal head regulators more than the head in the barrage relative to the crest of the offtake canal spillway.

This approach is the general operational case for most barrages, except for a 2 to 3-week period in late December - early January. During this period, the canals are closed for cleaning and barrage water levels drop to the lowest levels below the offtake canal crest levels, thereby making it impossible for the canals to flow.

In most cases, observation data has been used to obtain average daily or monthly operating target levels for barrages that operate with target levels.

The following sections detail how barrages have been configured in the IRSM. The calculation procedures outlined for Chashma Barrage in Section 2.9.2, incorporating equations 3 and 4 have been applied to all barrages to estimate stage discharge curves for all barrage outlets.

Punjab barrages

Marala

Marala Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target. Outlets on Marala are modelled as gated spillways and include the main barrage, Marala Ravi Link and Upper Chenab Link Canal.

Figure 24 Marala Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the under-sluice bays is 241.3 m above mean sea level(795ft);
- the crest level of the main weir is 243.8 m above mean sea level(800ft);
- the upstream floor level is 239.9 m above mean sea level(787 ft);
- no storage capacity information was available for this study, however a volume of 28.6 km^3 at maximum barrage water level has been inferred from aerial photography;
- there are 46 standard bays on the main weir 18.288 m across (60 ft);
- there are 20 under-sluice bays, 18.288 m across (60 ft);
- the maximum discharge for the barrage is 31,149 m^3/s (1,100,000 ft^3/s) at 248.9 m (816.7 ft) above mean sea level; and
- the maximum operational level of the barrage is 247.498 m (812 ft), or 7.62m above the upstream bed level of the barrage.

Historic water level time series for Marala (2001-2013) indicate that a seasonal operational water level pattern is applied at this barrage. Water level time series and an average weekly pattern derived from this dataset are provided below. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

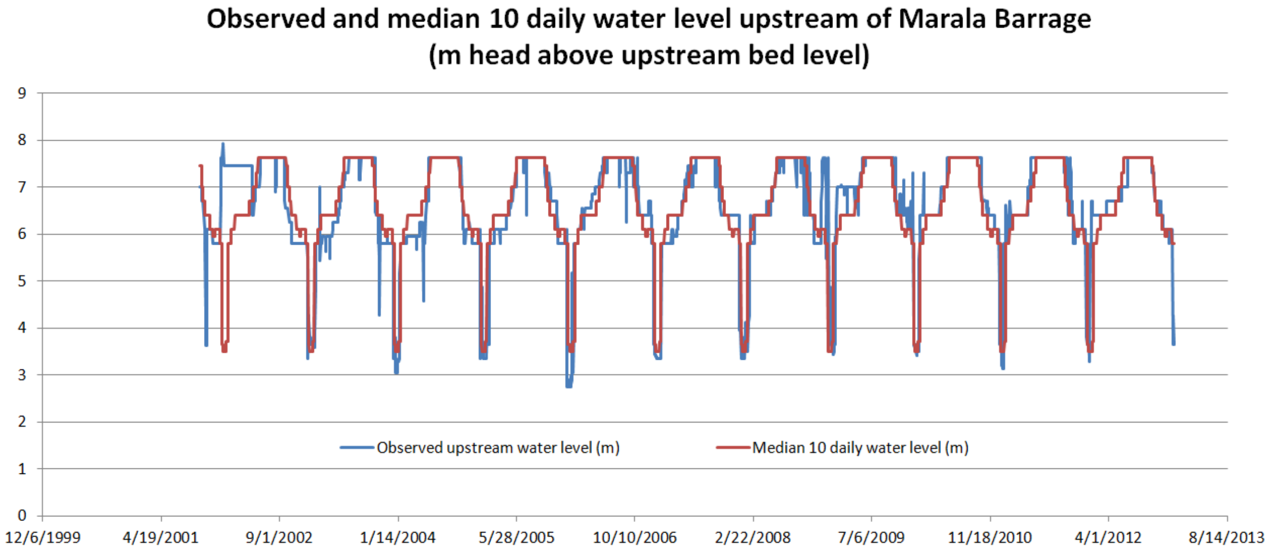


Figure 25 Marala Barrage operational water level pattern

The storage level-volume-area relationship applied to Marala Barrage, along with minimum and maximum barrage discharges (over the main weir and under-sluice gates), are provided in Table 14 and Table 15.

Table 14 Marala Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km³	Surface area (estimate) ha	Under-sluice discharge m³/s	Main weir discharge m³/s	Hydro discharge m³/s
Zero point, no water	239.878	0.000	0	0	0.0	0.0	0.0
Intermediate point	240.878	1.000	0.350	70	0.0	0.0	0.0
Under-sluice level, dead storage, MR Link Offtake	242.316	2.438	2.079	171	0.0	0.0	0.0
Main weir, UCC offtake	243.840	3.962	5.491	277	1,259.9	0.0	1,259.9
Intermediate point	244.878	5.000	8.743	350	2,745.5	1,627.9	4,373.3
Intermediate point	245.742	5.865	12.027	410	4,246.8	4,040.7	8,287.6
Intermediate point	246.878	7.000	17.135	490	6,524.1	8,154.0	14,678.1
Operational level	247.498	7.620	20.305	533	7,898.4	10,773.8	18,672.2
Intermediate point	247.878	8.000	22.381	560	8,783.1	12,495.6	21,278.7
Maximum barrage level	248.930	9.053	28.658	633	11,390.9	17,687.7	29,078.6

Table 15 Marala Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft³/s	Main weir discharge ft³/	Hydro discharge ft³/s
Zero point, no water	787.0	0.0	0.0000	0.0	0	0	0
Intermediate point	790.3	3.3	0.0003	172.8	0	0	0
Under-sluice level, dead storage, MR Link Offtake	795.0	8.0	0.0017	421.4	0	0	0
Main weir, UCC offtake	800.0	13.0	0.0045	684.8	44,492	0	44,492
Intermediate point	803.4	16.4	0.0071	864.1	96,955	57,488	154,442
Intermediate point	806.2	19.2	0.0098	1013.6	149,976	142,697	292,673
Intermediate point	810.0	23.0	0.0139	1209.8	230,397	287,955	518,352
Operational level	812.0	25.0	0.0165	1316.9	278,931	380,473	659,404
Intermediate point	813.2	26.2	0.0181	1382.6	310,171	441,280	751,451
Maximum barrage level	816.7	29.7	0.0232	1564.5	402,266	624,635	1,026,901

Offtake canal data for Marala Barrage include:

- the crest level of the Marala Ravi Link is 242.2 m (795 ft) above mean sea level;
- MR Link Canal has 8 bays at 12.192 m (40 ft) wide for a total width of 97.5m (320 ft);
- the crest level of the Upper Chenab Canal is assumed to be 243.8 m above mean sea level(800 ft);
- Upper Chenab Canal has 6 bays at 12.192 m (40 ft) wide for a total width of 73.15 m (240 ft); and

The level vs. maximum discharge relationships applied to Marala Ravi Link and Upper Chenab Canal are provided in Table 16.

Table 16 Marala Barrage offtake summary model data

Level description	Level		Depth		CJ Link discharge*		CRBC discharge*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	239.878	787.0	0.000	0.0	0	0	0	0
Intermediate point	240.878	790.3	1.000	3.3	0	0	0	0
Under-sluice level, dead storage, MR Link Offtake	242.316	795.0	2.438	8.0	0	0	0	0
Main weir, UCC offtake	243.840	800.0	3.962	13.0	503.9	17,797	0	0
Intermediate point	244.878	803.4	5.000	16.4	1,098.2	38,782	212.3	7,498
Intermediate point	245.742	806.2	5.865	19.2	1,698.7	59,990	527.0	18,613
Intermediate point	246.878	810.0	7.000	23.0	2,609.7	92,159	1,063.6	37,559
Operational level	247.498	812.0	7.620	25.0	3,159.4	111,572	1,405.3	49,627
Intermediate point	247.878	813.2	8.000	26.2	3,513.2	124,068.0	1,629.9	57558
Maximum barrage level	248.930	816.7	9.053	29.7	4,556.4	160,906.0	2,307.1	81474

* Discharge refers to maximum theoretical discharge applying equation 4 (submerged orifice) with coefficient of discharge = 0.62. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Khanki

Khanki Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target. Outlets on Khanki are modelled as gated spillways and include the main barrage and Lower Chenab Canal Link.

Data provided for this study (IRSA 2015) include:

- the crest level of the under-sluice bays is 217.93m (715ft) above mean sea level;
- the crest level of the bays 1 and 2 of main weir is 219.6 m (720.5ft) above mean sea level;
- the crest level of new bays 219.8 m (721ft) above mean sea level;
- the upstream floor level is 216.4 m (710 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 65 km^3 at operational water level has been inferred from aerial photography.;
- there are 6 standard bays on the main weir 145.694 m (478 ft) across;
- there are 48 under-sluice bays, 6.096m across (20 ft);
- the maximum design discharge for the barrage is 22,653 m^3/s (800,000 ft^3/s) at 223.4 m (733 ft) above mean sea level; and
- historic water level time series for Khanki (2001-2013) indicate that a seasonal operational water level pattern is applied at this barrage. Water level time series and an average weekly pattern derived from this

dataset is shown in Figure 27. The 10 daily pattern is used in Source as the operational water level target for the barrage.

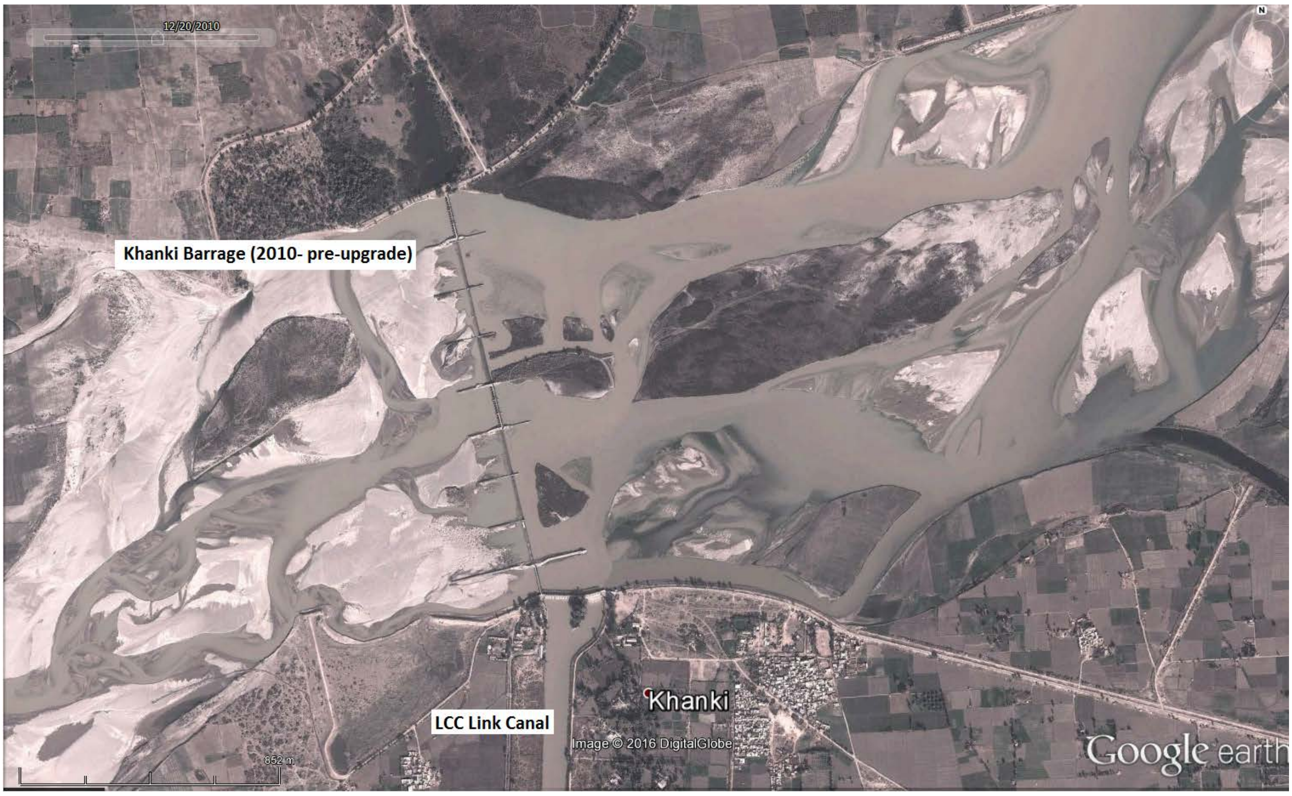


Figure 26 Khanki Barrage showing main barrage and offtake canal

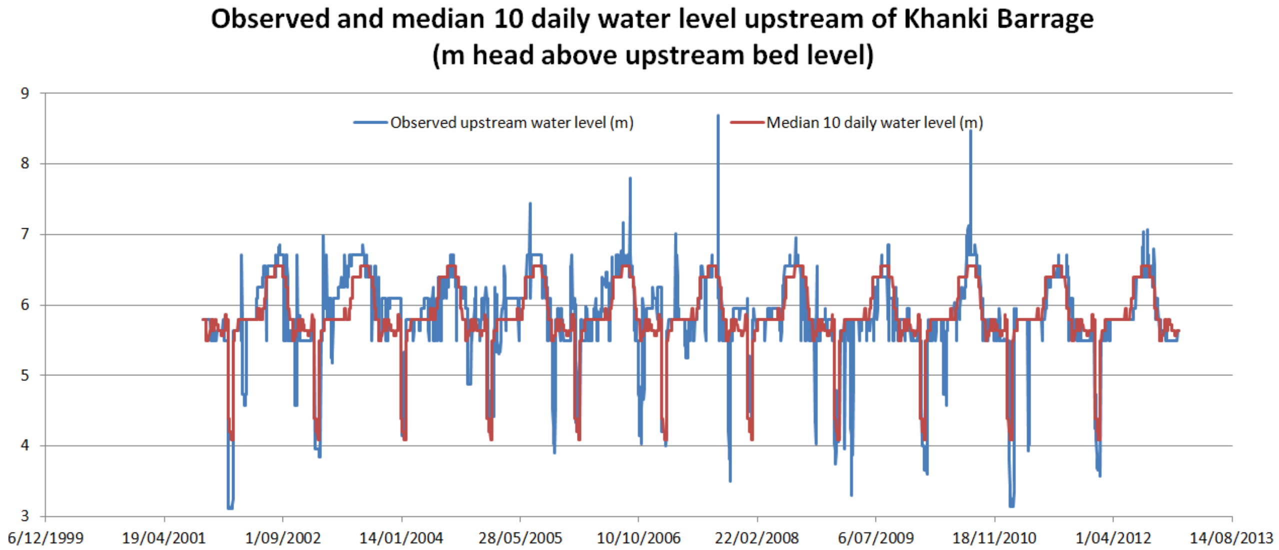


Figure 27 Khanki Barrage operational water level pattern

The storage level-volume-area relationship applied to Khanki barrage, along with minimum and maximum barrage discharges (over the main weir and under-sluice gates) are provided in Table 17 and Table 18.

Table 17 Khanki Barrage summary model data (metric units)

Level description	Level above mean sea	Depth	Volume (estimate)	Surface area (estimate)	Under-sluice discharge	Main weir discharge	Hydro discharge
	m	m	km^3	ha	m^3/s	m^3/s	m^3/s
Zero point, no water	216.408	0	0	0	0	0	0
Under-sluice level, dead storage	217.932	1.524	5.009	657	0	0	0
Intermediate point	218.770	2.362	12.033	1019	492.5	0	492.5
Weir 1	219.608	3.200	22.088	1380	1392.9	0	1392.9
Weir 2	219.761	3.353	24.242	1446	1587.1	114.1	1701.2
Intermediate Point	220.500	4.092	36.109	1765	2640.9	1614.1	4255.0
Intermediate point	221.000	4.592	45.473	1981	3448.6	3147.3	6596.0
Intermediate point	221.500	5.092	55.915	2196	4325.1	4987.9	9313.0
Intermediate point	222.000	5.592	67.435	2412	5265.4	7090.9	12356.4
Maximum barrage level	223.418	7.010	105.983	3024	8247.0	14258.0	22505.0

Table 18 Khanki Barrage summary model data (imperial units)

Level description	level above mean sea	Depth	Volume (estimate)	Surface area (estimate)	Under-sluice discharge	Main weir discharge	Hydro discharge
	Ft	ft	MAF	acres	ft^3/s	ft^3/s	ft^3/s
zero point, no water	710.0	0	0	0	0	0	0
Under-sluice level, dead storage	715.0	5.0	0.0041	1624	0	0	0
Intermediate point	717.8	7.8	0.0098	2518	17392	0	17392
weir 1	720.5	10.5	0.0179	3411	49191	0	49191
weir 2	721.0	11.0	0.0197	3573	56049	4028	60077
Intermediate Point	723.4	13.4	0.0293	4361	93263	57001	150264
Intermediate point	725.1	15.1	0.0369	4894	121787	111147	232934
Intermediate point	726.7	16.7	0.0453	5427	152741	176145	328886
Intermediate point	728.3	18.3	0.0547	5960	185947	250414	436362
maximum barrage level	733.0	23.0	0.0859	7471	291239	503517	794756

Offtake canal data for Khanki include:

- the crest level of the LCC Link is estimated to be equivalent to the under-sluice level of 217.9 m above mean sea level(715ft); and
- LCC Link Canal is estimated to have 18 bays at 20 ft wide for a total of 109.723m of weir (300 ft).

The level vs maximum discharge relationships applied to LCC Link is provided in Table 19.

Table 19 Khanki Barrage offtake summary model data

Level description	Level		Depth		LCC Link discharge*	
	m	ft	m	ft	m^3/s	ft^3/s
Zero point, no water	216.408	710.0	0.000	0.0	0.0	0
Under-sluice level, dead storage	217.932	715.0	1.524	5.0	0.0	0
Intermediate point	218.770	717.8	2.362	7.8	277.0	9783
Weir 1	219.608	720.5	3.200	10.5	783.5	27670
Weir 2	219.761	721.0	3.353	11.0	892.8	31528
Intermediate Point	220.500	723.4	4.092	13.4	1485.5	52461
Intermediate point	221.000	725.1	4.592	15.1	1939.8	68505
Intermediate point	221.500	726.7	5.092	16.7	2432.9	85917
Intermediate point	222.000	728.3	5.592	18.3	2961.8	104595
Maximum barrage level	223.418	733.0	7.010	23.0	4638.9	163822

* Discharge refers to maximum theoretical discharge applying equation 4 (submerged orifice) with coefficient of discharge = 0.743. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Rasul

Rasul Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target to account for reduced water levels during canal closure periods. Outlets on Khanki are modelled as gated spillways including R-Q Link and Lower Jhelum Irrigation canal.

Figure 28 Rasul Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the under-sluice bays is 212.9 m (698.5ft) above mean sea level;
- the crest level of the main weir is 214.3 m (703 ft) above mean sea level;
- the upstream floor level is 211.8 m (695 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 51 km^3 at operational water level has been inferred from aerial photography;
- there are 42 standard bays on the main weir 18.288 m (60 ft) across;
- there are 6 under-sluice bays, 18.288 m (60 ft) across;
- the maximum design discharge for the barrage is 24069 m^3/s (850,000 ft^3/s) at 218.2 m (716 ft) above mean sea level; and
- historic water level time series for Rasul (2001-2013) indicates that barrage levels are maintained at approximately 219.151m (719 ft) for most of the year, except for an annual cleaning period in early January. Water level time series and an average weekly pattern derived from this dataset are shown in Figure 29. The 10 daily pattern is used in the IRSM as the operational water level target for the barrage.

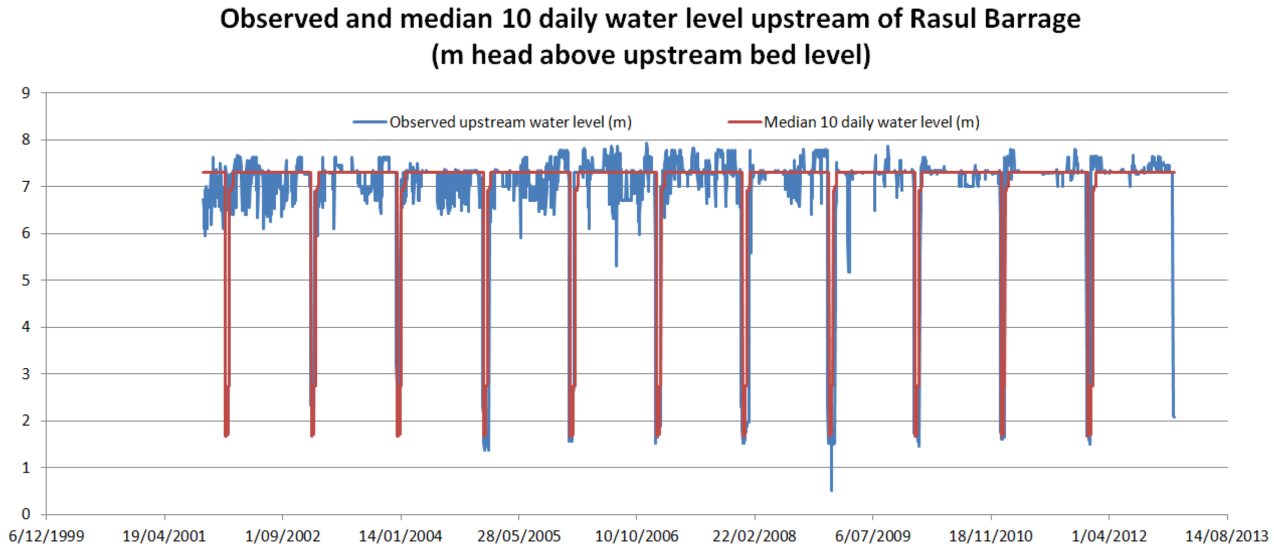


Figure 29 Rasul Barrage operational water level pattern

The storage level-volume-area relationship applied to Rasul Barrage, along with minimum and maximum barrage discharges (over the main weir and under-sluice gates), are provided in Table 20 and Table 21. Note that in estimating the discharge of the under-sluice, a submerged orifice equation as per IRSA (2015) has been applied.

Table 20 Rasul Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km³	Surface area (estimate) ha	Under-sluice discharge m³/s	Main weir discharge m³/s	Hydro discharge m³/s
Zero point, no water	211.836	0.000	0	0	0.0	0.0	0.0
Under-sluice level, dead storage	212.903	1.067	1.098	206	0.0	0.0	0.0
Main weir	214.274	2.438	5.738	471	369.7	0.0	369.7
Intermediate point	214.836	3.000	8.685	579	618.6	678.0	1296.6
Intermediate point	215.836	4.000	15.440	772	1156.2	3143.8	4300.0
Intermediate Point	216.836	5.000	24.125	965	1795.3	6605.0	8400.3
Intermediate point	217.836	6.000	34.740	1158	2521.7	10828.6	13350.4
Operational level	219.151	7.315	51.639	1412	3594.7	17350.3	20945.0
Maximum barrage level	219.608	7.772	58.296	1500	3996.4	19846.6	23842.9

Table 21 Rasul Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft³/s	Main weir discharge ft³/s	Hydro discharge ft³/s
Zero point, no water	695.0	0.0	0.0000	0	0	0	0
Under-sluice level, dead storage	698.5	3.5	0.0009	509	0	0	0
Main weir	703.0	8.0	0.0047	1163	13056	0	13056
Intermediate point	704.8	9.8	0.0070	1431	21846	23944	45791
Intermediate point	708.1	13.1	0.0125	1908	40830	111024	151853
Intermediate Point	711.4	16.4	0.0196	2385	63399	233253	296652
Intermediate point	714.7	19.7	0.0282	2861	89054	382409	471464
Operational level	719.0	24.0	0.0419	3489	126945	612722	739667
Maximum barrage level	720.5	25.5	0.0473	3707	141130	700875	842005

Offtake canal data for Rasul include:

- the crest level of the RQ Link and LJC is estimated to be equivalent to the main weir level of 214.3 m (703 ft) above mean sea level;
- RQ Link Canal is estimated to have 6 bays at 12.19 m (40 ft) wide; and
- LJC is estimated to have 2 bays at 12.19 m (40 ft) wide.

Table 22 Rasul Barrage offtake summary model data

Level description	Level		Local datum level		RQ Link discharge*		LJC Link discharge*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	211.836	695.0	0.000	0.0	0.0	0	0.0	0
Under-sluice level, dead storage	212.903	698.5	1.067	3.5	0.0	0	0.0	0
Main weir	214.274	703.0	2.438	8.0	0.0	0	0.0	0
Intermediate point	214.836	704.8	3.000	9.8	96.9	3421	32.3	1140
Intermediate point	215.836	708.1	4.000	13.1	449.1	15861	149.7	5287
Intermediate Point	216.836	711.4	5.000	16.4	943.6	33322	314.5	11107
Intermediate point	217.836	714.7	6.000	19.7	1546.9	54630	515.6	18210
Operational level	219.151	719.0	7.315	24.0	2478.6	87532	826.2	29177
Maximum barrage level	219.608	720.5	7.772	25.5	2835.2	100125	945.1	33375

* Discharge refers to maximum theoretical discharge applying equation 4 (submerged orifice) with coefficient of discharge = 0.71. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Qadirabad

Qadirabad Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target to account for reduced water levels during canal closure periods. Outlets on Qadirabad are modelled as gated spillways as is the only offtake Q-B Link canal.

Figure 30 Qadirabad Barrage showing main barrage and offtake canal

Data provided for this study (IRSA 2015) include:

- the crest level of the under-sluice bays is 207.3 m (680ft) above mean sea level;

- the crest level of the main weir is 208.6 m (684.5 ft) above mean sea level;
- the upstream floor level is 205.4 m (674 ft) above mean sea level;
- no capacity information was available for this study, however a ponded volume of approximately 109 km^3 at operational water level has been inferred from aerial photography;
- there are 45 standard bays on the main weir 18.288 m (60 ft) across;
- there are 5 under-sluice bays, 18.288 m (60 ft) across;
- the maximum design discharge for the barrage is 25485 m^3/s (900,000 ft^3/s) at 214 m (702 ft) above mean sea level; and
- historic water level time series for Qadirabad (2001-2013) indicates that barrage levels are maintained at approximately 213.665m (701 ft) for most of the year, except for an annual cleaning period in early January. Water level time series and an average weekly pattern derived from this dataset is shown in Figure 31. The 10 daily pattern is used in the IRSM as the operational water level target for the barrage.

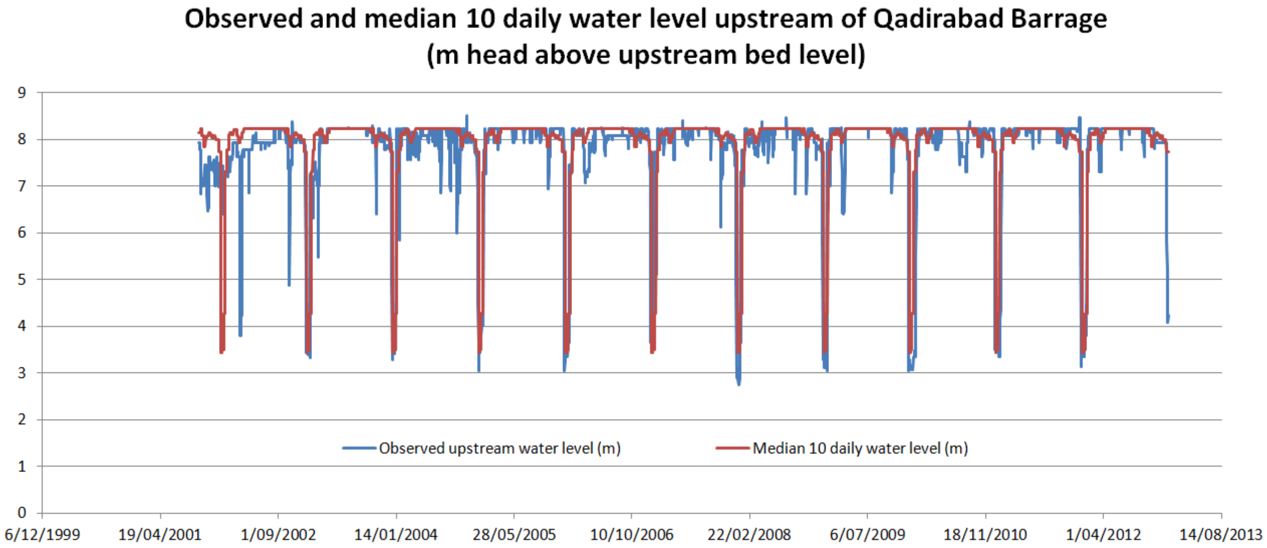


Figure 31 Qadirabad Barrage operational water level pattern

The storage level-volume-area relationship applied to Qadirabad Barrage, along with minimum and maximum barrage discharges (over the main weir and under-sluice gates) are provided in Table 23 and Table 24. Note that in estimating the discharge of the under-sluice, a free orifice with unsubmerged gates equation as per IRSA (2015) has been applied.

Table 23 Qadirabad Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	205.435	0.000	0	0	0.0	0.0	0.0
Under-sluice level, dead storage	207.264	1.829	1.060	116	0.0	0.0	0.0
Weir	208.636	3.200	6.097	381	319.2	0.0	319.2
Additional point	209.435	4.000	12.118	606	635.7	1278.6	1914.2
Additional point	210.435	5.000	24.006	960	1122.0	4317.0	5439.1
Additional point	211.435	6.000	41.872	1396	1692.7	8376.5	10069.1
Additional point	212.435	7.000	66.932	1912	2336.5	13244.2	15580.7
Additional point	212.935	7.500	82.540	2201	2683.4	15942.6	18626.1
Operational level	213.665	8.230	109.413	2659	3217.6	20168.2	23385.7

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Just above operational	213.715	8.280	111.432	2692	3255.3	20469.7	23725.0
Maximum barrage level	213.970	8.534	122.161	2863	3450.1	22029.1	25479.2

Table 24 Qadirabad Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Zero point, no water	674.0	0.0	0.0000	0	0	0	0
Under-sluice level, dead storage	680.0	6.0	0.0009	286	0	0	0
Weir	684.5	10.5	0.0049	941	11271	0	11271
Additional point	687.1	13.1	0.0098	1497	22448	45153	67601
Additional point	690.4	16.4	0.0195	2373	39625	152453	192078
Additional point	693.7	19.7	0.0339	3449	59775	295813	355588
Additional point	697.0	23.0	0.0543	4725	82512	467714	550226
Additional point	698.6	24.6	0.0669	5439	94764	563009	657773
Operational level	701.0	27.0	0.0887	6571	113627	712232	825859
Just above operational	701.2	27.2	0.0903	6651	114961	722880	837841
Maximum barrage level	702.0	28.0	0.0990	7074	121839	777952	899791

Offtake canal data for Qadirabad include:

- the crest level of the QB Link is estimated to be equivalent to the main weir level of 208.6 m (684.5 ft) above mean sea level
- QB Link Canal is estimated to have 6 bays at 12.19 m (40 ft) wide.

Table 25 Qadirabad Barrage offtake summary model data

Level description	Level		Depth		QB Link discharge*	
	m	ft	m	ft	m^3/s	ft^3/s
Zero point, no water	674.000	674.0	0.000	0.0	0.0	0
Under-sluice level, dead storage	680.000	680.0	1.829	6.0	0.0	0
Weir	684.500	684.5	3.200	10.5	0.0	0
Additional point	687.123	687.1	4.000	13.1	164.6	5811
Additional point	690.404	690.4	5.000	16.4	555.6	19621
Additional point	693.685	693.7	6.000	19.7	1078.1	38072
Additional point	696.966	697.0	7.000	23.0	1704.6	60196
Additional point	698.606	698.6	7.500	24.6	2051.9	72461
Operational level	701.000	701.0	8.230	27.0	2595.7	91667
Just above operational	701.164	701.2	8.280	27.2	2634.5	93037
Maximum barrage level	702.000	702.0	8.534	28.0	2835.2	100125

* Discharge refers to maximum theoretical discharge applying equation 4 (submerged orifice) with coefficient of discharge = 0.71. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Balloki

Balloki Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target to account for reduced water levels during canal closure periods. Outlets on Balloki are modelled as gated spillways including Balloki-Sulemanki Link and Lower Bari Doab Canal (LBDC).

Figure 32 Balloki Barrage showing main barrage and offtake canals

Figure 33 Balloki Barrage showing main barrage

Data provided for this study (IRSA 2015) and observed in the field include:

- the crest level is 190.3 m (624.5 ft) above mean sea level;
- the upstream floor level is 189.3 m (621 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 24 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 35 standard bays on the main weir 12.192 m (40 ft) across;

- the maximum design discharge for the barrage is 6371 m^3/s (225,000 ft^3/s) at 194.5 m (638 ft) above mean sea level; and
- historic water level time series for Balloki (2001-2013) indicates that barrage levels are maintained at varying levels throughout the season including an annual cleaning period in early January. Water level time series and an average weekly pattern derived from this dataset is shown in Figure 34. The 10 daily pattern is used in the IRSM as the operational water level target for the barrage.

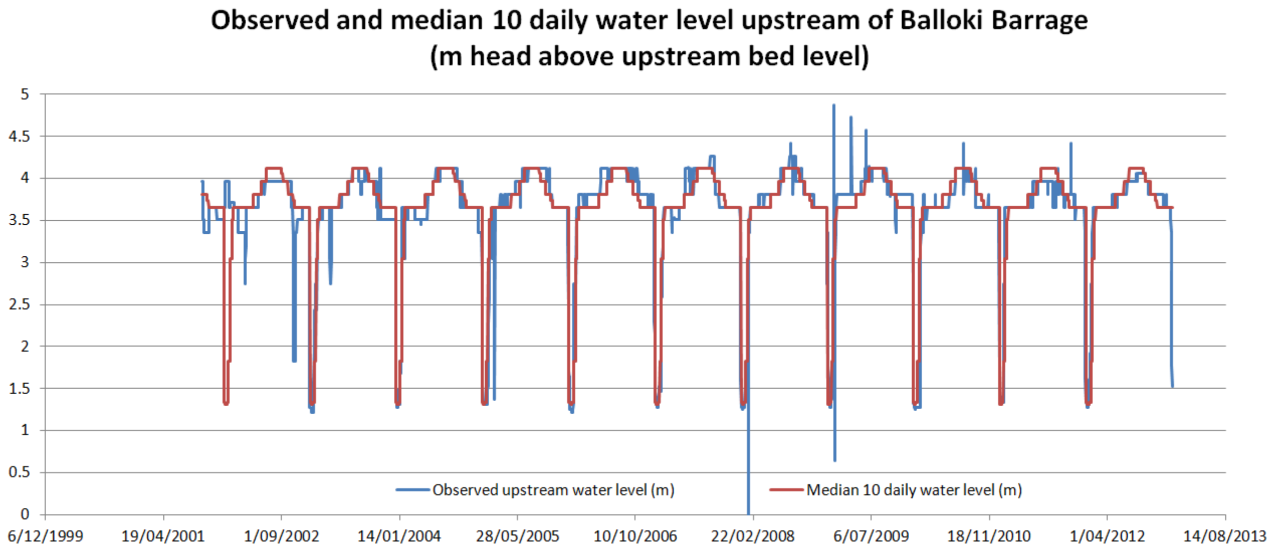


Figure 34 Balloki Barrage operational water level pattern

The storage level-volume-area relationship applied to Balloki barrage, along with minimum and maximum barrage discharges (over the main weir), are provided below.

Table 26 Balloki Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Discharge Main weir m^3/s
Zero point, no water	189.281	0.000	0.000	0	0.0
Weir	190.348	1.067	1.022	192	0.0
BS Link	190.451	1.170	1.230	210	25.9
LBDC	191.235	1.954	3.428	351	649.5
Additional point	192.281	3.000	8.082	539	2089.2
Low Operational level	192.938	3.658	12.015	657	3241.3
Intermediate Point	193.167	3.886	13.561	698	3679.4
Upper Operating level	193.395	4.115	15.203	739	4135.6
Maximum barrage level	194.462	5.182	24.110	931	6487.6

Table 27 Balloki Barrage summary model data (imperial units)

Level description	Level above mean sea ft)	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Discharge Main weir(ft^3/s
Zero point, no water	621.0	0.0	0.0000	0	0
Weir	624.5	3.5	0.0008	473	0
BS Link	624.8	3.8	0.0010	519	916
LBDC	627.4	6.4	0.0028	867	22938
Additional point	630.8	9.8	0.0066	1331	73779
Low Operational level	633.0	12.0	0.0097	1623	114464

Level description	Level above mean sea ft)	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Discharge Main weir(ft^3/s
Intermediate Point	633.7	12.7	0.0110	1725	129936
Upper Operating level	634.5	13.5	0.0123	1826	146049
Maximum barrage level	638.0	17.0	0.0195	2300	229109

Offtake canal data for Balloki include:

- the crest level of the BS Link is 190.5 m (624.84 ft) above mean sea level;
- the crest level of the LBDC is 191.2 m (627.4 ft) above mean sea level;
- BS Link Canal now has 19 bays at 7.3m (24 ft) (previously 11 bays); and
- LJC is estimated to have 15 bays at 6.10m (20 ft) wide.

Table 28 Balloki Barrage offtake summary model data

Level description	Level		Local datum level		BS Link discharge*		LBDC discharge*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	189	621.0	0.000	0.0	0.0	0.0	0.0	0
Weir	190	624.5	1.067	3.5	0.0	0.0	0.0	0
BS Link	190	624.8	1.170	3.8	0.0	0.0	0.0	0
LBDC	191	627.4	1.954	6.4	263.4	107.7	0.0	0
Additional point	192	630.8	3.000	9.8	939.8	384.1	267.3	9438
Low Operational level	193	633.0	3.658	12.0	1489.5	608.8	555.5	19618
Intermediate Point	193	633.7	3.886	12.7	1699.4	694.6	670.9	23694
Upper Operating level	193	634.5	4.115	13.5	1918.4	784.1	793.4	28020
Maximum barrage level	194	638.0	5.182	17.0	3050.7	1246.9	1448.7	51159

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.617. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Sulemanki

Sulemanki Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target. Outlets on Sulemanki are modelled as gated spillways including Upper Pakpattan, Eastern Sadiqia and Fordwah canals.

Figure 35 Sulemanki Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the main weir is 170.7 m (560 ft) above mean sea level;
- the crest level of the undersluice weir is 168.3 m (552 ft) above mean sea level;
- the upstream floor sump level is 167.3 m (549 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 18 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 24 standard bays on the main weir 18.288 m (60 ft) across;
- there are 16 standard bays on the main weir 9.144 m (30 ft) across;
- the maximum design discharge for the barrage is 9202 m^3/s (325,000 ft^3/s) at 174.3 m (572 ft) above mean sea level; and
- historic water level time series for Sulemanki (2010-2016) have been provided by PID and indicate that barrage levels are maintained at varying levels throughout the season including an annual cleaning period in early January. Water level time series and an average weekly pattern derived from this dataset are shown in Figure 36. The 10 daily pattern is used in the IRSM as the operational water level target for the barrage.

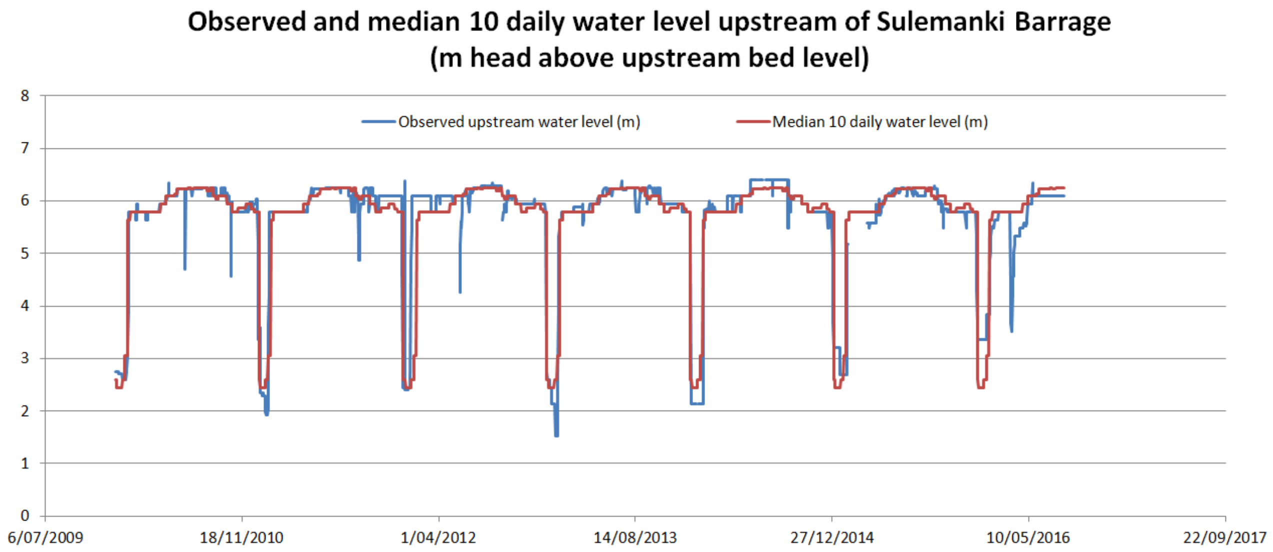


Figure 36 Sulemanki Barrage operational water level pattern

The storage level-volume-area relationship applied to Sulemanki barrage, along with minimum and maximum barrage discharges (over the main weir) are provided in Table 29.

Table 29 Sulemanki Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km³	Surface area (estimate) ha	Under-sluice Discharge m³/s	Main weir discharge m³/s	Hydro discharge m³/s
Zero point, no water	167.335	0.000	0	0	0.0	0.0	0.0
Under-sluice	168.250	0.914	0.405	88	0.0	0.0	0.0
Additional point	169.335	2.000	1.936	194	307.5	0.0	307.5
Upper Pakpattan and E. Sadiqia Offtake	170.383	3.048	4.495	295	847.0	0.0	847.0
Main weir	170.688	3.353	5.440	324	1035.0	0.0	1035.0
Fordwah Canal Offtake	171.145	3.810	7.024	369	1339.3	574.2	1913.4
Additional point	172.335	5.000	12.098	484	2244.8	2355.1	4599.9
Operational level	173.431	6.096	17.983	590	3206.3	4595.2	7801.5
H Design	174.041	6.706	21.759	649	3788.4	6040.6	9829.0
Maximum barrage level	174.346	7.010	23.782	678	4091.4	6811.2	10902.6

Offtake canal data for Sulemanki include:

- the crest level of the Upper Pakpattan and Eastern Sadiqia is 170.4 m (559 ft) above mean sea level;
- the crest level of the Fordwah Canal is 171.1 m (561.5ft) above mean sea level;
- Upper Pakpattan has 8 bays at 6.069 m (20 ft);
- Upper Sadiqia has 7 bays at 6.069 m (20 ft); and
- Upper Pakpattan has 5 bays at 6.069 m (20 ft).

Table 30 Sulemanki Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft³/s	Main weir discharge ft³/s	Hydro discharge ft³/s
Zero point, no water	549.0	0.0	0.0000	0	0	0	0
Under-sluice	552.0	3.0	0.0003	219	0	0	0
Additional point	555.6	6.6	0.0016	478	10858	0	10858

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Upper Pakpattan and E. Sadiqia Offtake	559.0	10.0	0.0036	729	29913	0	29913
Main weir	560.0	11.0	0.0044	802	36552	0	36552
Fordwah Canal Offtake	561.5	12.5	0.0057	911	47296	20277	67572
Additional point	565.4	16.4	0.0098	1196	79276	83169	162445
Operational level	569.0	20.0	0.0146	1458	113228	162279	275507
H Design	571.0	22.0	0.0176	1604	133786	213321	347107
Maximum barrage level	572.0	23.0	0.0193	1677	144486	240534	385020

Table 31 Sulemanki Barrage offtake summary model data

Level description	Level		Depth		Fordwah*		E. Sadiqia*		UPC*	
	m	ft	m	ft	m^3/s	ft3/s	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	167	549.0	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0
Under-sluice	168	552.0	0.914	3.0	0.0	0.0	0.0	0.0	0.0	0
Additional point	169	555.6	2.000	6.6	0.0	0.0	0.0	0.0	0.0	0
Upper Pakpattan and E. Sadqia Offtake	170	559.0	3.048	10.0	0.0	0.0	0.0	0.0	0.0	0
Main weir	171	560.0	3.353	11.0	0.0	0.0	17.9	631.0	20.4	721
Fordwah Canal Offtake	171	561.5	3.810	12.5	0.0	0.0	70.5	2491.0	80.6	2847
Additional point	172	565.4	5.000	16.4	98.3	3473.0	289.2	10214.0	330.5	11673
Operational level	173	569.0	6.096	20.0	261.8	9246.0	564.3	19929.0	644.9	22775
H Design	174	571.0	6.706	22.0	373.2	13181.0	741.8	26196.0	847.8	29939
Maximum barrage level	174	572.0	7.010	23.0	433.7	15315.0	836.4	29538.0	955.9	33758

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.561. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Islam

Islam Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target to account for the canal closure period. Outlets on Islam are modelled as gated spillways including Upper Bahawal and Upper Qiam canals.

Figure 37 Sulemanki Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the main weir bays 5-10 and 22-25 is 134.4 m (441 ft) above mean sea level;
- the crest level of the bays 11-21 is 132.7 m (435.5 ft) above mean sea level;
- the crest level of the under-sluice bays is 134.4 m (441 ft) above mean sea level;
- the upstream floor sump level is 132.3 m (434 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 50 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 10 standard bays on the main weir 18.288 m (60 ft) across;
- there are 11 shorter bays on the main weir 8.839 m (29 ft) across;
- there are 8 under-sluice bays on the main weir 18.288 m (60 ft) across;
- the maximum design discharge for the barrage is 8495 m^3/s (300,000 ft^3/s) at 139.4 m (457.5 ft) above mean sea level; and
- historic water level time series for Islam (2010-2016) has been provided by PID and indicates that barrage levels are maintained at or near 138.98 m (456 ft) (6.24m depth), although in more recent years, a barrage level of 138.684 m (455 ft) (5.944 m depth) may be more appropriate. Water level time series and an average 10 daily pattern derived from this dataset is shown in Figure 37. The 10 daily pattern is used in Source as the operational water level target for the barrage.

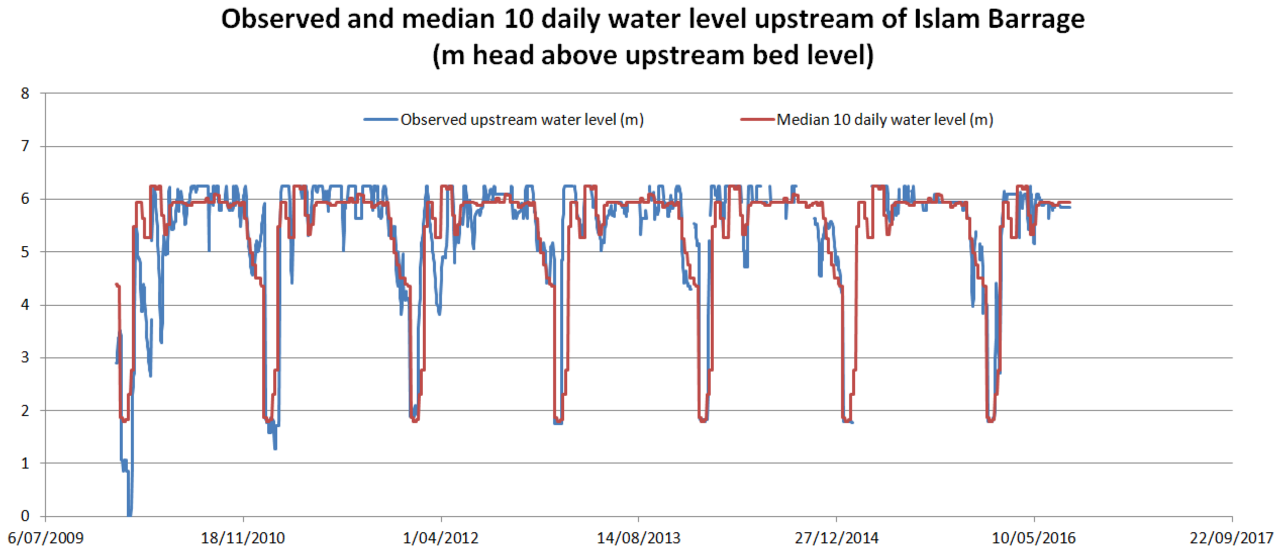


Figure 38 Islam Barrage operational water level pattern

The storage level-volume-area relationship applied to Islam Barrage, along with minimum and maximum barrage discharges (over the main weir), are provided in Table 32 and Table 33.

Table 32 Islam Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water (hypothetical)	132.740	0.000	0	0	0.0	0.0	0.0
Weir bays 11-21	132.740	0.000	0	0	0.0	0.0	0.0
Weirs 5-10, 22-25 and under-sluice	134.417	1.676	2.540	303	0.0	331.9	331.9
Additional point	135.740	3.000	9.176	612	350.4	1232.7	1583.1
Additional point	136.740	4.000	17.717	886	815.1	2242.3	3057.3
Additional point	137.739	4.999	29.861	1195	1393.7	3451.4	4845.1
Lower operational level	138.684	5.944	45.138	1519	2028.4	4751.5	6780.0
Upper operational level	138.989	6.248	51.518	1649	2249.6	5200.6	7450.2
Maximum barrage level	139.446	6.706	60.459	1803	2595.3	5899.7	8495.1

Table 33 Islam Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/)	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Zero point, no water (hypothetical)	435.5	0.0	0.0000	0	0	0	0
Weir bays 11-21	435.5	0.0	0.0000	0	0	0	0
Weirs 5-10, 22-25 and under-sluice	441.0	5.5	0.0021	749	0	11722	11722
Additional point	445.3	9.8	0.0074	1512	12375	43531	55906
Additional point	448.6	13.1	0.0144	2189	28783	79185	107969
Additional point	451.9	16.4	0.0242	2952	49217	121885	171103
Lower operational level	455.0	19.5	0.0366	3753	71633	167799	239433
Upper operational Level	456.0	20.5	0.0418	4075	79444	183659	263102
Maximum barrage level	457.5	22.0	0.0490	4456	91654	208346	300000

Offtake canal data for Islam include:

- the crest level of the Upper Bahawal and Qiam canals is assumed to be and Eastern Sadiqia is 134.4 m (441 ft) above mean sea level;
- Upper Bahawal is assumed to have has 7 bays at 6.069 m (20 ft); and
- Upper Qiam is assumed to have has 2 bays at 2.44 m (8 ft).

Table 34 Islam Barrage offtake summary model data

Level description	Level		Depth		Upper Bahawal discharge*		Upper Qiam discharge*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water (hypothetical)	133	435.5	0.000	0.0	0.0	0.0	0.0	0
Weir bays 11-21	133	435.5	0.000	0.0	0.0	0.0	0.0	0
Weirs 5-10, 22-25 and under-sluice	134	441.0	1.676	5.5	0.0	0.0	0.0	0
Additional point	136	445.3	3.000	9.8	166.8	5890.0	19.1	673
Additional point	137	448.6	4.000	13.1	387.9	13699.0	44.3	1566
Additional point	138	451.9	4.999	16.4	663.3	23425.0	75.8	2677
Lower operational level	139	455.0	5.944	19.5	965.4	34094.0	110.3	3896
Upper operational Level	139	456.0	6.248	20.5	1070.7	37811.0	122.4	4321
Maximum barrage level	139	457.5	6.706	22.0	1235.2	43622.0	141.2	4985

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.579. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Punjnad

Punjnad Barrage is set up in the IRSM with a static level-volume-area curve and a 10 daily operating target. Outlets on Punjnad are modelled as gated spillways including Punjnad, Abbasia and Abbasia Link Canals.

Figure 39 Punjnad Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the main weir and under-sluice is 99.1 m (325 ft) above mean sea level;
- the upstream floor level is 97.5 m (320 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 45 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 29 standard bays on the main weir 18.288 m (60 ft) across;
- there are 18 under-sluice bays on the main weir 18.288 m (60 ft) across;
- the maximum design discharge for the barrage is 19821 m^3/s (700,000 ft^3/s) at 104.4 m (342.4 ft) above mean sea level; and
- historic water level time series for Punjnad (2002-2012) indicate that barrage levels are vary throughout the year and include an annual cleaning period in January. Water level time series and an average 10 daily pattern derived from this dataset is shown in Figure 40. The 10 daily pattern is used in Source as the operational water level target for the barrage.

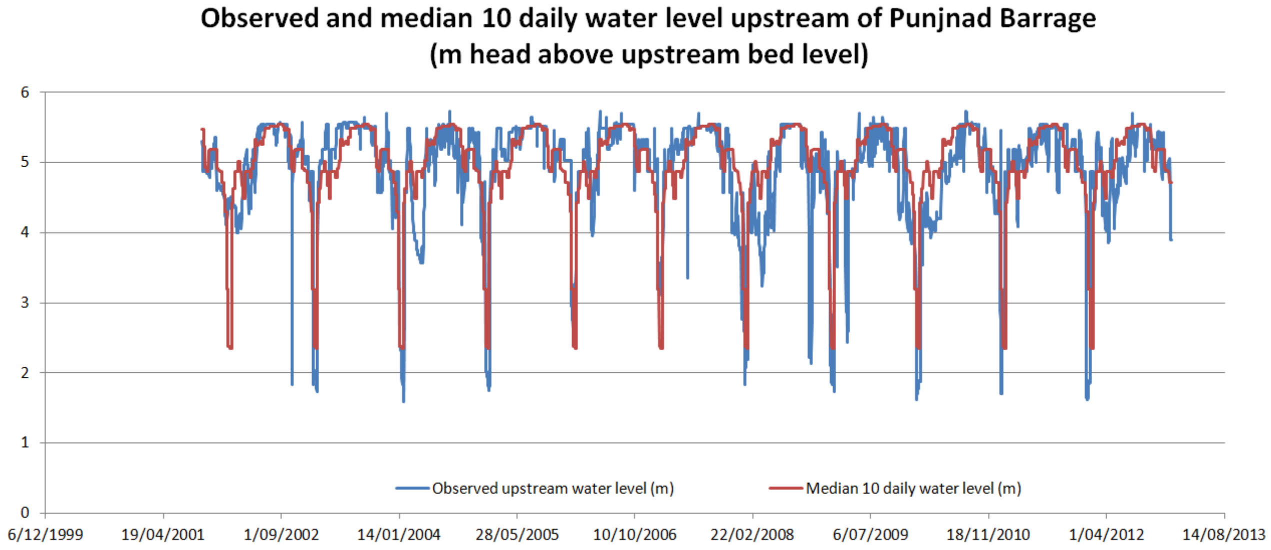


Figure 40 Punjnad Barrage operational water level pattern

The storage level-volume-area relationship applied to Punjnad Barrage, along with minimum and maximum barrage discharges (over the main weir), are provided in Table 35 and Table 36.

Table 35 Punjnad Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Undersluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	97.536	0.000	0	0	0.0	0.0	0.0
Main weir	99.060	1.524	4.214	553	0.0	0.0	0.0
Intermediate	99.536	2.000	6.300	630	197.5	338.8	536.4
Intermediate	100.036	2.500	9.844	788	577.3	1002.1	1579.4
Intermediate	100.536	3.000	14.175	945	1074.8	1840.7	2915.5
Intermediate	101.036	3.500	19.294	1103	1656.0	2878.0	4534.0
Intermediate	101.536	4.000	25.200	1260	2326.3	3981.1	6307.4
Intermediate	102.036	4.500	31.894	1418	3068.4	5275.1	8343.5
Intermediate	102.536	5.000	39.375	1575	3884.7	6634.6	10519.3
Operational Level	102.870	5.334	44.326	1662	4446.6	7610.6	12057.2
H max	104.089	6.553	67.637	2064	6752.2	11545.3	18297.5
H Design max	104.364	6.828	73.419	2151	7301.7	12497.0	19798.7

Table 36 Punjnad Barrage summary model data (imperial units)

Level description	level above mean sea (ft)	Depth (ft)	Volume MAF (estimate)	Surface Area acres (estimate)	Undersluice Discharge (ft^3/s)	Main weir Discharge (ft^3/s)	Hydro Discharge (ft^3/s)
zero point, no water	320.0	0.0	0.0000	0	0	0	0
Main weir	325.0	5.0	0.0034	1366	0	0	0
intermediate	326.6	6.6	0.0051	1557	6976	11965	18941
intermediate	328.2	8.2	0.0080	1946	20387	35390	55777
intermediate	329.8	9.8	0.0115	2335	37955	65003	102958
intermediate	331.5	11.5	0.0156	2724	58481	101636	160117
intermediate	333.1	13.1	0.0204	3114	82151	140593	222744
intermediate	334.8	14.8	0.0259	3503	108361	186288	294649
intermediate	336.4	16.4	0.0319	3892	137185	234299	371484
Operational Level	337.5	17.5	0.0359	4107	157030	268767	425797
H max	341.5	21.5	0.0548	5101	238453	407717	646169
H Design max	342.4	22.4	0.0595	5314	257859	441326	699185

Offtake canal data for Punjnad include:

- the crest level of the offtake canals is unknown and assumed to be that of the main barrage at 99 m (325 ft) above mean sea level;
- Punjnad Main Line Canal is estimated to have 12 bays at 7.32 m (24 ft);
- Abbasia Link Canal is estimated to have 6 bays at 7.32m (24 ft);
- Abbasia Canal is estimated to have 2 bays at 6.10 m (20 ft).

Table 37 Punjnad Barrage offtake summary model data

Level description	Level m	Level (ft)	Depth (m)	Depth (ft)	Punjnad Main Line Discharge (m^3/s)*	Punjnad Main Line Discharge (ft^3/s)*	Abbasia Link (m^3/s) *	Abbasia Link (ft^3/s) *	Abbasia (m^3/s) *	Abbasia (ft^3/s) *
Zero point, no water	97.5	320.0	0.000	0.0	0.0	0	0.0	0	0.0	0
Main weir	99.1	325.0	1.524	5.0	0.0	0	0.0	0	0.0	0
Intermediate	99.5	326.6	2.000	6.6	83.7	2956	41.9	1478	11.6	411
Intermediate	100.0	328.2	2.500	8.2	245.8	8679	122.9	4339	34.1	1205
Intermediate	100.5	329.8	3.000	9.8	457.0	16141	228.5	8070	63.5	2242
Intermediate	101.0	331.5	3.500	11.5	708.0	25002	354.0	12501	98.3	3472
Intermediate	101.5	333.1	4.000	13.1	993.0	35068	496.5	17534	137.9	4871
Intermediate	102.0	334.8	4.500	14.8	1308.5	46210	654.3	23105	181.7	6418
Intermediate	102.5	336.4	5.000	16.4	1651.8	58332	825.9	29166	229.4	8102
Operational level	102.9	337.5	5.334	17.5	1895.5	66938	947.7	33469	263.3	9297
H max	104.1	341.5	6.553	21.5	2874.6	101516	1437.3	50758	399.2	14099
H design max	104.4	342.4	6.828	22.4	3113.0	109935	1556.5	54967	432.4	15269

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.656. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Trimmu

Trimmu Barrage is set up in the IRSM with a static level-volume-area curve and a weekly operating target. Outlets on Trimmu are modelled as gated spillways including Upper Rangpur, Haveli and TS Link canals.

Figure 41 Trimmu Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the main weir is 145.5 m (477.5 ft) above mean sea level;
- the crest level of the under-sluice is 143.9 m (472 ft) above mean sea level;

- the upstream floor level is 142.6 m (468 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 37 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 37 standard bays on the main weir 18.288 m (60 ft) across;
- there are 14 under-sluice bays on the main weir 9.144 m (30 ft) across;
- the maximum design discharge for the barrage is 18264 m^3/s (645,000 ft^3/s) at 150.4 m (493.5 ft) above mean sea level; and
- historic water level time series for Trimmu (2002-2012) indicate that barrage levels are vary slightly throughout the year and include an annual cleaning period in January (Figure 42). The weekly pattern is used in the IRSM as the operational water level target for the barrage.

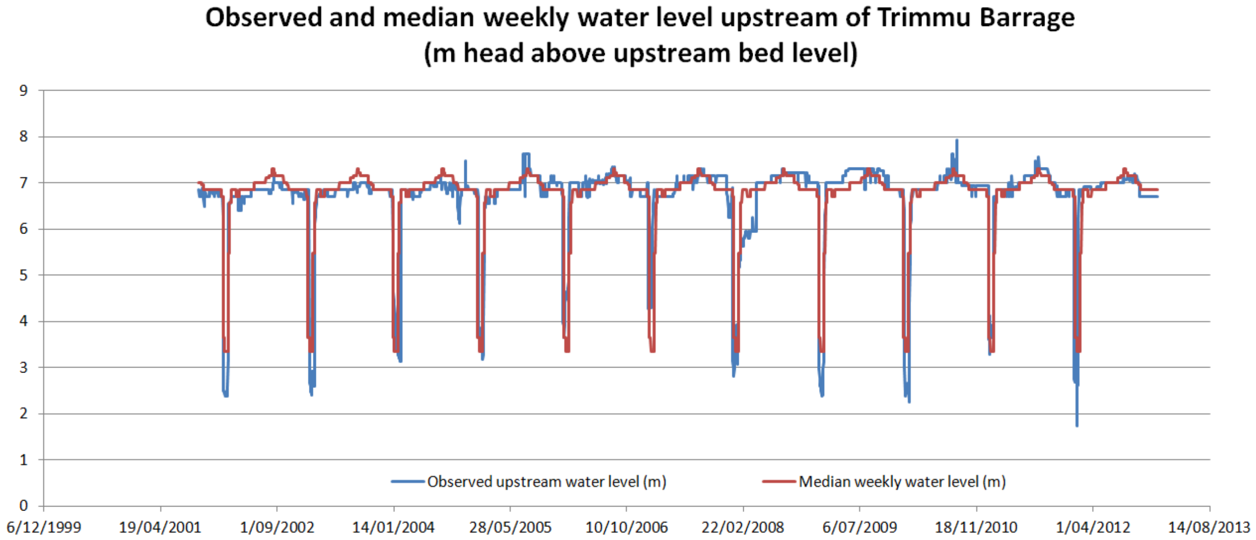


Figure 42 Trimmu Barrage operational water level pattern

The storage level-volume-area relationship applied to Trimmu Barrage, along with maximum barrage discharges (over the main weir), are provided in Table 38 and Table 39.

Table 38 Trimmu Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	142.646	0.000	0	0	0.0	0.0	0.0
Under-sluice	143.866	1.219	1.035	170	0.0	0.0	0.0
Main weir	145.542	2.896	5.840	403	573.9	0.0	573.9
Intermediate point	145.646	3.000	6.269	418	637.7	466.8	1104.6
Intermediate point	146.646	4.000	11.144	557	1230.4	2623.1	3853.4
Intermediate point	147.646	5.000	17.413	697	1892.4	5383.1	7275.5
Intermediate point	148.646	6.000	25.074	836	2599.0	8433.2	11032.1
Lower operational level	149.496	6.850	32.682	954	3252.5	11361.8	14614.3
Upper operational Level	149.956	7.310	37.218	1018	3625.1	13063.9	16689.0
H Design	150.266	7.620	40.442	1061	3883.4	14254.8	18138.3
H max	150.419	7.772	42.076	1083	4012.5	14852.9	18865.4

Offtake canal data for Trimmu include:

- the crest level of the offtake canals is unknown and assumed to be that of the main barrage at 145.5 m (477.5 ft) above mean sea level;

- TS Link Line Canal is estimated to have 10 bays at 7.32 m (24 ft);
- Haveli Main Line Canal is estimated to have 5 bays at 7.32 m (24 ft); and
- Upper Rangpur Canal is estimated to have 3 bays at 7.32 m (24 ft).

Table 39 Trimmu Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Zero point, no water	468.0	0.0	0.0000	0	0	0	0
Under-sluice	472.0	4.0	0.0008	420	0	0	0
Main weir	477.5	9.5	0.0047	997	20266	0	20266
Intermediate point	477.8	9.8	0.0051	1033	22522	16486	39008
Intermediate point	481.1	13.1	0.0090	1377	43450	92634	136083
Intermediate point	484.4	16.4	0.0141	1721	66828	190104	256932
Intermediate point	487.7	19.7	0.0203	2065	91781	297815	389596
Lower operational level	490.5	22.5	0.0265	2358	114860	401238	516098
Upper operational Level	492.0	24.0	0.0302	2516	128019	461347	589366
H design	493.0	25.0	0.0328	2623	137142	503405	640546
H max	493.5	25.5	0.0341	2675	141700	524525	666225

Table 40 Trimmu Barrage maximum offtake summary model data

Level description	Level		Depth		TS Link discharge*		Haveli discharge*		Upper Rangpur discharge*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	142.6	468.0	0.000	0.0	0.0	0	0.0	0	0.0	0
Under-sluice	143.9	472.0	1.219	4.0	0.0	0	0.0	0	0.0	0
Main weir	145.5	477.5	2.896	9.5	0.0	0	0.0	0	0.0	0
Intermediate point	145.6	477.8	3.000	9.8	6.7	238	3.4	119	2.0	71
Intermediate point	146.6	481.1	4.000	13.1	232.0	8192	116.0	4096	69.6	2458
Intermediate point	147.6	484.4	5.000	16.4	610.1	21547	305.1	10773	183.0	6464
Intermediate point	148.6	487.7	6.000	19.7	1093.2	38606	546.6	19303	328.0	11582
Lower operational level	149.5	490.5	6.850	22.5	1571.7	55503	785.8	27751	471.5	16651
Upper operational Level	150.0	492.0	7.310	24.0	1853.7	65464	926.9	32732	556.1	19639
H design	150.3	493.0	7.620	25.0	2052.4	72479	1026.2	36240	615.7	21744
H max	150.4	493.5	7.772	25.5	2152.5	76014	1076.2	38007	645.7	22804

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.617. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Sidhnai

Sidhnai Barrage is set up in the IRSM with a static level-volume-area curve and a set operating target that only deviates for the cleaning period in January. Outlets on Sidhnai are modelled as gated spillways including SMB Link and Sidhnai Canals. Karanga Canal does not originate from Sidhnai Barrage but crossed over at this point.

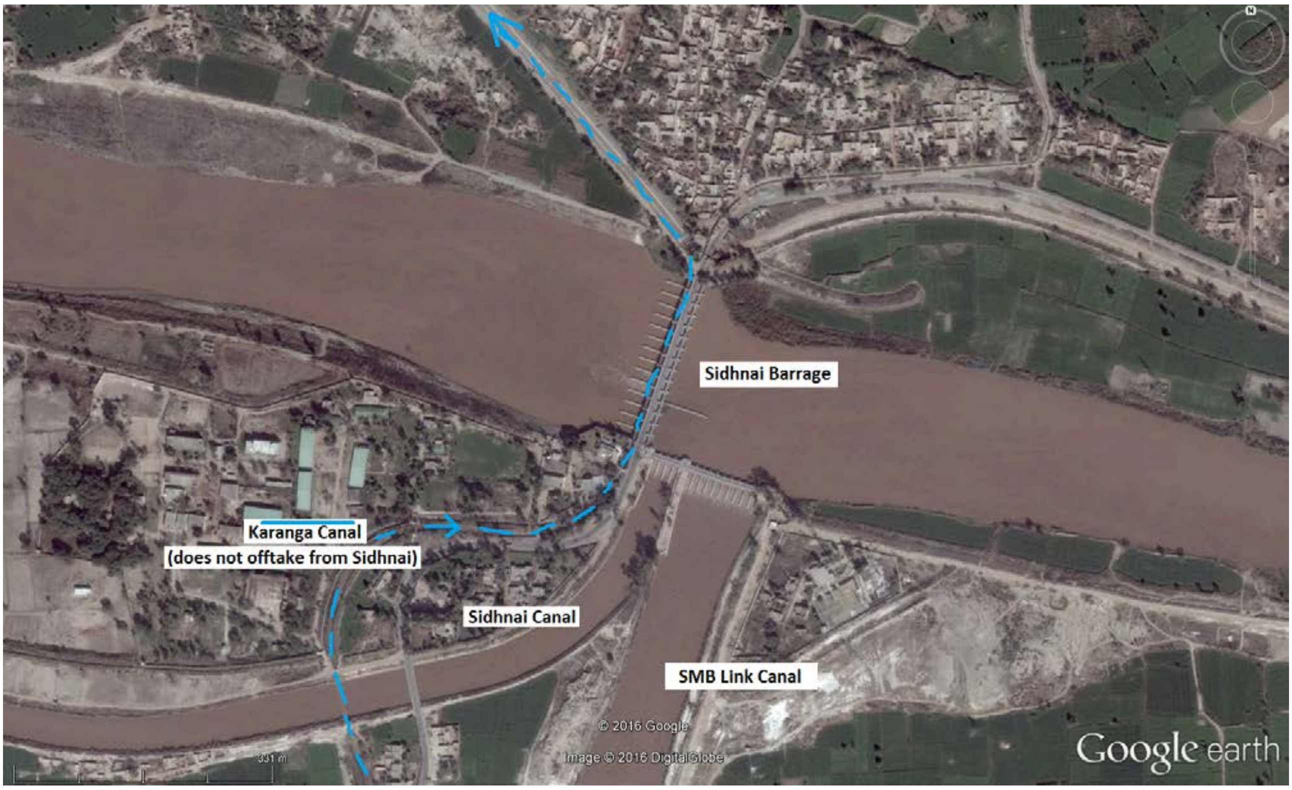


Figure 43 Sidhnai Barrage showing main barrage and offtake canals

Data provided for this study (IRSA 2015) include:

- the crest level of the main weir and under-sluice is 136.9 m (449 ft) above mean sea level;
- the upstream floor level is 133.2 m (437 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 16 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 11 standard bays on the main weir 12.192 m (40 ft) across;
- there are 4 unde-rsluice bays on the main weir 12.192 m (40 ft) across;
- the maximum design discharge for the barrage is 4247 m^3/s (150,000 ft^3/s) at 144.8 m (475 ft) above mean sea level; and
- historic water level time series for Sidhnai (2002-2012) indicate that barrage levels are held consistent throughout the year except for the annual cleaning period in January. Water level time series and an average weekly pattern derived from this dataset is shown in Figure 44. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

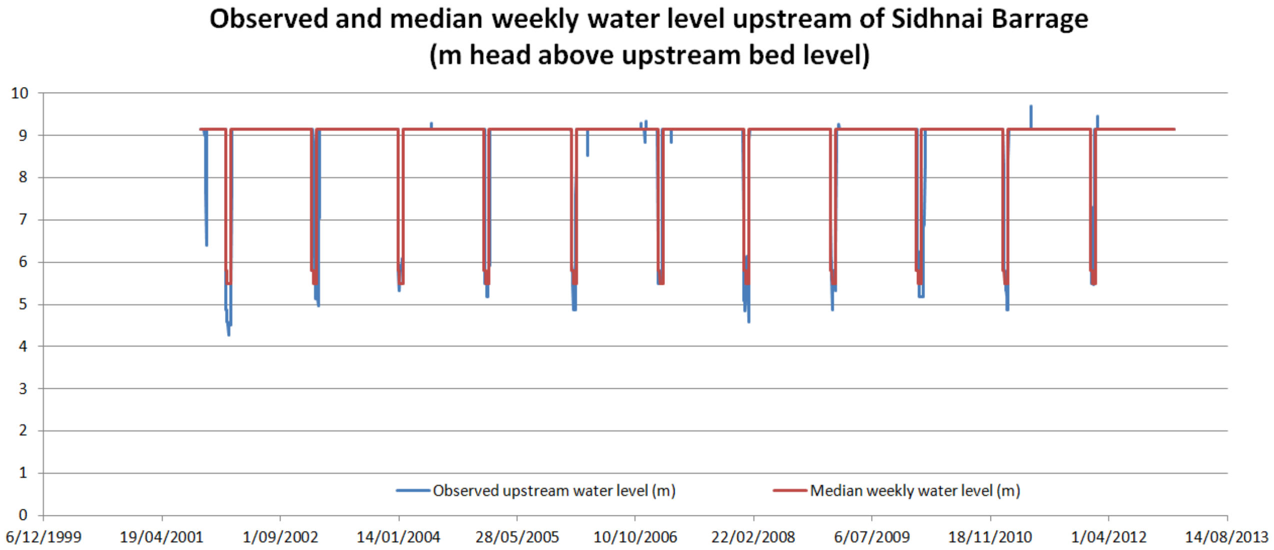


Figure 44 Sidhnai Barrage operational water level pattern

The storage level-volume-area relationship applied to Sidhnai Barrage, along with minimum and maximum barrage discharges (over the main weir), are provided in Table 41 and Table 42.

Table 41 Sidhnai Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	133.198	0.000	0	0	0.0	0.0	0.0
Under-sluice	136.855	3.658	2.582	141	0.0	0.0	0.0
Main weir	138.379	5.182	5.182	200	122.9	0.0	122.9
Additional point	139.198	6.000	6.948	232	231.4	138.4	369.7
SM Link and Sidhnai Canal Offtake	139.598	6.401	7.907	247	292.2	245.4	537.7
Additional point	140.198	7.000	9.457	270	391.6	439.6	831.2
Additional point	141.198	8.000	12.352	309	577.6	837.9	1415.6
Additional point	141.698	8.500	13.944	328	679.3	1066.9	1746.2
Typical operational level	142.342	9.144	16.139	353	818.0	1387.8	2205.9
Maximum operational barrage level	142.646	9.449	17.231	365	886.7	1549.2	2435.9
Additional point	143.698	10.500	21.278	405	1136.9	2149.3	3286.3
Design maximum	144.780	11.582	25.891	447	1415.5	2832.1	4247.5

Offtake canal data for Sidhnai include:

- the crest level of the offtake canals is at 139.6 m (458 ft) above mean sea level;
- Sidhnai Canal has 4 bays at 7.32 m (24 ft); and
- SMB Link has 10 bays at 7.32 m (24 ft).

Table 42 Sidhnai Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Zero point, no water	437.0	0.0	0.0000	0	0	0	0
Under-sluice	449.0	12.0	0.0021	349	0	0	0
Main weir	454.0	17.0	0.0042	494	4341	0	4341
Additional point	456.7	19.7	0.0056	572	8171	4886	13056
SM Link and Sidhnai Canal Offtake	458.0	21.0	0.0064	611	10320	8668	18987
Additional point	460.0	23.0	0.0077	668	13829	15525	29353
Additional point	463.2	26.2	0.0100	763	20398	29592	49990
Additional point	464.9	27.9	0.0113	811	23988	37679	61667
Typical operational level	467.0	30.0	0.0131	872	28889	49011	77900
Maximum operational barrage level	468.0	31.0	0.0140	901	31312	54711	86023
Additional point	471.4	34.4	0.0173	1002	40151	75902	116053
Design max	475.0	38.0	0.0210	1105	49987	100013	150000

Table 43 Sidhnai Barrage offtake summary model data

Level description	Level		Depth		Sidhnai Canal*		SMB Link*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	133.2	437.0	0.000	0.0	0.0	0	0.0	0
Under-sluice	136.9	449.0	3.658	12.0	0.0	0	0.0	0
Main weir	138.4	454.0	5.182	17.0	0.0	0	0.0	0
Additional point	139.2	456.7	6.000	19.7	0.0	0	0.0	0
SM Link and Sidhnai Canal Offtake	139.6	458.0	6.401	21.0	0.0	0	0.0	0
Additional point	140.2	460.0	7.000	23.0	35.2	1242	88.0	3106
Additional point	141.2	463.2	8.000	26.2	153.4	5417	383.5	13543
Additional point	141.7	464.9	8.500	27.9	230.7	8147	576.8	20368
Typical operational level	142.3	467.0	9.144	30.0	344.6	12171	861.6	30427
Maximum operational barrage level	142.6	468.0	9.449	31.0	403.6	14254	1009.1	35636
Additional point	143.7	471.4	10.500	34.4	629.5	22232	1573.9	55580
Design max	144.8	475.0	11.582	38.0	894.7	31595	2236.7	78989

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.585. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Jinah (Kalabagh)

Jinah (Kalabagh) Barrage is set up in the IRSM with a static level-volume-area curve and a set operating target that includes the cleaning period in January/early February. Outlets on Jinah include gated spillways for the main barrage and Thal canal, in addition to a hydropower valve on the main barrage (2012).

Figure 45 Jinah Barrage showing main barrage 2012 hydropower and Thal Canal offtake

Data provided for this study (IRSA 2015) include:

- the crest level of the main weir is 206.7 m (678 ft) above mean sea level;
- the crest level of the under-sluice is 205.7 m (675 ft) above mean sea level;
- the upstream floor level is 205.1 m (673 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 45 km^3 at operational water level has been inferred from aerial photography and barrage width and depth;
- there are 42 standard bays on the main weir 18.288 m (60 ft) across;
- there are 14 under-sluice bays on the main weir 18.288 m (60 ft) across;
- the maximum discharge for the barrage is 31148 m^3/s (1,100,000 ft^3/s) at 211.5 m (694 ft) above mean sea level; and
- historic water level time series for Jinah (2002-2012) indicate that barrage levels are held relatively consistent throughout the year with the main exception being for the annual cleaning period in late January to early February. Water level time series and an average weekly pattern derived from this dataset is shown in Figure 46. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

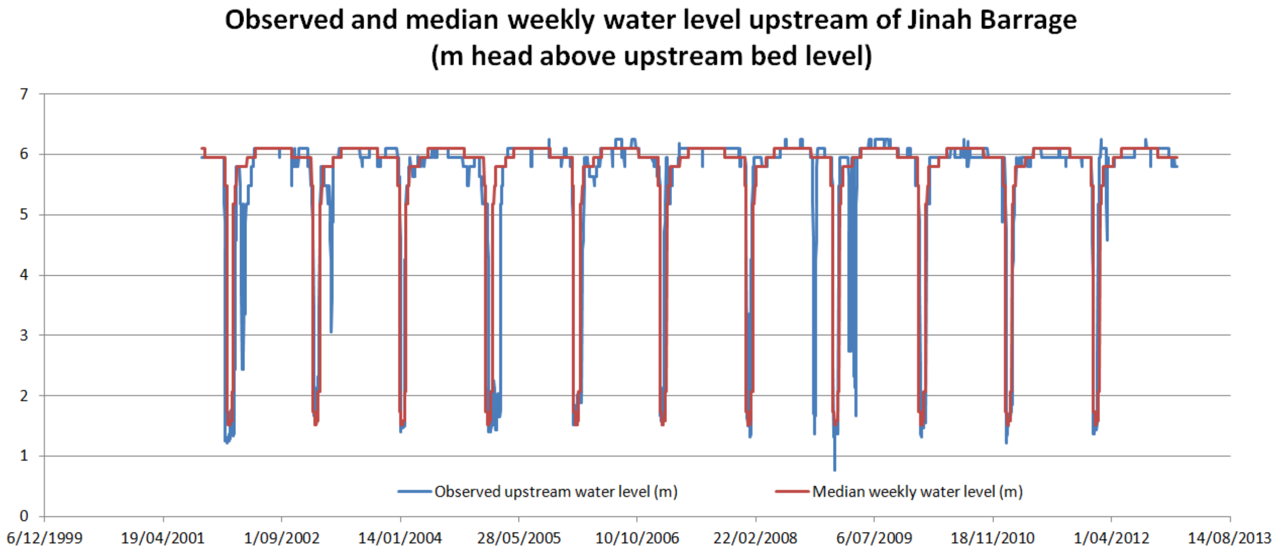


Figure 46 Jinah Barrage operational water level pattern

The storage level-volume-area relationship applied to Jinah Barrage, along with minimum and maximum barrage discharges (over the main weir), are provided in Table 44 and Table 45.

Table 44 Jinah Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km³	Surface area (estimate) ha	Under-sluice discharge m³/s	Main weir discharge m³/s	Hydro discharge m³/s
Zero point, no water	205.130	0.000	0	0	0.0	0.0	0.0
Hydroelectric*	205.331	0.201	0.051	51	0.0	0.0	0.0
Under-sluice level, dead storage	205.740	0.610	0.474	155	0.0	0.0	45.6
Main Weir and Thal Canal	206.654	1.524	2.965	389	458.4	0.0	265.4
Intermediate point	207.000	1.870	4.463	477	741.4	319.5	375.9
Intermediate point	208.000	2.870	10.513	733	1781.0	2454.7	760.3
Intermediate point	209.000	3.870	19.117	988	3085.6	5649.5	1225.5
Intermediate point	210.000	4.870	30.274	1243	4609.2	9623.6	1759.3
Intermediate point	210.500	5.370	36.811	1371	5444.0	11859.7	2049.3
Operational level	211.074	5.944	45.171	1520	6457.8	14611.8	2400.0
Maximum barrage level	211.531	6.401	52.237	1632	7305.7	16936.8	2692.2

Offtake canal data for Jinah include:

- the crest level of the offtake canals is assumed to be the same as the main weir at 206.7 m (678 ft) above mean sea level; and
- Thal Canal has 7 bays at 7.32 m (20 ft).

Table 45 Jinah Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Zero point, no water	673.0	0.0	0.0000	0	0	0	0
Hydroelectric*	673.7	0.7	0.0000	127	0	0	0
Under-sluice level, dead storage	675.0	2.0	0.0004	384	0	0	1610
Main Weir and Thal Canal	678.0	5.0	0.0024	962	16187	0	9374
Intermediate point	679.1	6.1	0.0036	1180	26183	11284	13277
Intermediate point	682.4	9.4	0.0085	1811	62896	86688	26851
Intermediate point	685.7	12.7	0.0155	2442	108965	199510	43278
Intermediate point	689.0	16.0	0.0245	3073	162771	339856	62128
Intermediate point	690.6	17.6	0.0298	3388	192253	418822	72371
Operational level	692.5	19.5	0.0366	3756	228056	516010	84755
Maximum barrage level	694.0	21.0	0.0423	4033	257997	598116	95075

Table 46 Jinah Barrage offtake summary model data

Level description	Level		Depth		Thal Canal*	
	m	ft	m	ft	m^3/s	ft^3/s
Zero point, no water	205.1	673.0	0.000	0.0	0.0	0
Hydroelectric*	205.3	673.7	0.201	0.7	0.0	0
Under-sluice level, dead storage	205.7	675.0	0.610	2.0	0.0	0
Main Weir and Thal Canal	206.7	678.0	1.524	5.0	0.0	0
Intermediate point	207.0	679.1	1.870	6.1	23.0	811
Intermediate point	208.0	682.4	2.870	9.4	176.5	6232
Intermediate point	209.0	685.7	3.870	12.7	406.1	14343
Intermediate point	210.0	689.0	4.870	16.0	691.8	24432
Intermediate point	210.5	690.6	5.370	17.6	852.6	30109
Operational level	211.1	692.5	5.944	19.5	1050.4	37095
Maximum barrage level	211.5	694.0	6.401	21.0	1217.6	42998

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.598. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Taunsa

Taunsa Barrage is set up in the IRSM with a static level-volume-area curve and a set operating target that includes the cleaning period in January/early February. Outlets on Taunsa include gated spillways for the main barrage, under-sluices and navigation locks, in addition to TP link, D.G. Khan and Muzzafaragah canals. Kachhi canal has also been included in the model structure but is treated as non-operational during the modelling period.

Figure 47 Taunsa Barrage showing main barrage and offtakes

Data provided for this study include:

- the crest level of the main weir is 130.5 m (428 ft) above mean sea level;
- the crest level of the under-sluice is 129.5 m (425ft) above mean sea level;
- the upstream floor level is 128.3 m (421 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 170 km^3 at operational water level has been estimated to coincide with approximately 2 days canal supply;
- there are 53 standard bays (not including the fish ladders) on the main weir 18.288 m (60 ft) across;
- there are 11 under-sluice bays on the main weir 18.288 m (60 ft) across;
- there is one navigation lock at approximately 6.7m (22 ft) across;
- the maximum discharge for the barrage is 28316 m^3/s (1,000,000 ft^3/s) at 136.2 m (446.8 ft) above mean sea level; and
- water level time series and an average weekly pattern derived from this dataset is shown in Figure 48. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

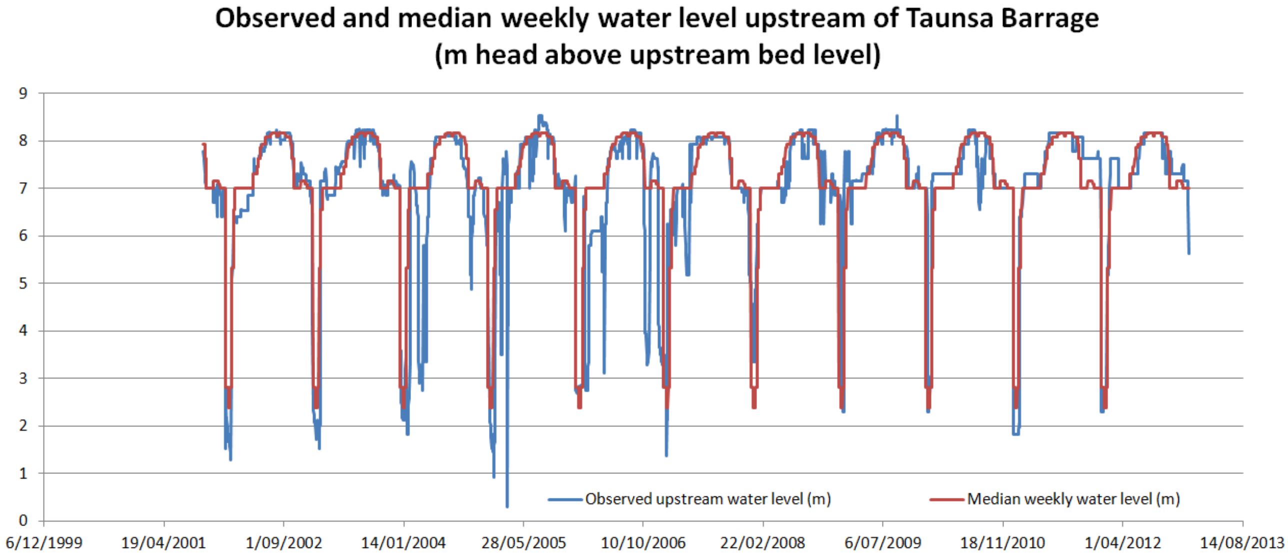


Figure 48 Taunsa Barrage operational water level pattern

The storage level-volume-area relationship applied to Taunsa Bbarrage, along with minimum and maximum barrage discharges (over the main weir), are provided in Table 47 and Table 48.

Table 47 Taunsa Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	128.321	0.000	0	0	0.0	0.0	0.0
Under-sluice level	129.540	1.219	0.221	36	0.0	0.0	0.0
Main weir level and off taking canals	130.454	2.134	1.586	149	258.0	0.0	258.0
Intermediate point	131.454	3.134	6.137	392	781.7	1703.0	2484.7
Intermediate point	132.454	4.134	16.274	787	1468.2	4816.8	6285.1
Intermediate point	133.454	5.134	34.897	1360	2285.4	8849.1	11134.5
Intermediate point	134.454	6.134	65.304	2129	3214.9	13624.1	16839.0
Intermediate point	135.454	7.134	111.146	3116	4244.6	19040.2	23284.8
Normal operating Level	135.941	7.620	140.203	3680	4778.8	21885.1	26663.9
Maximum design barrage level	136.185	7.864	156.647	3984	5054.4	23360.2	28414.6
Maximum barrage level	136.550	8.230	183.840	4468	5477.5	25632.1	31109.6

Offtake canal data for Taunsa include:

- the crest level of the offtake canals is assumed to be the same as the main weir at 130.5 m (428 ft) above mean sea level;
- T P Link Canal is estimated to have 7 bays at 7.32 m (24 ft) width;
- Muzaffaragarh Canal is estimated to have 5 bays at 7.32 m (24 ft) width; and
- D G Khan Canal is estimated to have 7 bays at 7.32 m (24 ft) width.

Table 48 Taunsa Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Zero point, no water	421.0	0.0	0.0000	0	0	0	0
Under-sluice level	425.0	4.0	0.0002	90	0	0	0
main weir level and off taking canals	428.0	7.0	0.0013	367	9112	0	9112
Intermediate point	431.3	10.3	0.0050	968	27604	60141	87745
Intermediate point	434.6	13.6	0.0132	1946	51850	170105	221955
Intermediate point	437.8	16.8	0.0283	3360	80708	312503	393212
Intermediate point	441.1	20.1	0.0529	5262	113534	481130	594664
Intermediate point	444.4	23.4	0.0901	7700	149895	672400	822295
Normal operating Level	446.0	25.0	0.1137	9093	168761	772865	941626
Maximum design barrage level	446.8	25.8	0.1270	9845	178496	824958	1003454
Maximum barrage level	448.0	27.0	0.1490	11040	193435	905190	1098625

Table 49 Taunsa Barrage offtake summary model data

Level description	Level		Depth		TP Link Canal*		Muzaffargarh*		D G Khan*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	128.3	421.0	0.000	0.0	0.0	0	0.0	0	0.0	0
Under-sluice level	129.5	425.0	1.219	4.0	0.0	0	0.0	0	0.0	0
Main weir level and off taking canals	130.5	428.0	2.134	7.0	0.0	0	0.0	0	0.0	0
Intermediate point	131.5	431.3	3.134	10.3	90.0	3177	64.3	2269	90.0	3177
Intermediate point	132.5	434.6	4.134	13.6	254.5	8987	181.8	6419	254.5	8987
Intermediate point	133.5	437.8	5.134	16.8	467.5	16510	333.9	11793	467.5	16510
Intermediate point	134.5	441.1	6.134	20.1	719.8	25418	514.1	18156	719.8	25418
Intermediate point	135.5	444.4	7.134	23.4	1005.9	35523	718.5	25374	1005.9	35523
Normal operating level	135.9	446.0	7.620	25.0	1156.2	40831	825.9	29165	1156.2	40831
Maximum design barrage level	136.2	446.8	7.864	25.8	1234.1	43583	881.5	31130	1234.1	43583

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.595. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Sindh Barrages

Guddu

Guddu Barrage is the first of three Sindh Barrages and is set up in the IRSM with a static Level-volume-area curve and a set operating target that includes the cleaning period in April, just before the expected Kharif flows. Outlets on Guddu include gated spillways for the main barrage, undersluices and navigation lock, in addition to Desert and Pat feeder, Begari Canal and Ghokti Feeder. Raini Canal has also been included in the IRSM but is treated as a flood canal during the modelling period.

Figure 49 Guddu Barrage showing main barrage and offtakes

Data provided for this study include:

- the crest level of the main weir is 71.9 m (236 ft) above mean sea level;
- the crest level of the undersluice is 71.8 m (235.5 ft) above mean sea level;
- the upstream floor level is 69.5 m (228 ft) above mean sea level;
- no storage capacity information was available for this study, however a volume of approximately 300 km^3 at operational water level has been estimated based on aerial photography and water depth;
- there are 54 standard bays (not including the fish ladders or navigation lock) on the main weir 18.288 m (60 ft) across;
- there are 10 undersluice bays on the main weir 18.288 m (60 ft) across;
- there is 1 navigation lock at approximately 15.24m (50 ft) across;
- the maximum discharge for the barrage is 33980 m^3/s (1,200,000 ft^3/s) at 79 m (259.3 ft) above mean sea level; and
- water level time series and an average weekly pattern derived from this dataset are shown in Figure 50. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

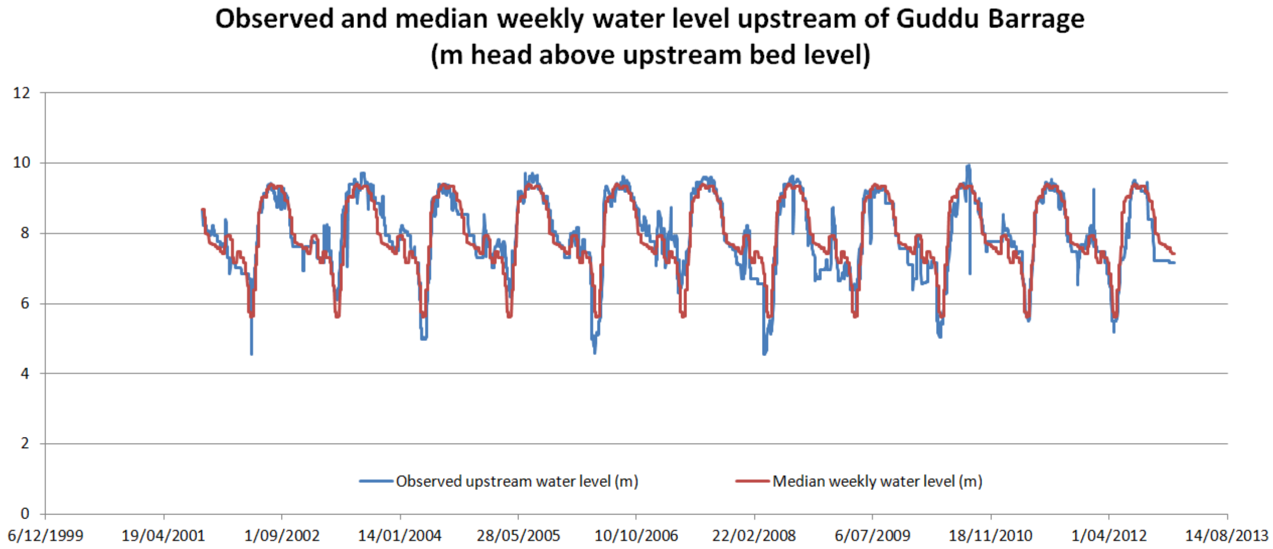


Figure 50 Guddu Barrage operational water level pattern

The storage level-volume-area relationship applied to Guddu Barrage, along with minimum and maximum barrage discharges (over the main weir and undersluices) which have been provided for this study are presented in Table 50 and Table 51.

Table 50 Guddu Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) ha	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	69.494	0.000	0	0	0.0	0.0	0.0
Intermediate point	70.694	1.200	9.636	1606	0.0	0.0	0.0
Under-sluice level, dead storage	71.780	2.286	26.586	2326	0.0	0.0	0.0
Main weir	71.933	2.438	29.590	2427	20.0	0.0	20.0
Intermediate point	72.494	3.000	41.990	2799	202.6	67.6	270.2
Intermediate point	73.494	4.000	69.245	3462	753.6	189.1	942.7
Desert and Pat feeder	74.541	5.046	104.855	4156	1540.2	472.7	2012.8
Intermediate point	75.494	6.000	143.642	4788	2403.9	1181.7	3585.6
Intermediate point	76.494	7.000	190.785	5451	3437.5	2127.0	5564.5
Intermediate point	77.494	8.000	244.557	6114	4587.3	6144.8	10732.1
Operating level	77.876	8.382	266.847	6367	5055.0	8744.5	13799.5
Intermediate point	78.494	9.000	304.958	6777	5842.8	16543.6	22386.4
Maximum level (design)	79.035	9.540	340.348	7135	6562.0	27418.2	33980.2
Maximum level	79.858	10.363	397.974	7681	7709.8	30723.8	38433.6

Table 51 Guddu Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft³/s	Main weir discharge ft³/s	Hydro discharge ft³/s
zero point, no water	228.0	0.0	0.0000	0	0	0	0
Intermediate point	231.9	3.9	0.0078	3969	0	0	0
Under-sluice level, dead storage	235.5	7.5	0.0216	5748	0	0	0
Main weir	236.0	8.0	0.0240	5997	706	0	706
Intermediate point	237.8	9.8	0.0340	6917	7156	2387	9543
Intermediate point	241.1	13.1	0.0561	8555	26615	6677	33292
Desert and Pat feeder	244.6	16.6	0.0850	10269	54390	16692	71082
Intermediate point	247.7	19.7	0.1165	11832	84893	41731	126623
Intermediate point	251.0	23.0	0.1547	13470	121392	75116	196508
Intermediate point	254.2	26.2	0.1983	15108	162001	217000	379001
Operating level	255.5	27.5	0.2163	15734	178515	308808	487323
Intermediate point	257.5	29.5	0.2472	16746	206338	584232	790570
Maximum level (design)	259.3	31.3	0.2759	17631	231737	968263	1200000
Maximum level	262.0	34.0	0.3226	18979	272269	1085002	1357271

Offtake canal data for Guddu include:

- the crest level of all offtake canals (indicated by Pat and Desert feeder in the above tables) is 74.5 m (244.6 ft) above mean sea level and in the absence of further information, all other offtake canals are assumed to have the same crest level;
- Pat and Desert feeder is estimated to have 9 bays at 6.706 m (22 ft) width;
- Begari Canal is estimated to have 10 bays at 6.706 m (22 ft) width;
- Ghokti Canal is estimated to have 6 bays at 6.706 m (22 ft) width; and
- Begari Canal is estimated to have 8 bays at 6.706 m (22 ft) width.

Table 52 Guddu Barrage offtake summary model data

Level description	Level		Depth		Pat and Desert feeder		Begari*	
	m	ft	m	ft	m³/s	ft³/s	m³/s	ft³/s
Zero point, no water	69.5	228.0	0.000	0.0	0.0	0	0.0	0
Intermediate Point	70.7	231.9	1.200	3.9	0.0	0	0.0	0
Under-sluice level, dead storage	71.8	235.5	2.286	7.5	0.0	0	0.0	0
Main weir	71.9	236.0	2.438	8.0	0.0	0	0.0	0
Intermediate point	72.5	237.8	3.000	9.8	0.0	0	0.0	0
Intermediate point	73.5	241.1	4.000	13.1	0.0	0	0.0	0
Desert and Pat feeder	74.5	244.6	5.046	16.6	0.0	0	0.0	0
Intermediate point	75.5	247.7	6.000	19.7	123.7	4368	137.4	4854
Intermediate point	76.5	251.0	7.000	23.0	362.7	12807	403.0	14230
Intermediate point	77.5	254.2	8.000	26.2	674.1	23807	749.0	26452
Operating level	77.9	255.5	8.382	27.5	809.1	28571	898.9	31746
Intermediate point	78.5	257.5	9.000	29.5	1044.0	36868	1160.0	40965
Maximum level (design)	79.0	259.3	9.540	31.3	1265.1	44677	1405.7	49642

Table 53 Guddu Barrage offtake summary model data

Level description	Level		Depth		Ghokti		Raini*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	69.5	228.0	0.0	0.0	0.0	0	0.0	0
Intermediate point	70.7	231.9	1.2	3.9	0.0	0	0.0	0
Under-sluice level, dead storage	71.8	235.5	2.3	7.5	0.0	0	0.0	0
Main weir	71.9	236.0	2.4	8.0	0.0	0	0.0	0
Intermediate point	72.5	237.8	3.0	9.8	0.0	0	0.0	0
Intermediate point	73.5	241.1	4.0	13.1	0.0	0	0.0	0
Desert and Pat feeder	74.5	244.6	5.0	16.6	0.0	0	0.0	0
Intermediate point	75.5	247.7	6.0	19.7	82.5	2912	110.0	3883
Intermediate point	76.5	251.0	7.0	23.0	241.8	8538	322.4	11384
Intermediate point	77.5	254.2	8.0	26.2	449.4	15871	599.2	21162
Operating level	77.9	255.5	8.4	27.5	539.4	19048	719.2	25397
Intermediate point	78.5	257.5	9.0	29.5	696.0	24579	928.0	32772
Maximum level (design)	79.0	259.3	9.5	31.3	843.4	29785	1124.6	39713

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.595. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Sukkur

Sukkur Barrage is the second of three Sindh Barrages and is set up in the IRSM with a static level-volume-area curve and a set operating target that includes the cleaning period in January. Outlets on Sukkur include gated spillways for the main barrage and under-sluices, in addition to North West (Kirthar), Rice, Dadu, Nara, Khairpur East and West and Rhori Canal.

Figure 51 Sukkur Barrage showing main barrage and offtakes

Data sourced or provided and sourced for this study include:

- the crest level of the main weir is 54 m (177 ft) above mean sea level;
- the crest level of the under-sluice is 53.6 m (176 ft) above mean sea level;

- the upstream floor level is 52.1 m (171 ft) above mean sea level;
- limited storage capacity information was available for this study, however a volume of approximately 200 km^3 at maximum water level has been estimated based on aerial photography and water depth.
- there are 56 standard bays (not including the closed bays) on the main weir 18.288 m (60 ft) across;
- there are 12 under-sluice bays on the main weir 18.288 m (60 ft) across;
- the maximum discharge for the barrage is 42475.3 m^3/s (1,500,000 ft^3/s) at 62.3 m (204.5 ft) above mean sea level; and
- water level time series and an average weekly pattern derived from this dataset is shown in Figure 52. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

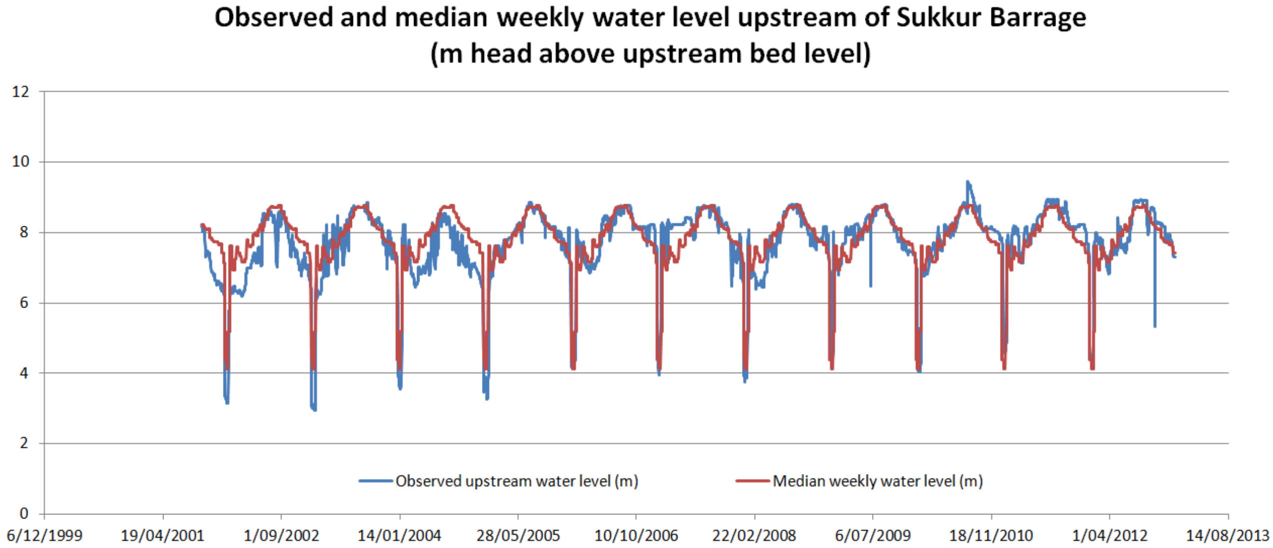


Figure 52 Sukkur Barrage operational water level pattern

The storage level-volume-area relationship applied to Sukkur Barrage, along with minimum and maximum barrage discharges (over the main weir and under-sluices) which have been calculated for this study, are presented in Table 54 and Table 55.

Table 54 Sukkur Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km^3	Surface area (estimate) h	Under-sluice discharge m^3/s	Main weir discharge m^3/s	Hydro discharge m^3/s
Zero point, no water	52.121	0.000	0	0	0.0	0.0	0.0
Under-sluice level, dead storage	53.645	1.524	4.191	550	0.0	0.0	0.0
Main weir	53.950	1.829	6.042	661	78.7	0.0	78.7
Intermediate point	55.000	2.879	15.011	1043	737.6	1351.0	2088.6
Intermediate point	56.000	3.879	27.275	1406	1690.0	3684.4	5374.4
Intermediate point	57.000	4.879	43.176	1770	2873.6	6685.7	9559.3
Offtake canals	58.061	5.940	64.026	2156	4339.6	10462.5	14802.0
Intermediate point	58.561	6.440	75.269	2337	5097.0	12427.8	17524.8
Intermediate point	59.061	6.940	87.420	2519	5894.0	14502.8	20396.8
Full supply discharge	59.284	7.163	93.116	2600	6260.7	15459.4	21720.1
Intermediate point	59.784	7.663	106.581	2782	7111.6	17683.3	24794.9
Intermediate point	60.284	8.163	120.954	2964	7997.9	20004.6	28002.6
Intermediate point	60.784	8.663	136.237	3145	8918.3	22419.5	31337.8
Intermediate point	61.284	9.163	152.428	3327	9871.4	24924.4	34795.8
Intermediate point	60.000	9.663	169.528	3509	10856.3	27516.2	38372.6
Max barrage design level	62.332	10.211	189.314	3708	11971.0	30453.4	42424.4

Table 55 Sukkur Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Undersluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s)
Zero point, no water	171.0	0.0	0.0000	0	0	0	0
Under-sluice level, dead storage	176.0	5.0	0.0034	1359	0	0	0
Main weir	177.0	6.0	0.0049	1633	2779	0	2779
Intermediate point	180.4	9.4	0.0122	2577	26050	47709	73759
Intermediate point	183.7	12.7	0.0221	3475	59681	130115	189796
Intermediate point	187.0	16.0	0.0350	4373	101479	236104	337583
Offtake canals	190.5	19.5	0.0519	5327	153251	369478	522729
Intermediate point	192.1	21.1	0.0610	5776	179999	438884	618884
Intermediate point	193.8	22.8	0.0709	6225	208145	512162	720307
Full supply discharge	194.5	23.5	0.0755	6425	221094	545944	767039
Intermediate point	196.1	25.1	0.0864	6874	251144	624480	875624
Intermediate point	197.8	26.8	0.0981	7323	282443	706457	988901
Intermediate point	199.4	28.4	0.1104	7772	314945	791738	1106683
Intermediate point	201.1	30.1	0.1236	8221	348606	880198	1228804
Intermediate point	196.9	31.7	0.1374	8671	383387	971727	1355114
Max barrage design level	204.5	33.5	0.1535	9163	422753	1075450	1498204

Offtake canal data for Sukkur include:

- the crest level of all offtake canals is assumed to be 58.1 m (190.5 ft) above mean sea level;
- Nara Canal is estimated to have 16 bays at 7.62 m (25 ft) width;
- Khairpur East is estimated to have 2 bays at 7.62 m (25 ft) width;
- Khairpur West is estimated to have 2 bays at 7.62 m (25 ft) width;
- Rhori is estimated to have 12 bays at 7.62 m (25 ft) width;

- North West Canal is estimated to have 6 bays at 7.62 m (25 ft) width;
- Rice is estimated to have 13 bays at 7.62 m (25 ft) width; and
- Dadu is estimated to have 4 bays at 7.62 m (25 ft) width.

Table 56 Sukkur Barrage offtake summary data (table 1 of 3)

Level description	Level		Depth		Nara*		Khairpur East*		Rhori*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	52.1	171.0	0.000	0.0	0.0	0	0.0	0	0.0	0
Under-sluice level, dead storage	53.6	176.0	1.524	5.0	0.0	0	0.0	0	0.0	0
Main weir	53.9	177.0	1.829	6.0	0.0	0	0.0	0	0.0	0
Intermediate point	55.0	180.4	2.879	9.4	0.0	0	0.0	0	0.0	0
Intermediate point	56.0	183.7	3.879	12.7	0.0	0	0.0	0	0.0	0
Intermediate point	57.0	187.0	4.879	16.0	0.0	0	0.0	0	0.0	0
Offtake canals	58.1	190.5	5.940	19.5	0.0	0	0.0	0	0.0	0
Intermediate point	58.6	192.1	6.440	21.1	124.1	4383	15.5	548	93.1	3287
Intermediate point	59.1	193.8	6.940	22.8	351.0	12396	43.9	1550	263.3	9297
Full supply discharge	59.3	194.5	7.163	23.5	474.4	16753	59.3	2094	355.8	12565
Intermediate point	59.8	196.1	7.663	25.1	793.5	28021	99.2	3503	595.1	21016
Intermediate point	60.3	197.8	8.163	26.8	1163.0	41069	145.4	5134	872.2	30802
Intermediate point	60.8	199.4	8.663	28.4	1576.7	55682	197.1	6960	1182.6	41762
Intermediate point	61.3	201.1	9.163	30.1	2030.5	71706	253.8	8963	1522.9	53780
Intermediate point	60.0	196.9	9.663	31.7	2521.0	89027	315.1	11128	1890.7	66770
Max barrage design level	62.3	204.5	10.211	33.5	3097.7	109394	387.2	13674	2323.3	82045

Table 57 Sukkur Barrage offtake summary data (table 2 of 3)

Level description	Level		Depth		Khairpur West*		Dadu*		Rice*	
	m	ft	m	ft	m^3/s)	ft^3/s	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	52.1	171.0	0.0	0.0	0.0	0	0.0	0	0.0	0
Under-sluice level, dead storage	53.6	176.0	1.5	5.0	0.0	0	0.0	0	0.0	0
Main weir	53.9	177.0	1.8	6.0	0.0	0	0.0	0	0.0	0
Intermediate point	55.0	180.4	2.9	9.4	0.0	0	0.0	0	0.0	0
Intermediate point	56.0	183.7	3.9	12.7	0.0	0	0.0	0	0.0	0
Intermediate point	57.0	187.0	4.9	16.0	0.0	0	0.0	0	0.0	0
Offtake canals	58.1	190.5	5.9	19.5	0.0	0	0.0	0	0.0	0
Intermediate point	58.6	192.1	6.4	21.1	15.5	548	31.0	1096	100.8	3561
Intermediate point	59.1	193.8	6.9	22.8	43.9	1550	87.8	3099	285.2	10072
Full supply discharge	59.3	194.5	7.2	23.5	59.3	2094	118.6	4188	385.5	13612
Intermediate point	59.8	196.1	7.7	25.1	99.2	3503	198.4	7005	644.7	22767
Intermediate point	60.3	197.8	8.2	26.8	145.4	5134	290.7	10267	944.9	33369
Intermediate point	60.8	199.4	8.7	28.4	197.1	6960	394.2	13921	1281.1	45242
Intermediate point	61.3	201.1	9.2	30.1	253.8	8963	507.6	17927	1649.8	58261
Intermediate point	60.0	196.9	9.7	31.7	315.1	11128	630.2	22257	2048.3	72335
Maximum barrage design level	62.3	204.5	10.2	33.5	387.2	13674	774.4	27348	2516.9	88882

Table 58 Sukkur Barrage offtake summary data (table 3 of 3)

Level description	Level		Depth		North West*	
	m	ft	m	ft	m^3/s	ft^3/s
Zero point, no water	52.1	171.0	0.0	0.0	0.0	0
Under-sluice level, dead storage	53.6	176.0	1.5	5.0	0.0	0
Main weir	53.9	177.0	1.8	6.0	0.0	0
Intermediate point	55.0	180.4	2.9	9.4	0.0	0
Intermediate point	56.0	183.7	3.9	12.7	0.0	0
Intermediate point	57.0	187.0	4.9	16.0	0.0	0
Offtake canals	58.1	190.5	5.9	19.5	0.0	0
Intermediate point	58.6	192.1	6.4	21.1	46.5	1644
Intermediate point	59.1	193.8	6.9	22.8	131.6	4649
Full supply discharge	59.3	194.5	7.2	23.5	177.9	6282
Intermediate point	59.8	196.1	7.7	25.1	297.5	10508
Intermediate point	60.3	197.8	8.2	26.8	436.1	15401
Intermediate point	60.8	199.4	8.7	28.4	591.3	20881
Intermediate point	61.3	201.1	9.2	30.1	761.4	26890
Intermediate point	60.0	196.9	9.7	31.7	945.4	33385
Maximum barrage design level	62.3	204.5	10.2	33.5	1161.6	41023

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.650. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Kotri

Kotri Barrage is the third Sindh Barrage and is set up in the IRSM with a static level-volume-area curve and a set operating target that includes the cleaning period in January. Outlets on Kotri include gated spillways for the main barrage and under-sluices, in addition to Kalri Beghar Feeder, Lined Canal (Akram Wah Canal), Fuleli Canal and Pinyari Canal.

Figure 53 Kotri Barrage showing main barrage and offtakes

Data sourced or provided and sourced for this study include:

- the crest level of the main weir is 14.6 m (48 ft) above mean sea level;
- the crest level of the undersluice is 14.6 m (48 ft) above mean sea level;
- the upstream floor level is 11.6 m (38 ft) above mean sea level;
- limited storage capacity information was available for this study, however a volume of approximately 200 km^3 at maximum water level has been estimated;
- there are 34 standard bays on the main weir 18.288 m (60 ft) across;
- there are 10 undersluice bays on the main weir 18.288 m (60 ft) across;
- the maximum discharge for the barrage is 24777 m^3/s (875000 ft^3/s) at 21.6 m (71 ft) above mean sea level; and
- historic water level time series for Kotri (2002-2012) indicate that barrage levels can vary throughout the year corresponding with river flows with the highest barrage levels corresponding with the highest flows. Water level time series and an average weekly pattern derived from this dataset are shown in Figure 54. The weekly pattern is used in the IRSM as the operational water level target for the barrage.

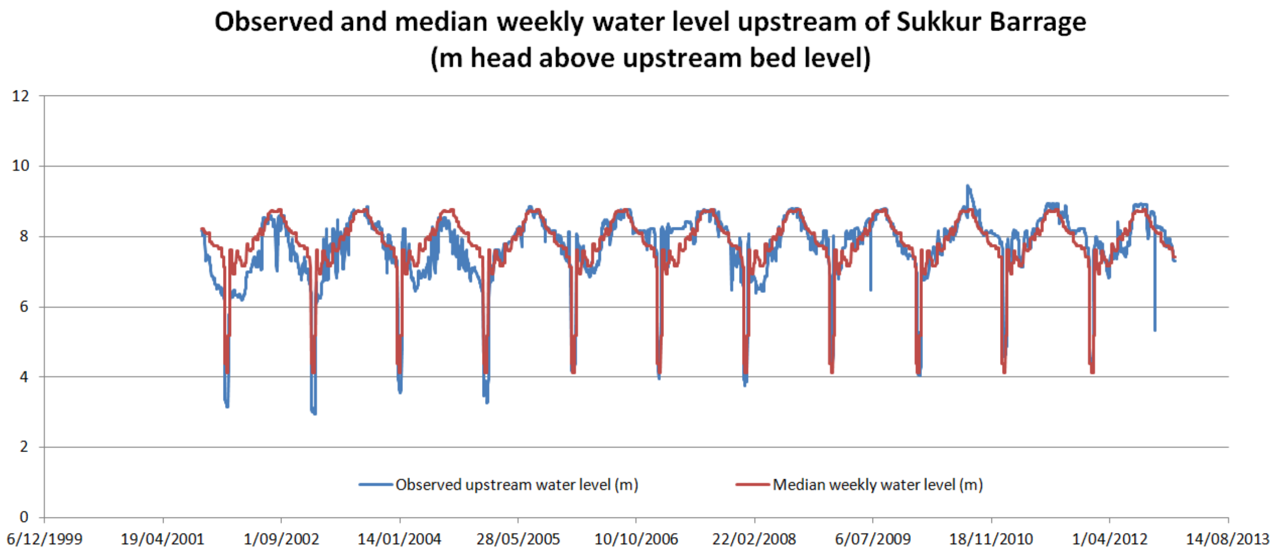


Figure 54 Kotri Barrage operational water level pattern

Table 59 Kotri Barrage summary model data (metric units)

Level description	Level above mean sea m	Depth m	Volume (estimate) km³	Surface area (estimate) ha	Under-sluice discharge m³/s	Main weir discharge m³/s	Hydro discharge m³/s
Zero point, no water	11.582	0.000	0	0	0.0	0.0	0.0
Intermediate	13.082	1.500	3.338	445	0.0	0.0	0.0
Under-sluice level, dead storage	14.630	3.048	13.594	892	0.0	0.0	0.0
Intermediate point	15.582	4.000	23.266	1163	267.3	946.5	1213.8
Intermediate point	16.582	5.000	36.208	1448	784.7	2779.1	3563.7
Intermediate point	17.582	6.000	51.999	1733	1459.3	5168.4	6627.7
Pinyari/Fuleli offtake	18.839	7.257	75.893	2092	2484.6	8799.5	11284.0
Lined canal	19.081	7.499	81.001	2160	2701.5	9567.8	12269.2
Kalri feeder	19.522	7.940	90.756	2286	3112.9	11024.9	14137.8
Intermediate point	20.082	8.500	103.947	2446	3662.7	12972.1	16634.8
Intermediate point	20.582	9.000	116.474	2588	4178.0	14796.9	18974.9
Intermediate point	21.082	9.500	129.713	2731	4715.3	16700.1	21415.4
Full supply discharge	21.427	9.845	139.265	2829	5098.6	18057.5	23156.1
Maximum barrage level	21.641	10.058	145.344	2890	5340.5	18914.4	24254.9

Table 60 Kotri Barrage summary model data (imperial units)

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft³/s	Main weir discharge ft³/s	Hydro discharge ft³/s
Zero point, no water	38.0	0.0	0.0000	0	0	0	0
Intermediate point	42.9	4.9	0.0027	1100	0	0	0
Under-sluice level, dead storage	48.0	10.0	0.0110	2204	0	0	0
intermediate point	51.1	13.1	0.0189	2875	9438	33426	42864
intermediate point	54.4	16.4	0.0294	3579	27711	98141	125852
intermediate point	57.7	19.7	0.0422	4283	51535	182519	234053
Pinyari/Fuleli offtake	61.8	23.8	0.0615	5168	87741	310750	398491
Lined canal	62.6	24.6	0.0657	5338	95402	337882	433284

Level description	Level above mean sea ft	Depth ft	Volume (estimate) MAF	Surface area (estimate) acres	Under-sluice discharge ft^3/s	Main weir discharge ft^3/s	Hydro discharge ft^3/s
Kalri feeder	64.0	26.0	0.0736	5649	109931	389339	499270
Intermediate point	65.9	27.9	0.0843	6044	129348	458107	587454
Intermediate point	67.5	29.5	0.0944	6396	147543	522549	670092
Intermediate point	69.2	31.2	0.1052	6748	166520	589759	756279
Full supply discharge	70.3	32.3	0.1129	6991	180055	637694	817749
Maximum barrage level	71.0	33.0	0.1178	7141	188599	667955	856553

Offtake canal data for Kotri include:

- the crest level of offtake canals ranges from 18.839-19.522 m (61.8 ft to 64 ft) above mean sea level.

Table 61 Kotri Barrage summary offtake data

Level description	Level		Depth		KB Feeder*		Pinyari Fuleli Feeder*		Lined Canal*	
	m	ft	m	ft	m^3/s	ft^3/s	m^3/s	ft^3/s	m^3/s	ft^3/s
Zero point, no water	11.6	38.0	0.000	0.0	0	0	0.0	0	0.0	0
Intermediate	13.1	42.9	1.500	4.9	0	0	0.0	0	0.0	0
Undersluice level, dead storage	14.6	48.0	3.048	10.0	0	0	0.0	0	0.0	0
Intermediate point	15.6	51.1	4.000	13.1	0	0	0.0	0	0.0	0
Intermediate point	16.6	54.4	5.000	16.4	0	0	0.0	0	0.0	0
Intermediate point	17.6	57.7	6.000	19.7	0	0	0.0	0	0.0	0
Pinyari/Fuleli offtake	18.8	61.8	7.257	23.8	0	0	0.0	0	0.0	0
Lined Canal	19.1	62.6	7.499	24.6	0	0	23.0	813	0.0	0
Kalri feeder	19.5	64.0	7.940	26.0	0	0	109.3	3861	9.5	334
Intermediate point	20.1	65.9	8.500	27.9	3511	1435	268.6	9484	32.4	1143
Intermediate point	20.6	67.5	9.000	29.5	9141	3736	446.0	15749	59.4	2099
Intermediate point	21.1	69.2	9.500	31.2	16317	6670	651.0	22991	91.5	3230
Full supply discharge	21.4	70.3	9.845	32.3	22019	9000	806.9	28495	116.1	4100
Maximum barrage level	21.6	71.0	10.058	33.0	25820	10553	908.7	32090	132.3	4672

* Discharge refers to maximum theoretical discharge applying with coefficient of discharge = 0.561. Downstream canal capacity (and water orders) will limit this theoretical discharge and is factored into canal maximum order constraint nodes in the model.

Canal command operations

Water flows to canal commands are facilitated through water orders that originate at *Minimum Flow Requirement* nodes. Water orders therefore drive the model operation and flows in the canal commands. Without water orders most canals and irrigation areas would not receive any flows due to the way the barrages are set up to typically only release the water that is ordered from upstream.

Water releases to canals are also tempered by the canal capacity (maximum order constraint node), the capacity of the gates releasing the water to the canal (in the Barrage Configuration) and the head in the barrage.

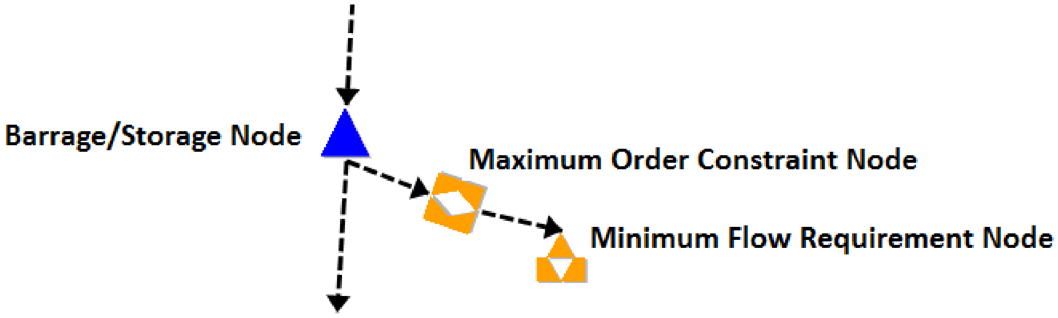


Figure 55 The Minimum Flow Requirement node (in Source) contains the orders that request water from upstream

Water orders in the IRSM can be generated in two ways: directly from entitlement time series obtained from provincial water departments and directly from the Water Apportionment Accord and subsequent provincial allocation to canal commands; or a mixture of either way. The implementation of the Water Apportionment Accord and provincial allocation is described later.

Water orders or entitlements are incorporated in the IRSM as time series demands at *Minimum Flow Requirement* nodes. These time series are either the actual 10-daily entitlement time series or 10-daily entitlement time series generated from the Water Apportionment Accord as described above and in proceeding sections. The 10-daily entitlement time series data have been interpolated to daily time series for the purposes of the IRSM.

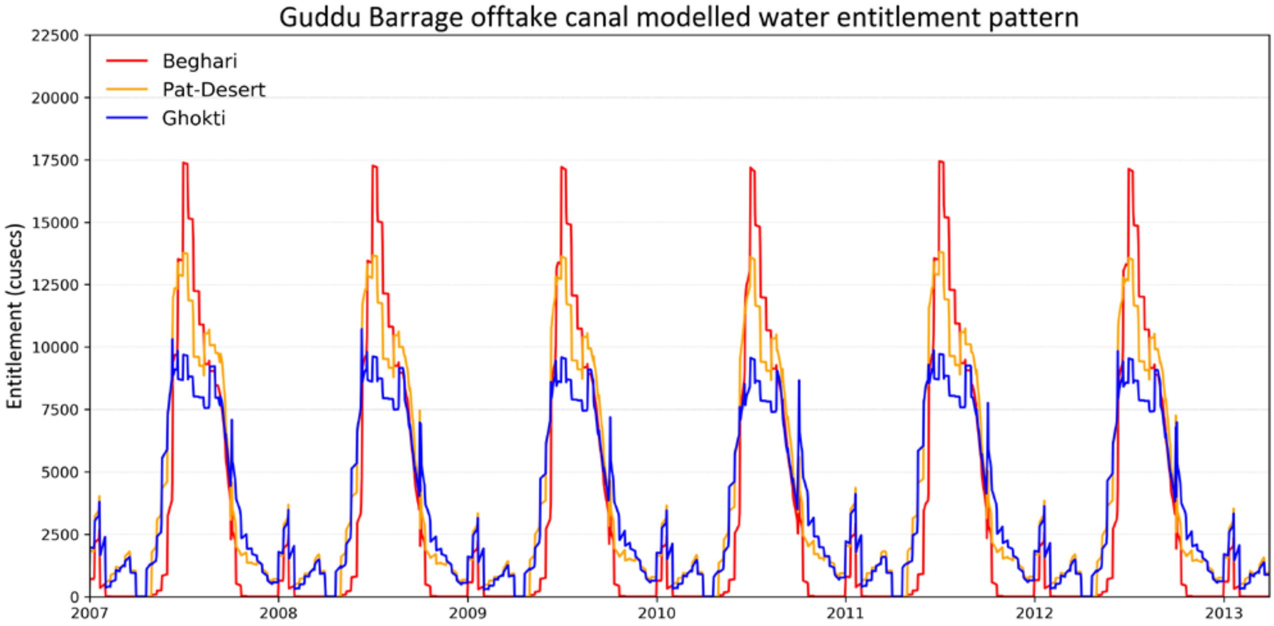


Figure 56 Example modelled canal command water entitlements at Guddu Barrage

Maximum order constraint nodes are used in the model to limit orders to the canal capacity. These have been used primarily on canals off taking from barrages and link canals. Limiting the orders allowed to pass up the canal ensures that the canal capacities are respected, and additional orders need to find an alternate route to the nearest storage if the canal capacity is already met.

2.9.4 Splitters and river confluences

Splitter nodes

Splitter nodes are used in the IRSM at several locations to split the water flow. Typically, these are used at locations where canal commands off take from a link canal, such as Lower Dipalpur (Figure 57). The most common setup for diversion nodes is to allow the water orders from downstream to set when water is diverted.

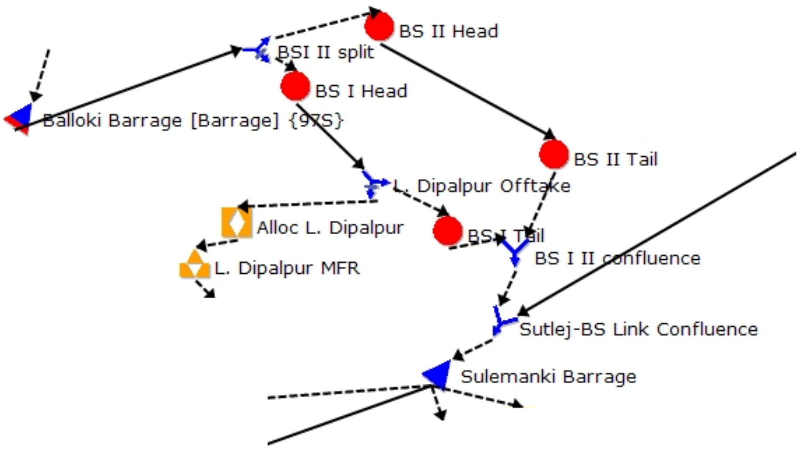


Figure 57 Example splitter node splitting water flows between BS Link I and II and Lower Dipaplur Command

Confluence nodes

Confluence nodes are a key feature of Source and are the principal mechanism by which orders (and hence water deliveries) are configured in the IRSM. Confluence nodes provide the opportunity to select the upstream branches of the river or canal that are most appropriate for the orders to pass. Three confluence node configurations are used in the IRSM:

- both upstream branches regulated, priorities set for both branches with the lowest priority assigned to the branch where orders are preferred to be sent. Using the example from Figure 57, the BS I II confluence sends water orders from Sulemanki up both BS Link branches, but with priority to BS Link I;
- one upstream branch regulated. The branch with regulation accepts and passes the orders up the model, however the other branch is not regulated. When the flows come down the unregulated branch, these flows can be used to fulfil a water order, but the water is not relied upon. The Sutlej - BS Link confluence (Figure 57) is an example of this configuration. Water orders are directed up the BS Link canals, and any flows down the Sutlej are used to fill any orders but are not relied upon;
- no upstream regulated branches. This can be used upstream of a storage where orders are terminated, such as Chashma or Islam Barrages. This ensures orders are fulfilled by the water in the barrage and not passed further up the model.

The confluence node setup is critical to the correct operation of the model. Priority data for major confluence nodes in the IRSM is presented in Figure 22.

2.9.5 Links and Link Routing

Links in Source enable water to flow from one node to another. Links in the IRSM are set up in one of three ways:

- straight through routing (no hydrograph translation or losses from upstream to downstream);
- storage routing with piecewise lag curves (allows hydrograph attenuation and losses, where calibration data are available); and
- storage routing with generic routing parameters (allows hydrograph attenuation and losses, where calibration data are *not* available).

Links provide a means to calibrate instream losses in the IRSM and are therefore very important components when considering mass balance across the entire system.

2.10 Implementation of water sharing rules

2.10.1 Implementation of the Water Apportionment Accord (1991)

Understanding the seasonal forecasting, allocation and distribution of Indus waters is a key water resource planning and operational requirement in Pakistan. Implementation of the Water Apportionment Accord 1991 (the Accord) principles is essential to the planning and operational procedures and therefore must be included in the IRSM.

The Accord is the cornerstone of the agreed distribution of the surface water resources of the Indus between the four Provinces of Balochistan, Khyber Pakhtunkhwa, Punjab and Sindh. The Accord sets out in 14 paragraphs how the surface water of the Indus is to be shared and the relative seasonal patterns of those shares.

Practical implementation of the Accord and associated seasonal forecasting and seasonal distribution is undertaken in the IRSM using Functions. The functions implemented to model the forecasting, allocation and seasonal distribution of water resources are expansive and complex. As such, the IRSM functions have been grouped into subfolders or blocks for ease of navigation and transparency. These blocks represent the major calculation steps or processes that form the cornerstone of the seasonal resource assessment and agreed distribution of water throughout the system.

There are 9 function blocks (Figure 58) associated with this part of the model. Their key features, purpose and relationship to other blocks are summarised below.

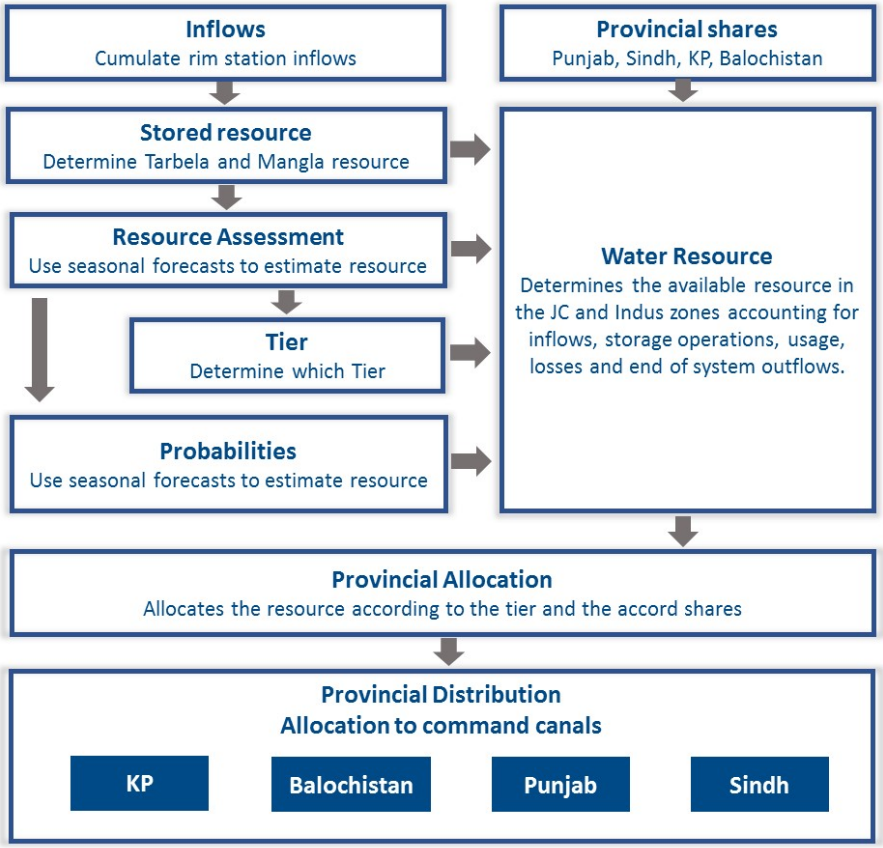


Figure 58 IRSM water forecasting, allocation and distribution system function blocks

Inflows Block

The Inflows Block contains functions that accumulate seasonal inflows over a defined period for each of the rim stations (Kabul, Indus, Jhelum, Chenab) and the two eastern rivers: Sutlej and Ravi.

The Inflows Block:

- calculates the cumulative seasonal inflow volumes at the *Rim Stations:*
  - Kharif 1st April to 30th September
  - Rabi 1st October to 11th March.

Stored Resource Block (rule curves)

The Stored Resource Block determines how much water is either available from or needs to be stored in Tarbela and Mangla reservoirs over the forecast period i.e. upper and lower bounds for the storages to be maintained at points in time (minimum and maximum rule curves). The rule curves reflect seasonal objectives of drawing storages down as much as possible in Kharif and ensuring storages are full at the start of the Rabi season.

The Stored Resource Block calculates seasonal filling and emptying fractions for Tarbela and Mangla Reservoirs. The Stored Resource Block:

- determines maximum storage volume each year (allowing for sedimentation and enlargement over time)
- determines active storage volume
- determines airspace volume
- calculates maximum and minimum filling fractions for different times of the year;
  - 1 October: Start of rabi season storage volume
  - 2 October to 30 March: Rabi
  - 1 April: Start of Kharif storage volumes
  - 2 April to 10 June: Start early kharif
  - 11 June to 1 July: End early kharif
  - 2 July to 1 September: Start kharif
  - 2 September to 30 September: End kharif.
- the minimum and maximum filling fractions are then used to calculate the forecast maximum and minimum live content curves.

Resource Assessment Block

The Resource Assessment block contains functions that use the cumulative seasonal inflow volumes for each rim station in associated minimum and maximum seasonal forecast lookup tables to determine a seasonal forecast of expected water resources at each rim station for rabi, early kharif and kharif seasons. The Indus and Kabul forecast are combined to define inflows for the Indus zone while the remaining rim stations are combined to define inflows for the Jhelum-Chenab (J-C) zone. These are used to determine resources in Indus, J-C zones as well as the combined systems.

The Resource Assessment block continues the calculations from the Inflows Block by:

- entering cumulative previous season inflow volumes (from the Inflows Block) into respective rim station forecast lookup tables to estimate minimum and maximum future forecasts for early kharif, kharif and rabi seasons (Figure 59)
- combining the early kharif ad late kharif forecasts to determine total kharif forecast

- calculating the likely rim station forecast is determined by averaging the respective minimum and maximum seasonal forecasts.

Then:

- The Indus minimum and maximum resource is estimated by combining the respective Indus and Kabul forecasts and subtracting Tarbela airspace for kharif and adding Tarbela active volume for Rabi – reflecting the need to fill storages in kharif and emptying storages in rabi.
- The Jhelum-Chenab minimum and maximum resource is estimated by combining the remaining rim station forecasts and subtracting Mangla airspace for kharif and adding Mangla active volume for Rabi. Reflecting the need to fill storages in kharif and emptying storages in rabi.
- The minimum total resource is determined by combining the minimum Indus and JC resources.

The minimum and maximum forecast tables are derived from observed cumulative inflows and minimum and maximum forecasts each year. The values are sorted based on the previous season inflows. Figure 59 shows an example table for the Indus River for late kharif forecasts.

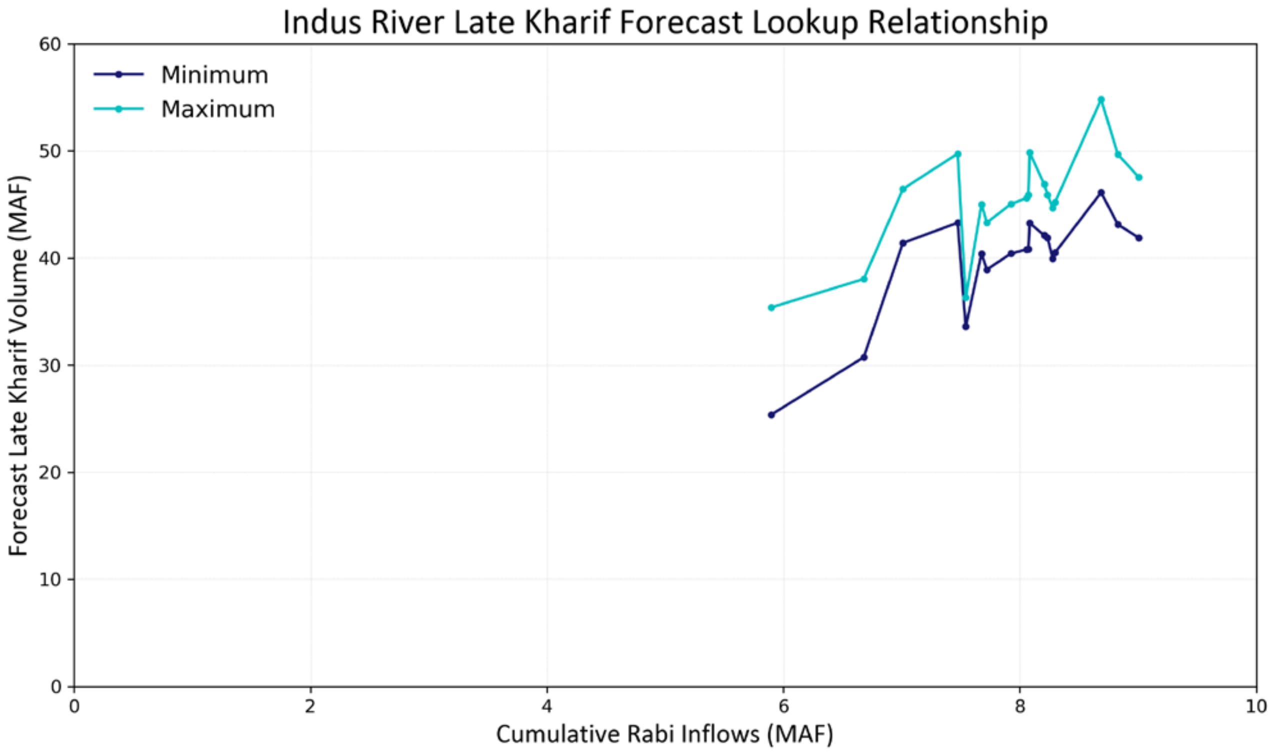


Figure 59 Indus late kharif forecast table

Probabilities Block

The Probabilities Block takes the likely seasonal forecast flows calculated in the Resource Assessment Block and looks up the corresponding seasonal flow probability and corresponding daily inflow patterns at each rim station. Then for likely probability and 10% either side, flows for each rim station for the current day in the simulation are looked up and returned as the likely, maximum and minimum expected inflow volume from the rim station. This method of estimating seasonal inflow patterns differs from the IRSA method in two ways:

- It is a daily estimate whereas IRSA method returns 10 daily flow estimates; and
- The IRSA method selects actual matching flow years within the probability range returned from the seasonal forecast. The method used in the IRSM looks up tables with these flows having already been combined and interpolated over a daily time step.

The exceedance probability tables associated with the seasonal flow volumes are not re-calculated in the IRSM as new seasonal flows become available, as is the case in the IRSA calculations. The probability tables are therefore static in the current version of the IRSM. The tables used in the IRSM are those used in the 2014 seasonal forecast representing 38 years of flow record. With such an extensive record, the addition or subtraction of a small number of years used to create the probability tables is likely to have only a small impact on the overall selection of seasonal flows.

The probability tables are determined from observed flows by WAPDA and provided to IRSA each year for water allocation calculations.

- For each rim station, three probability tables have been constructed and have been input to the IRSM:
  - An Early Kharif table relating the likely Early Kharif seasonal forecast volume to the exceedance probability of that volume of flow occurring based on the past 38 years of flow record;
  - A Late Kharif table relating the likely Late Kharif seasonal forecast volume to the exceedance probability of that volume of flow occurring based on the past 38 years of flow record; and
  - A Rabi table relating the likely Rabi seasonal forecast volume to the exceedance probability of that volume of flow occurring based on the past 38 years of flow record.
- Using the previously estimated likely seasonal forecast volume for each rim station, the probability of the forecast volume for the relevant season is found and rounded to the nearest 5%.
- The minimum and maximum probability is found by adding ±10% to the likely probability for each rim station.
- Using two-dimensional seasonal lookup tables based on probability and day of the year, the minimum and maximum anticipated inflow volume from the current day until the end of the season are found for each rim station.

The maximum and minimum forecast lookup tables are derived from observed flows and are updated each year. The tables are derived by sorting each previous season inflow volume and associated subsequent seasonal inflow time series, then looking for all previous years that fall within 5% of the previous season inflow volume and taking an average of the subsequent season inflow time series. These values are then sorted by the average of the previous season inflow volume and ranked. Then five percentile probability values are interpolated between these points.

Tier Block

Based on the minimum total resource determined in the resource assessment, the minimum Tier for the season is determined. The maximum Tier is assumed to be 2.

- Tier 1 <= 63.21 MAF (kharif), 33.69 MAF (rabi)
- Tier 2 > 63.21 <= 71.01 MAF (kharif), 34.84 MAF (rabi)
- Tier 3 > 71.01 MAF (kharif), > 34.84 MAF (rabi).

Provincial Shares Block

The Provincial Shares Block contains the daily flow patterns (based on observed usage in 1978-1982) for the four provinces of Balochistan, Khyber Pakhtunkhwa, Punjab and Sindh according to their shares as specified in the Water Apportionment Accord 1991.

The lookup tables contain the sum of 10 daily values from the current day until the end of the season. This provides an estimate of expected use for each province.

Water Resource (Forecast Operation) Block

The Water Resource Block brings together the daily flow patterns from the Probabilities Block, reservoir operations from the Stored Resource Block, the initial tier estimates from the Tier Block and provisional provincial shares from the Provincial Shares Block and undertakes the water apportionment between provinces over the seasonal allocation period. This apportionment considers an allowance for system losses and is undertaken on the Jhelum-Chenab (J-C) System, and then the Indus System which accounts for expected outflows from the J-C system.

The Forecast Operation Block is arguably the most important in terms of forecast river operations. Steps in the mass balance calculation are :

1. This mass balance calculation starts on the Jhelum-Chenab system by passing the Jhelum anticipated minimum and maximum anticipated flows through the Mangla storage operated according to the appropriate minimum and maximum rule curves. This creates a minimum and maximum Mangla outflow time series.
2. The Mangla outflow time series are then added to the anticipated flows from the Chenab and Eastern Rivers before seasonal losses are subtracted from the time series (the available water time series). The proportional seasonal losses assumed in the IRSM are detailed in Table 62.

Table 62 Proportional seasonal losses for Indus and Jhelum-Chenab zones

Season	Indus	Jhelum-Chenab
Early Kharif	0.3	0.15
Late Kharif	0.2	0.05
Rabi	0.05	0.05

3. Proposed canal withdrawals for the J-C system are then subtracted from the available water time series and any remainder becomes the J-C system outflow time series.
4. The Indus proportion of the mass balance starts by passing the Indus anticipated minimum and maximum anticipated flows through the Tarbela storage operated according to the appropriate minimum and maximum rule curves to create the minimum and maximum Tarbela outflow time series.
5. The Tarbela outflow time series is then added to the Kabul anticipated minimum and maximum flow time series before passing through Chashma Reservoir.
6. Next, the outflow from the J-C system is added to the anticipated flows downstream of Chashma.
7. Losses are then applied.
8. Finally, proposed canal withdrawals for the Indus system are subtracted from the available water time series and the remainder becomes the flows downstream of Kotri.

Provincial Allocation Block

The Provincial Allocation block allocates the water resource determined in the Water Resource Block to the provinces according to their provincial sharing rules specified in the 1991 Water Apportionment Accord and the 3-tier approach.

The Provincial Apportionment Block is largely a storage block for interpolated time series corresponding to provincial share allocations for Balochistan, Khyber Pakhtunkhwa, Punjab and Sindh according to Paragraph 2, 4 or 14 of the Water Apportionment Accord 1991.

High security water for Balochistan and Khyber Pakhtunkhwa is fixed.

Provincial Distribution Blocks (for each province)

The final four blocks in the IRSM forecast, allocation and distribution system are Provincial Distribution Blocks. Each of the four provinces is assigned a Block where the Provincial allocations determined in the Provincial Apportionment Block are distributed into seasonal Canal Command allocations that are subsequently used in the model to represent seasonal *Entitlements* at minimum flow nodes.

Historic time series of canal command proportions of total provincial flows are generally used to break up the provincial allocations to canal command allocations. The mechanism used in the IRSM to achieve this is using breakup tables assigning specific daily proportions of the total provincial share to each canal command. These are scaled proportionally according to the provincial shares to determine the daily allocation for every canal command.

3 Model calibration

3.1 Overview

The principal model calibration technique used for the IRSM is a step-wise manual calibration approach for physical aspects combined with interview/data assimilation techniques for management aspects. This approach applies to both the river routing and the operational decision-making calibrations and is outlined in further detail for specific model applications in the following sections.

There are four steps in the calibration process:

- River routing;
- Reach losses and gains;
- Operational decisions; and
- Water allocation and sharing.

Ultimately, model performance is assessed by comparing water volume and delivery patterns at barrages (including water levels), link canals and irrigation command canals simultaneously throughout the model domain.

3.2 Model versions

The Source version that was used in model development, calibration and for presentation of the results was V4.1.1.5345. The name of the Source project system file for the IRSM is *IRSM_V4_1_1_5345_Baseline_V4.rsproj*.

3.3 Calibration and validation period

The IRSM was calibrated using streamflow data from 2007 to 2012. Model validation was done for the period of 2002 to 2007 with an extended model period of 1990-2012 used for long term model validation.

3.4 River routing and reach losses and gains

The generalised techniques used to calibrate the routing and losses for individual river reaches are discussed in the following sections. The reaches are calibrated independently of each other and then these parameters are used in the complete IRSM. The performance of reaches in the IRSM is checked to ensure it does not differ substantially from the individual reach calibrations.

3.4.1 River routing

To calibrate the timing and attenuation of flows in a river reach the following general method has been used:

1. Gauged flow time series for the inflow and outflow of a reach must be known and form the input to a simplified reach model, in addition to an estimate of the length of a reach.
2. Observed and modelled the lag times between peaks for different flow rates form the points in the reach-based lookup table relating different flow rates to travel times (Figure 60).

3. The simplified reach model is run to check that the flows have been lagged appropriately. The reach is now ready for estimation of reach-based losses (Figure 61).

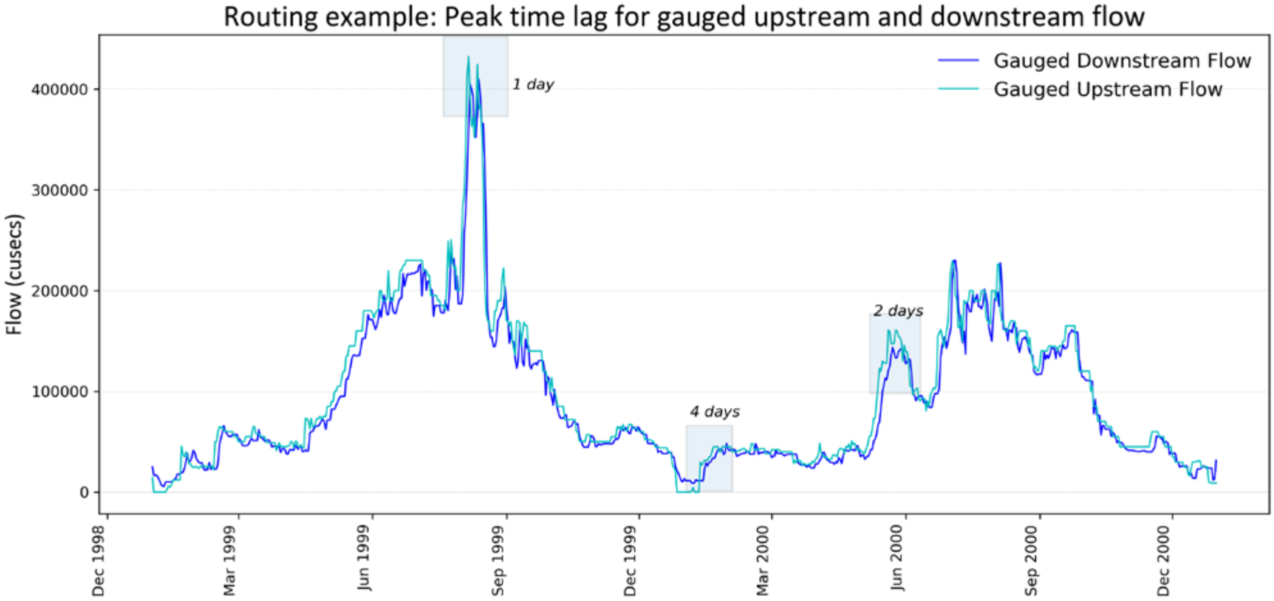


Figure 60 Selecting flow thresholds for the adjustment of water travel times

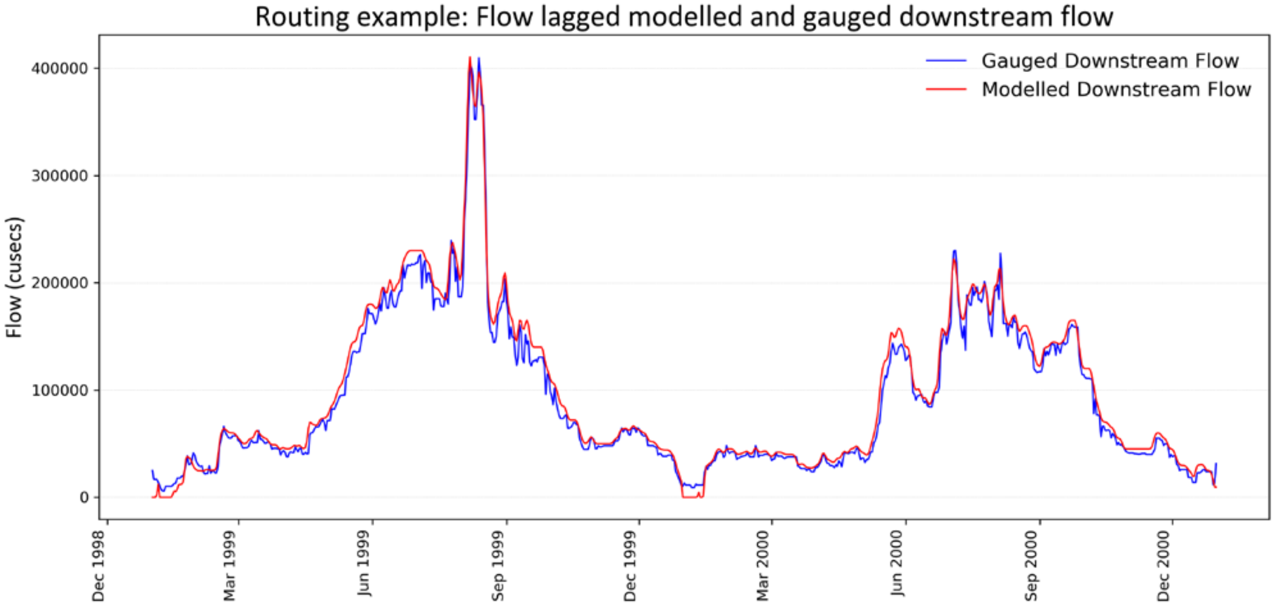


Figure 61 Example travel time adjusted flow time series

3.4.2 Estimating unaccounted losses and gains

Reach-based losses (or groundwater gains) can be estimated for different flow ranges by analysing the hydrographs of the modelled (routed) and gauged flows. The modelled and measured flow volumes and the flow duration curves (exceedance curve) are then used to calibrate the reach-based losses in a river reach:

1. During times where residual inflows are expected to be close to zero, the total measured downstream flow volume is compared to the corresponding total modelled flow volume in the reach model to obtain an overall percentage loss or gain in flow across the entire reach.

4. The flow duration curves for modelled and measured downstream flows are plotted and compared (Figure 62).
5. The difference between the modelled and measured flow duration curves is used to estimate the percentage loss (%) for different flow thresholds.

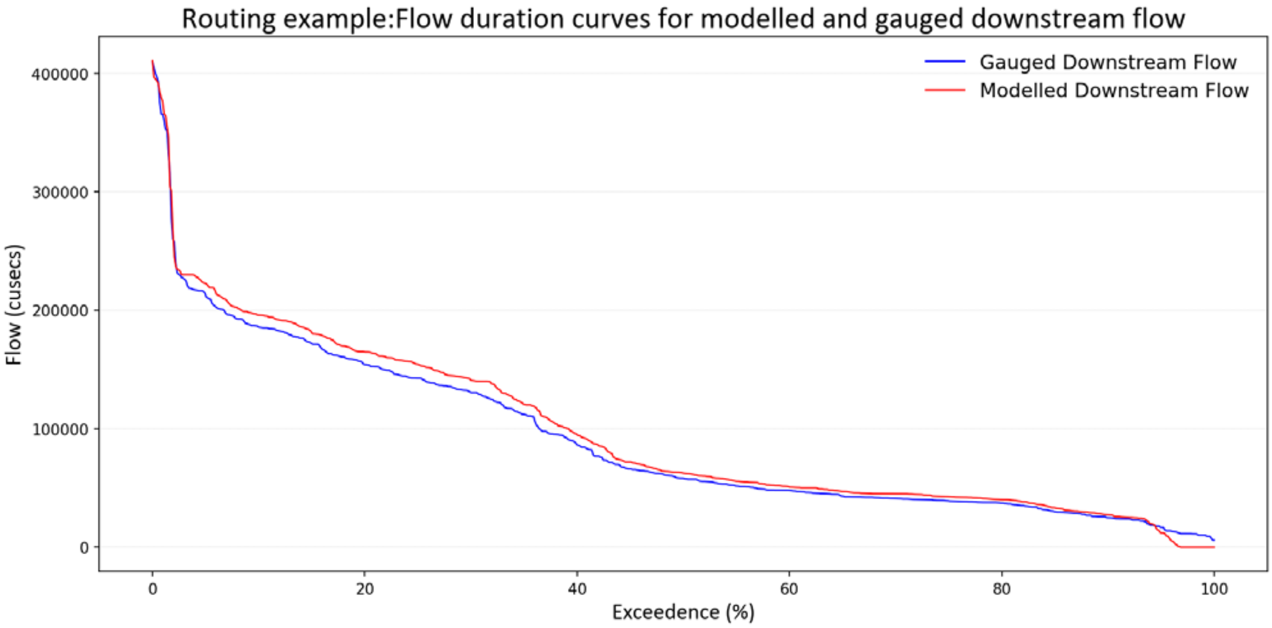


Figure 62 Flow duration curves of the modelled and measured time series are used to calculate losses and gains

6. The flow vs percentage loss table is input to the IRSM for the river reach and the model run again to check the overall mass balance across the reach (Figure 63), the timing of peaks and the new modelled and measured flow duration curves (Figure 64).

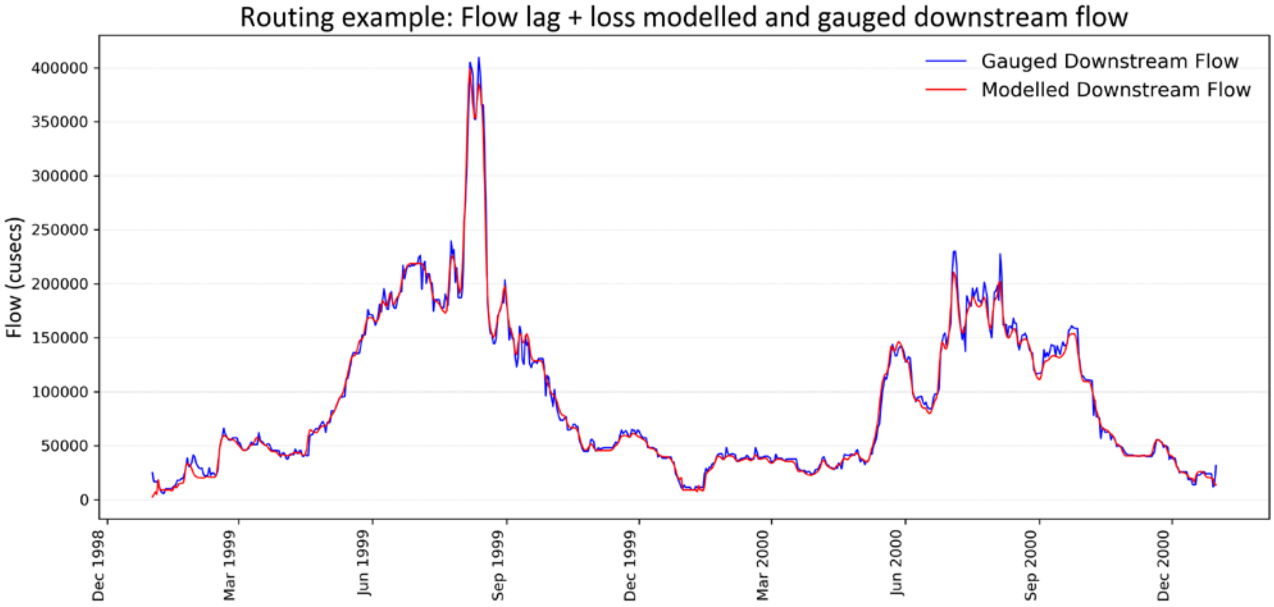


Figure 63 Final calibrated reach with adjusted peak travel times and incorporated losses

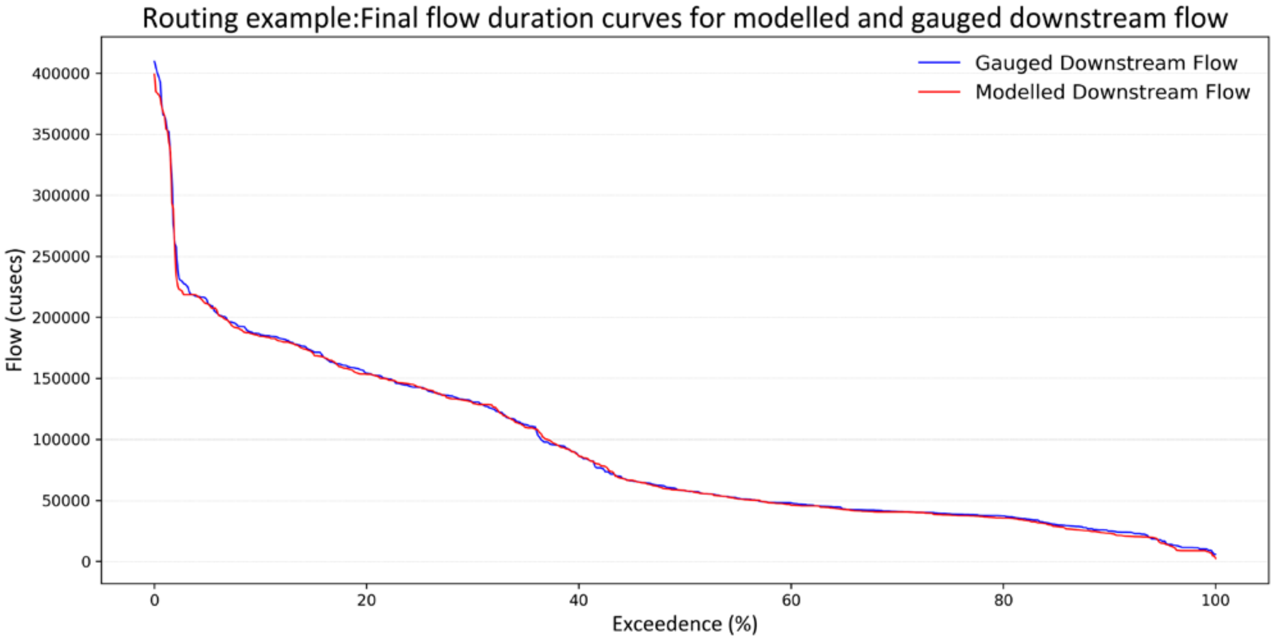


Figure 64 Final calibrated flow duration curves of modelled and measured time series

Note: Modelled losses and gains cannot be compared individually to recorded losses or recorded gains because these are not systematically measured but are inferred through a reach mass balance. However, model results adopting a similar mass balance technique have been compared as demonstrated in the next section.

3.4.3 Sukkur to Kotri example

The Indus River between Sukkur and Kotri is a ‘high loss’ reach possibly due to the length of time it typically takes water to pass along the reach, providing extended opportunities for infiltration compared to other reaches. The following section demonstrates the calibration of the routing and loss functions adopted in the baseline model for this reach.

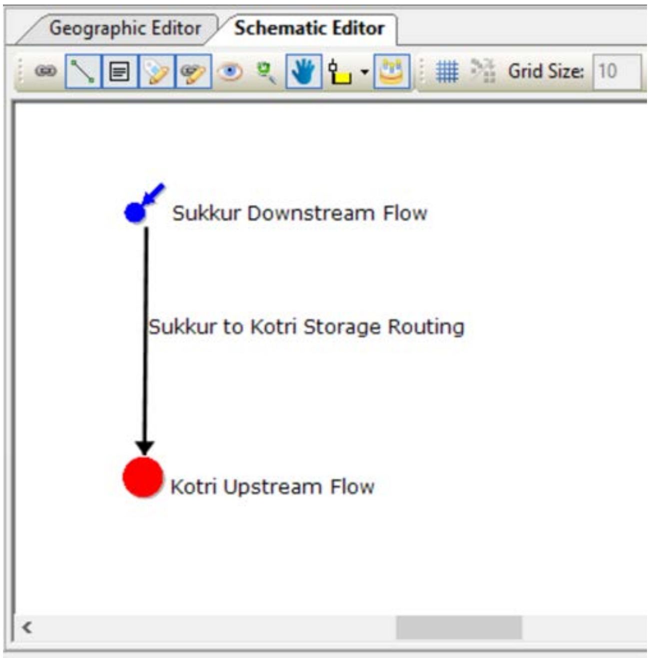


Figure 65 Example of a simple two node routing model

Figure 65 shows a simple, two node model, where the upstream flow is given by the outflow time series from Sukkur Barrage and the downstream gauge node represents the estimated inflow into Kotri Barrage. With no stream routing or losses applied, the modelled flows at the Kotri node are compared to highlight the difference in peak travel times and the difference in accumulated flow volume in this reach (Figure 66).

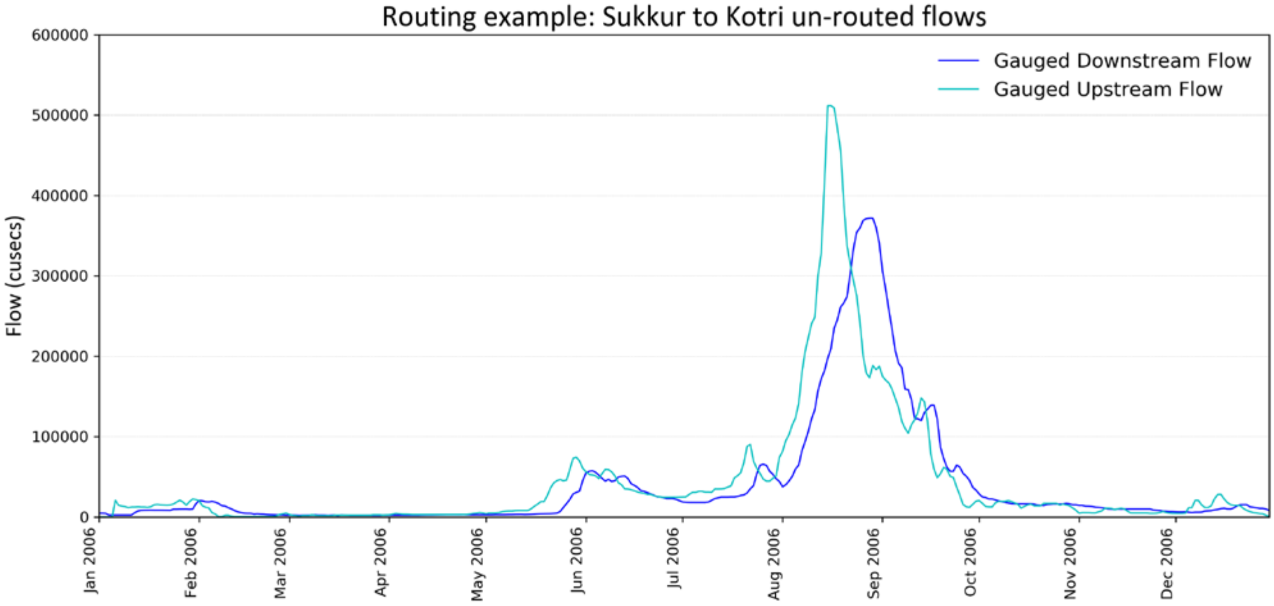
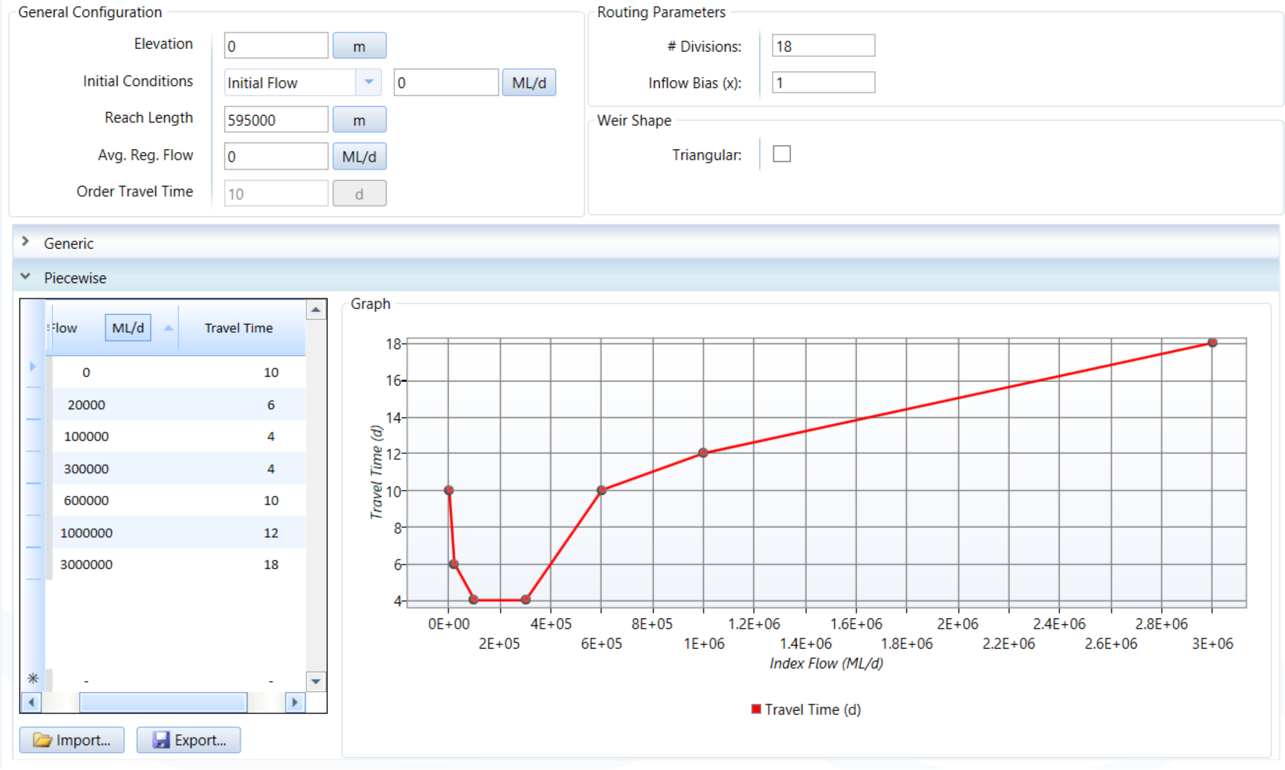


Figure 66 Sukkur to Kotri reach, no lags or losses applied Sukkur downstream flow (red) and Kotri inflow (blue)

Approximately 19% volume difference between the flows downstream of Sukkur and upstream of Kotri are observed, as are significant travel times of between 5 and 18 days.

Observing a range of peak sizes over several years of flow record reveals a non-linear flow vs travel time relationship for this reach. The relationship and the resultant impact on the lag routing for a year is shown in Figure 67 and Figure 68.



General Configuration

Elevation: 0 m

Initial Conditions: Initial Flow 0 ML/d

Reach Length: 595000 m

Avg. Reg. Flow: 0 ML/d

Order Travel Time: 10 d

Routing Parameters

Divisions: 18

Inflow Bias (x): 1

Weir Shape

Triangular: ☐

Generic

Piecewise

low ML/d	Travel Time
0	10
20000	6
100000	4
300000	4
600000	10
1000000	12
3000000	18

Figure 67 Sukkur to Kotri reach travel times applied to different flow thresholds

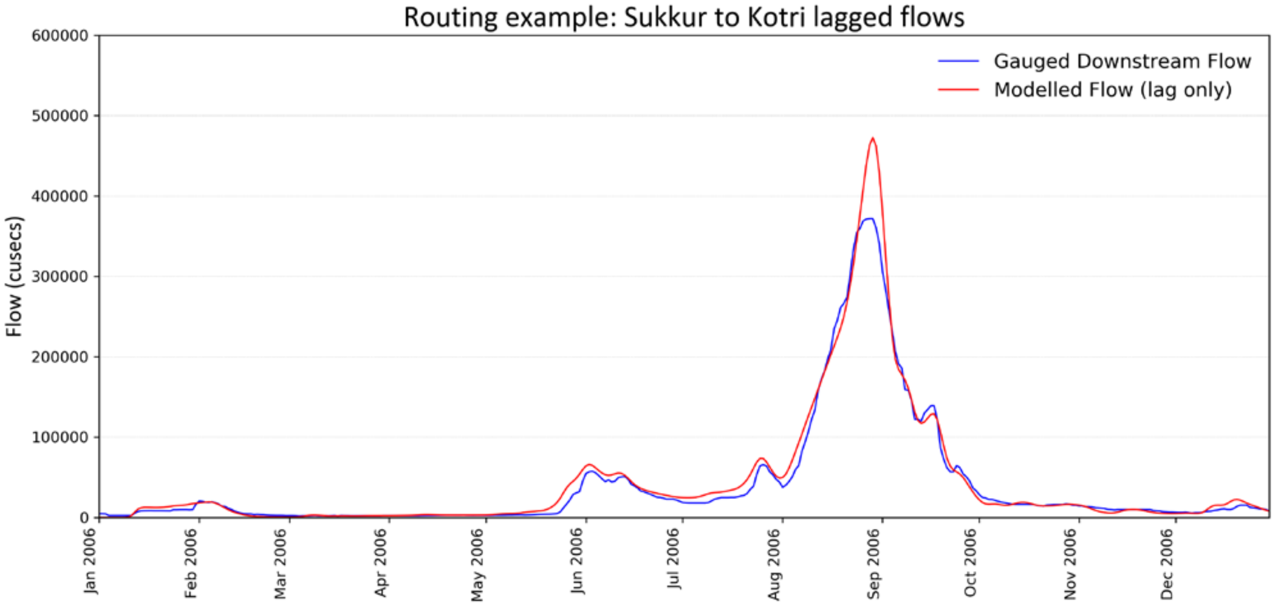


Figure 68 Sukkur to Kotri reach, routed flow and observed Kotri inflow

Plotting the flow duration curves of several years from the Sukkur to Kotri lagged flows reveals a discrepancy in the curves that can be exploited to derive an estimated loss rate (for various flow bands). Where the routed flow duration curve is above the gauged flow, a loss should be applied to that flow rate (Figure 69).

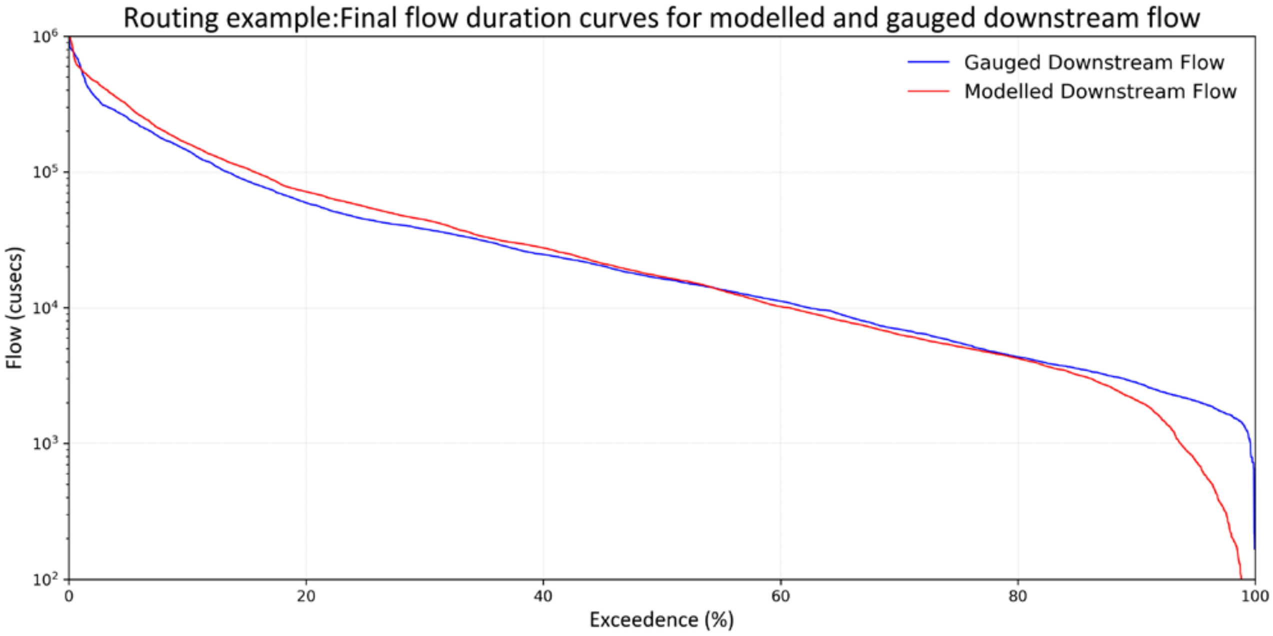
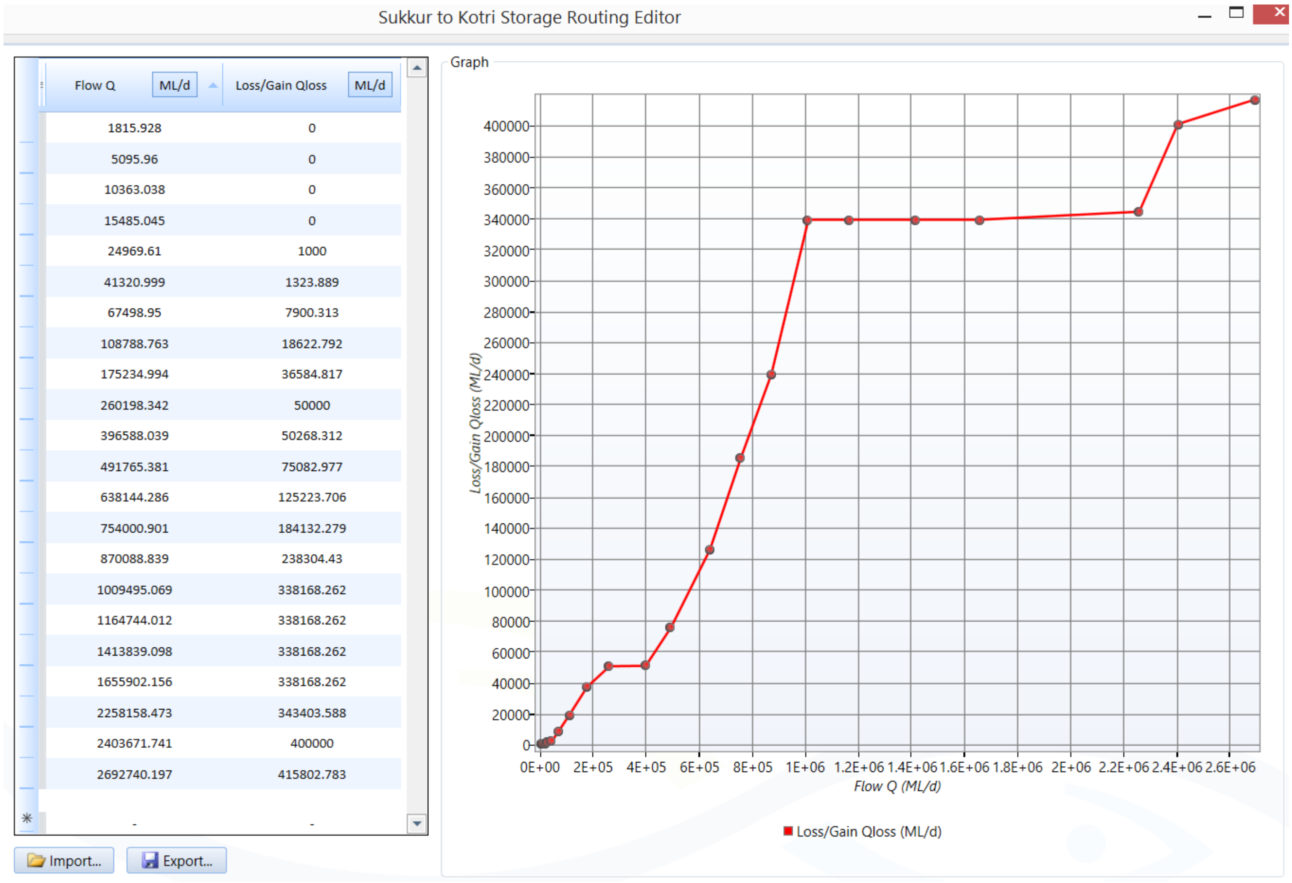


Figure 69 Sukkur to Kotri reach flow duration curves

The loss relationship that Source allows must be monotonically increasing, therefore, if higher losses are experienced at lower flows, compared to flows slightly higher, then only the loss that is greater than or equal to that of the lower flow band is allowed for the next flow band up. This is a limitation in the loss routing mechanism in Source.

The loss relationship for the Sukkur to Kotri reach is provided in Figure 70 and the resulting routed flows in Figure 71.



Flow Q ML/d	Loss/Gain Qloss ML/d
1815.928	0
5095.96	0
10363.038	0
15485.045	0
24969.61	1000
41320.999	1323.889
67498.95	7900.313
108788.763	18622.792
175234.994	36584.817
260198.342	50000
396588.039	50268.312
491765.381	75082.977
638144.286	125223.706
754000.901	184132.279
870088.839	238304.43
1009495.069	338168.262
1164744.012	338168.262
1413839.098	338168.262
1655902.156	338168.262
2258158.473	343403.588
2403671.741	400000
2692740.197	415802.783
-	-

Figure 70 Sukkur to Kotri reach losses applied for different flow thresholds. A positive gain/loss value denoted a loss

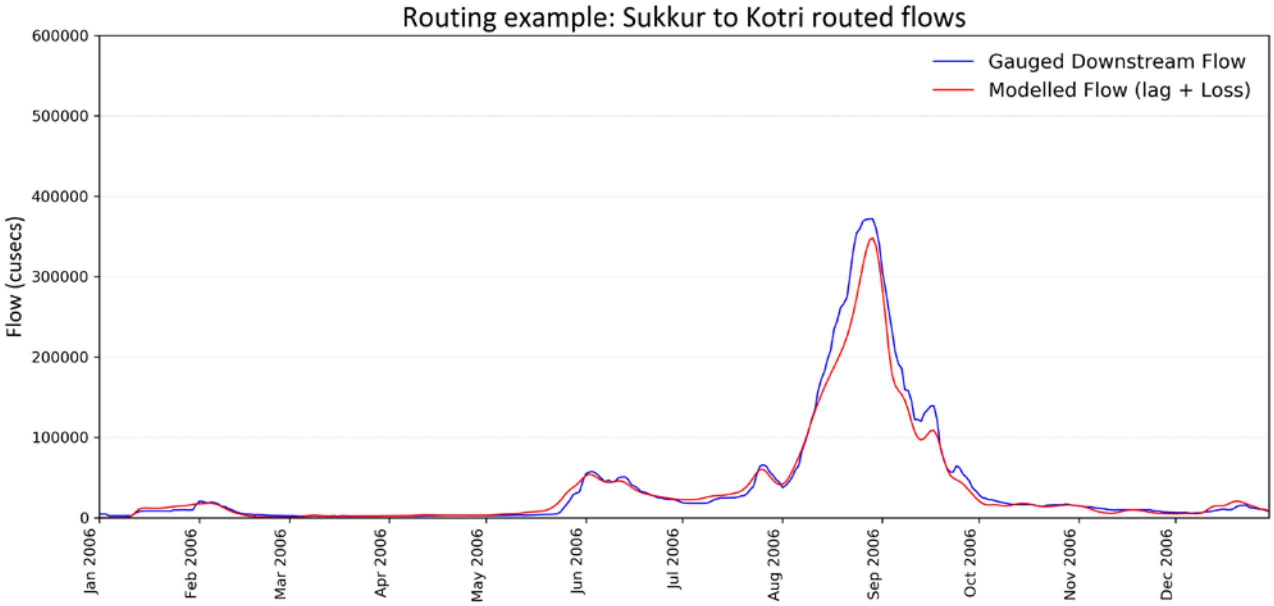


Figure 71 Sukkur to Kotri reach flows with lags and losses

Over time, the relationship derived for the Sukkur to Kotri reach appears to hold reasonably well, with just 2.6% discrepancy between the modelled flow volume and the recorded flow volume over the 13 year period from 2000–2012 (Figure 72). There does not appear to be a change in the loss relationship over time. The modelled loss in this reach is across all flows and model years is 19.4% of the inflow to the reach.

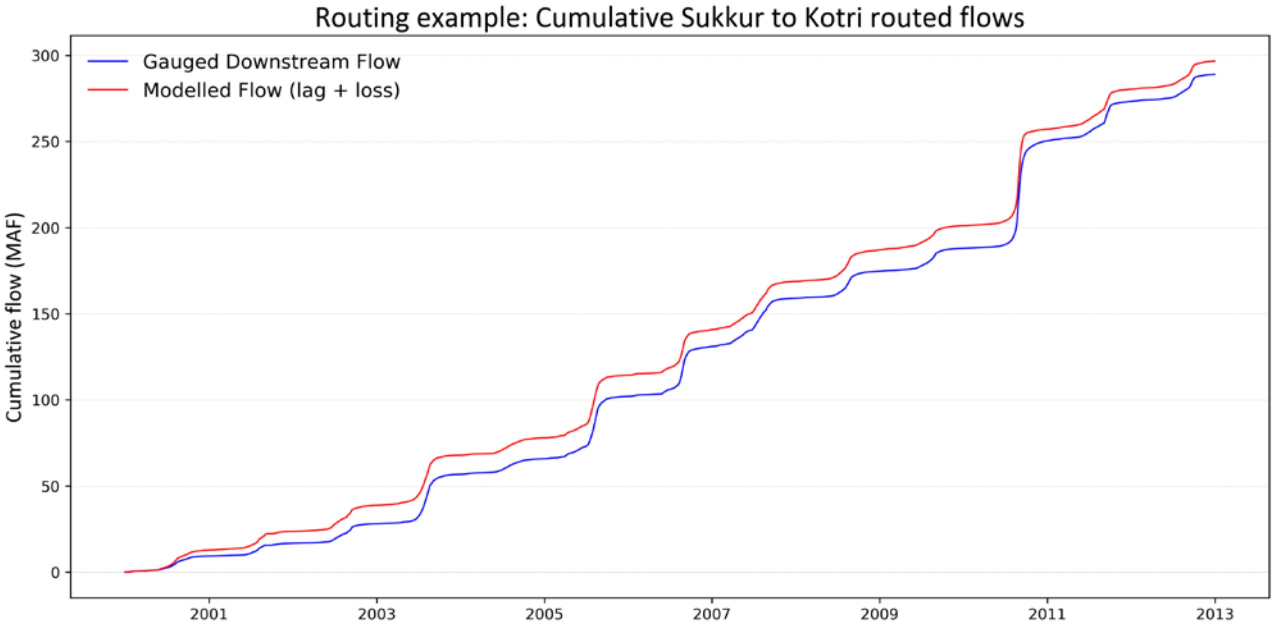


Figure 72 Kotri modelled and measured cumulative flow volumes

The routing parameters and loss relationships for all reaches are detailed in Appendix D.

3.4.4 System unaccounted differences

The same technique as that applied above has been used across most reaches in the Indus model. The proportion of mean annual unaccounted difference attributed to these reaches is shown in Figure 73. The figure shows that the lower Indus reaches are typically associated with the greatest proportion of unaccounted differences in the modelling system.

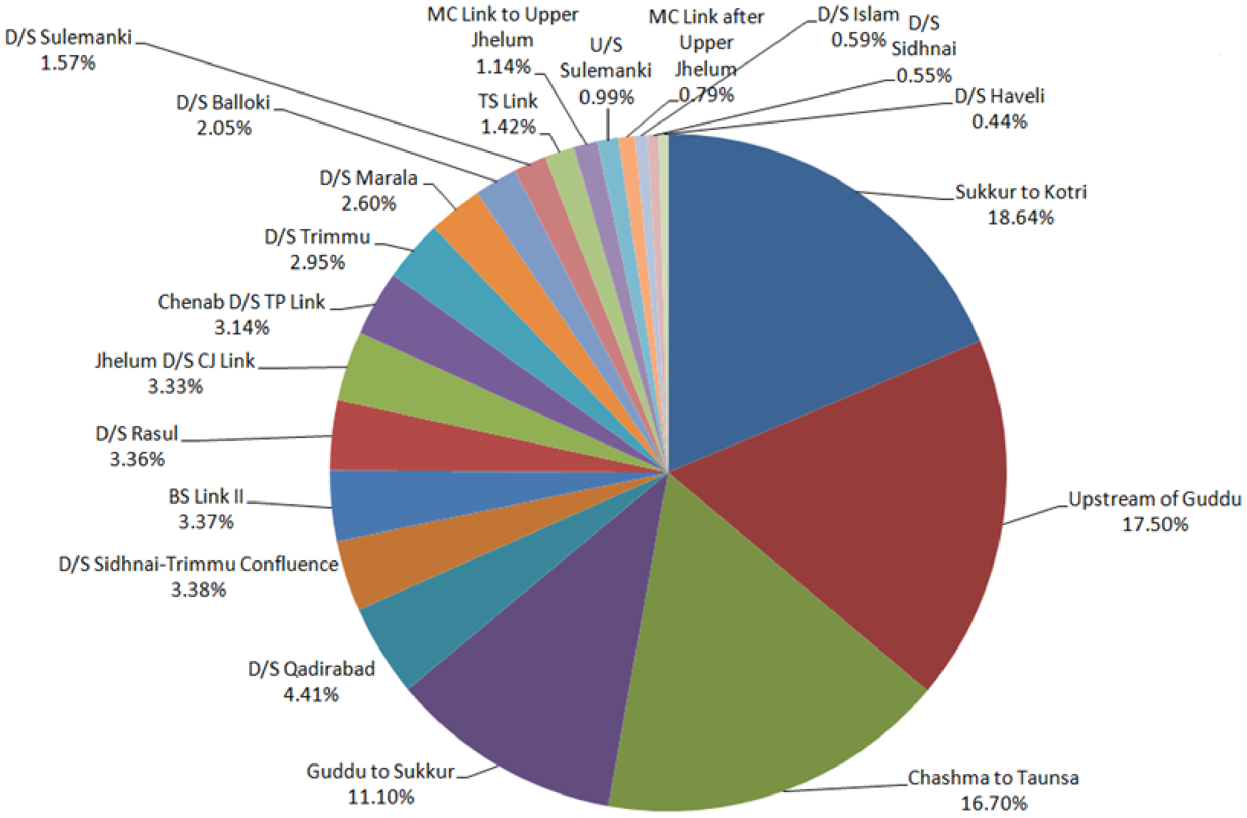


Figure 73 Reach based proportion of modelled unaccounted differences

3.5 Operational decisions

3.5.1 River delivery paths and canal operations

Operational decisions have the greatest influence on model outcomes in terms of matching observed flows with modelled flows. Operational decisions include opening and closing of command and link canals and selecting what combination of canal and river channels will be used to deliver water to downstream canal commands.

The operational decisions described above include:

- setting water level targets at barrages; and
- setting preferential flow paths for water orders.

Setting water level targets at barrages

Water levels for some barrages have different target levels at different times of the year and often also have a short period where the offtake canals are closed for cleaning and the barrage water level can reduce to the lowest level. The setting of barrage target levels was undertaken by analysing historic barrage water level data and deriving typical water levels targets for different times of the year. The derived target levels for main supply storages and barrages have been presented in the previous data chapter.

Configuring ordering paths

In Punjab Province, water from Mangla and Tarbela can take many different paths to arrive at designated canal command areas. The path that water takes to arrive at designated canal commands is typically the most efficient path with respect to instream losses and canal constraints as determined by irrigation engineers. For the model to replicate these decisions, the model *confluence* points must be appropriately configured to indicate the preferred path that water takes to arrive at a destination. To obtain this information, an interview process was undertaken with Punjab Irrigation to capture this information and include it in the model as part of the model refinement and calibration process.

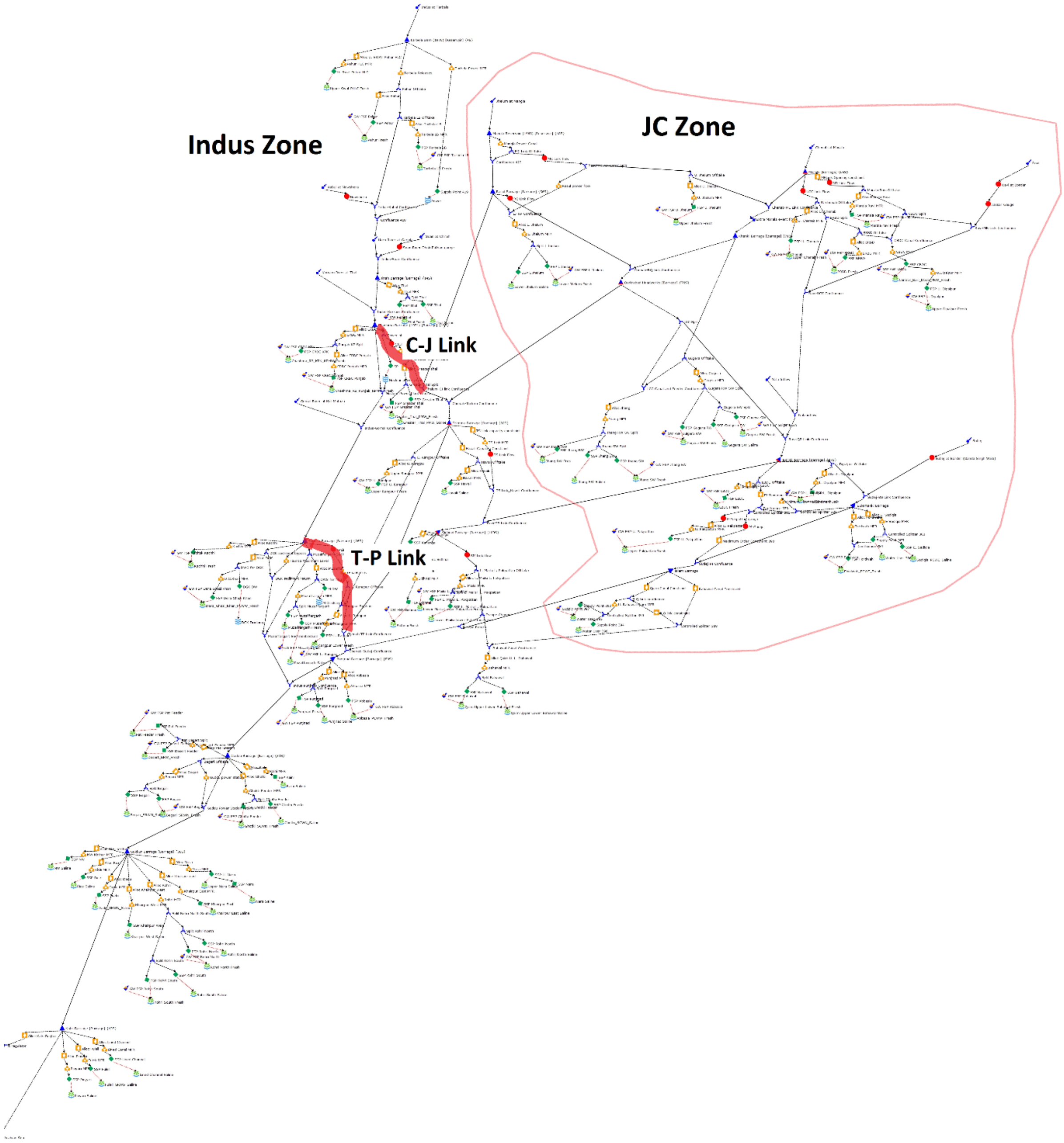


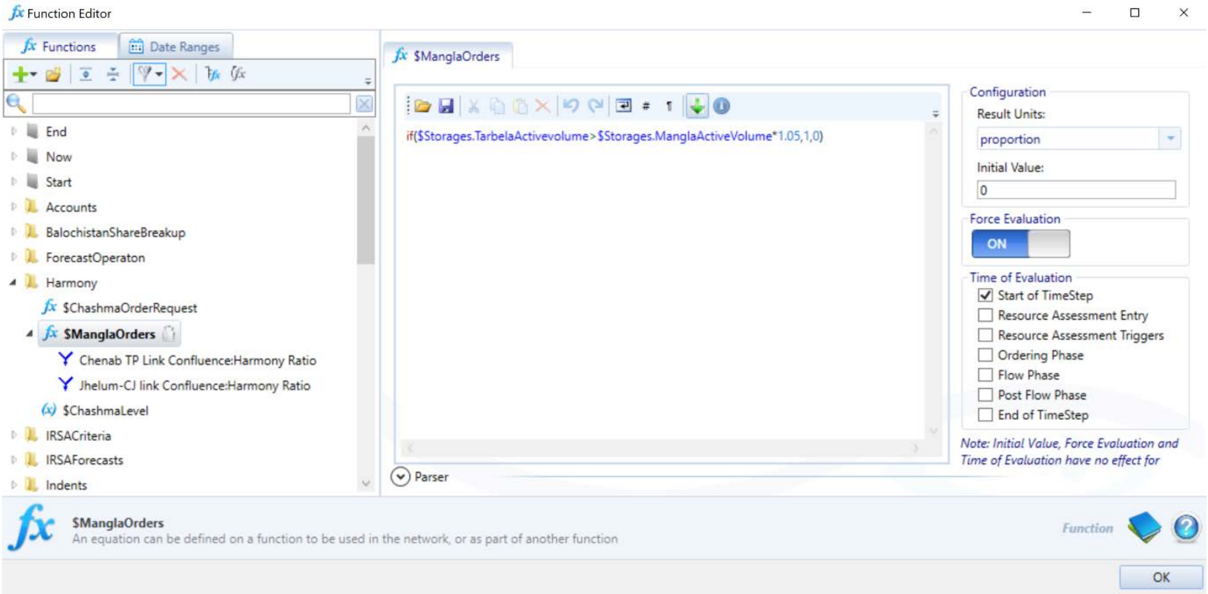
Figure 74 Indus link canals to Jhelum-Chenab zone

The C-J Link and T-P Link are two important link canals that facilitate the transfer of water from the Indus stem into the lower J-C system (Figure 74). Water transferred through these canals technically flows to Indus Canal Commands areas in Punjab. All canal commands upstream of these links are referred to as J-C Canal Command areas.

The operation of the C-J Link and T-P Link canals <u>*within the IRSM*</u> is subject to two general criteria:

1. The 10-daily share between Punjab and Sindh. The canals transfer water away from the Indus, which is the only supply for Sindh. Therefore, given that the waters at all rim stations (and held available in Tarbela and Mangla) are shared in accordance with the 1991 Water Apportionment Accord, some water may need to be transferred through these link canals to ensure sharing requirements are met.

2. The second criteria relate to harmony operations between Mangla and Tarbela. The passing of water orders up through the system is subject to decision points at every confluence to determine priority pathways. In the case for C-J Link and T-P Link, the order priority is set according to the relative volumes stored in Tarbela and Mangla. If the volume stored in Mangla is 5% greater than that stored in Tarbela, then orders from below C-J Link and below T-P Link are passed upstream toward Mangla (Figure 75). If more water is available in Tarbela, the water orders will be passed up through the link canals (subject to canal capacity), thereby releasing water from the Indus to the J-C system. Only water allocated to the Punjab Province in accordance with the Accord is passed down these link canals.



```
if($Storages.TarbelaActivevolume>$Storages.ManglaActiveVolume*1.05,1,0)
```

Configuration

Result Units: proportion

Initial Value: 0

Force Evaluation: ON

Time of Evaluation

☑ Start of TimeStep
☐ Resource Assessment Entry
☐ Resource Assessment Triggers
☐ Ordering Phase
☐ Flow Phase
☐ Post Flow Phase
☐ End of TimeStep

Note: Initial Value, Force Evaluation and Time of Evaluation have no effect for

$ManglaOrders
An equation can be defined on a function to be used in the network, or as part of another function

Figure 75 Source function used in the IRSM at CJ and TP links to manage the harmony operation of Mangla and Tarbela

3.5.2 Major storage and barrage release constraints

Water storage operations of Mangla and Tarbela are closely managed according to generated seasonal rule curves that are based on forecast inflows. In the IRSM, this management process has been captured in model function lookup tables that are based on advice from MoWR, IRSA, WAPDA and PID.

Releases from water storages have been calibrated by comparing the observed release volumes with corresponding water levels and then adjusting release curves within the IRSM so that the maximum water releases at different water levels are not exceeded.

Barrage releases have been calibrated to barrage head across the barrage by using appropriate weir equations, modified by coefficients obtained through measurement and supplied to the modelling team. The release characteristics of all the barrages have been discussed in the data section.

3.6 Surface water allocation and sharing

Capturing the surface water allocation and sharing behaviour is not a calibration in the sense that parameters are not adjusted to match observed data. The process is to check that the implementation of the rules in the IRSM match the observed allocation announcements and the subsequent provincial sharing at the command canal level. However, as part of the allocation and sharing process, specific decisions are made due to reasons outside of the IRSM’s understanding of the system, e.g. unplanned maintenance of canals or flood damage of infrastructure. Consequently, the IRSM aims to represent typical behaviour rather than match every element of the observed behaviour. This does create some minor differences at specific times.

Seasonal forecasting and water apportionment predicted by the IRSM were compared against historic recorded decisions and functions were adjusted to match the typical behaviour. Historic minimum, maximum and likely seasonal forecasts for each rim station have been compared with IRSM results as has IRSM provincial shares derived from these forecasts.

3.7 Limitations and assumptions

The key assumptions in the IRSM are listed below:

- Stationarity has been assumed for system inflows – that is; land use, groundwater levels, irrigation practices, reach unaccounted differences, supply efficiencies, and population and associated urban demands over the modelling period.

  Noting: As observed inflows are used in the model any geomorphic, infrastructure, land use (anthropogenic or natural), glacial volume or permanent snow pack changes that would impact on these inflows are not known but are encapsulated in the observed records.

  The system is supply based and consequently the demands predominantly exceed the supply. Consequently, changes in irrigation demand do not affect the overall delivery of water within the system. The IRSM does consider a change in crop areas over time based on numbers in Kirby et al. (2017) and Ahmad et al. (in review) but does not consider changes in canal capacity and farm efficiency. This may have an impact on crop production estimates. The IRSM does not consider changes in population over time. However, urban surface water demands are relatively small and consequently subtle changes in demand are difficult to quantify in the IRSM and have been ignored. The exception will be demands for Karachi which are reasonably large and growing. This may be an area for further IRSM enhancement.
- Attribution of unaccounted differences is intrinsically difficult and consequently no attribution has been made. On this basis these are not physically modelled and are assumed to remain as constant relationships throughout the modelling period.
- Parameterisation of storages is based on limited information and, where necessary, the following were estimated:
  - level, volume, surface area relationships
  - discharge relationship for the outlets.

4 Model performance

4.1 Overview

Performance of the IRSM is measured by two key indicators:

1. volumetric error, or the difference in measured and modelled water volumes for canal flows, barrage and storage releases and water deliveries to irrigation command areas; and
2. the Nash Sutcliffe coefficient of efficiency (NSE) - a measure of model fit between measured and modelled time series.

The volumetric error between measured and modelled flows indicates whether the overall quantity of water is being modelled appropriately, whereas the NSE statistic indicates how the daily, monthly or yearly variability in the modelled time series match with the recorded time series.

The following sections present the IRSM performance results for the 2003-2012 period, associated with the following aspects:

- water forecasting and provincial allocation
- major water storage behaviour
- barrage and canal flow calibration performance
- overall mass balance and loss modelling performance.

4.2 River section calibration performance

Mean annual flow volumes results, volumetric error and daily correlation between modelled and measured flows for upstream and downstream barrage flows are presented in Figure 76 to Figure 79.

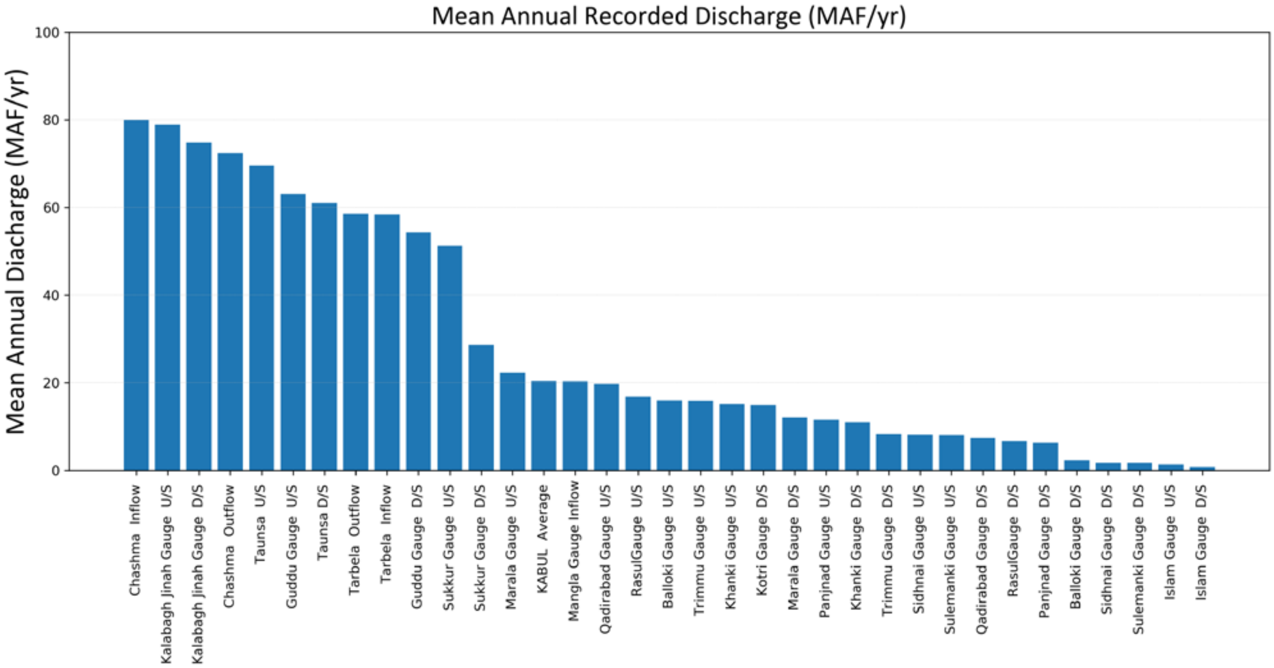


Figure 76 Mean annual discharge (MAF) for the period 2003-2012 at barrage locations

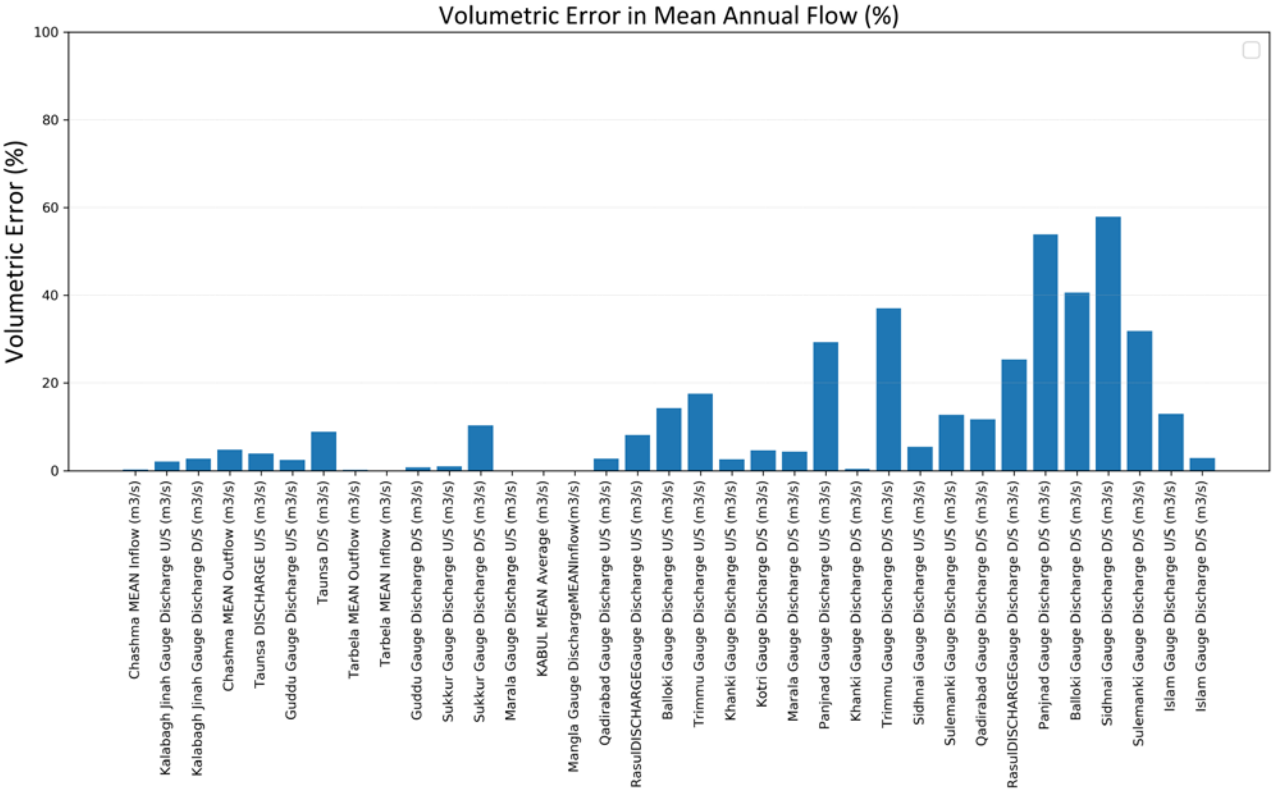


Figure 77 Mean annual modelled volumetric error (%) for the period 2003-2012 at barrage locations

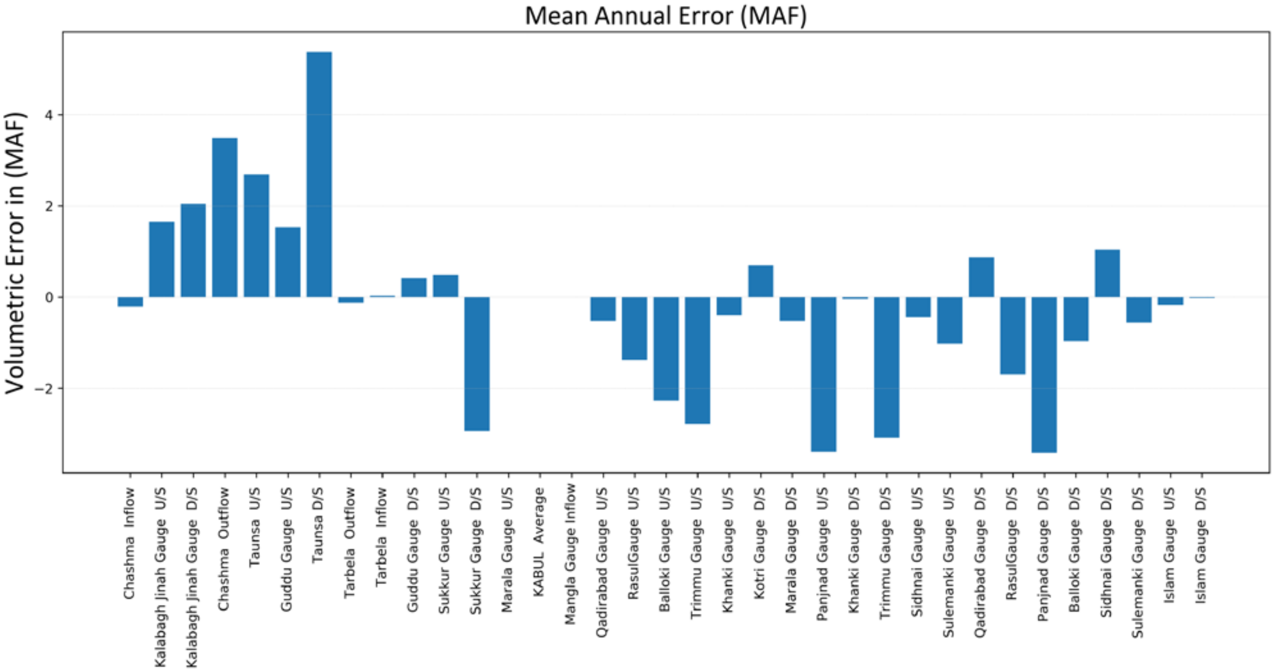


Figure 78 Mean annual modelled volumetric error (MAF) for the period 2003-2012 at barrage locations

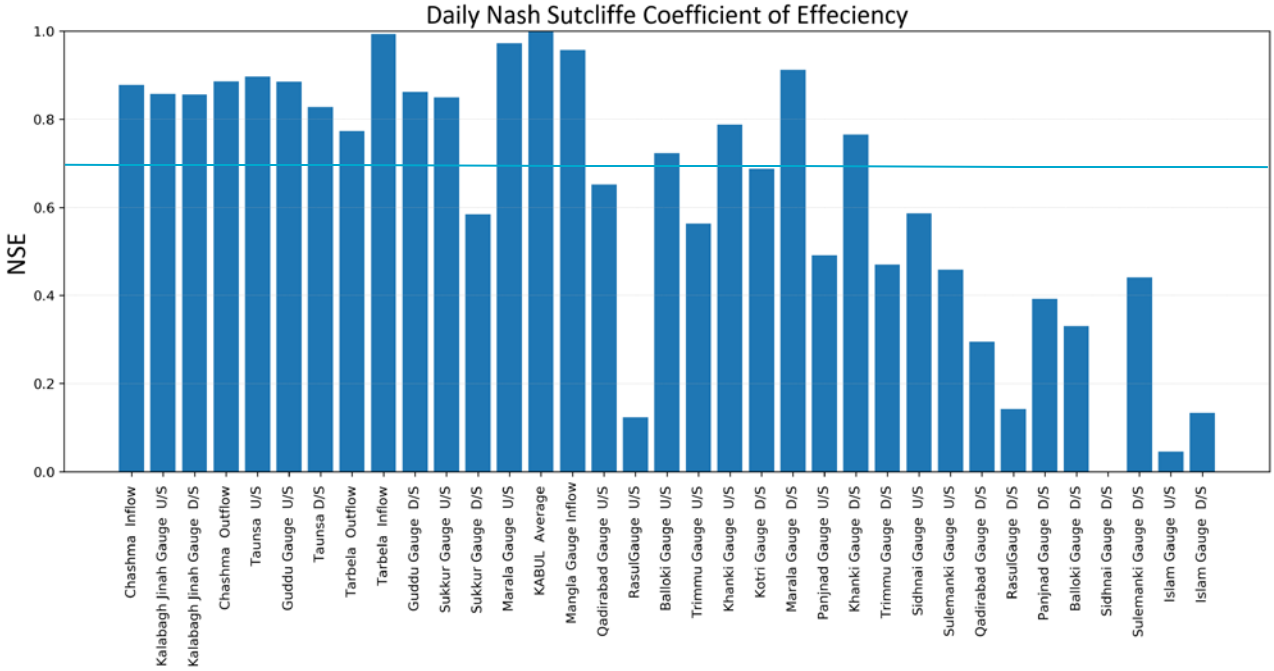


Figure 79 Model NSE coefficient of efficiency for the period 2003-2012 at barrage locations

The river section calibration results show:

- River sections with the highest flows are associated with the lowest volumetric error percentage and generally the best correlation between modelled and measured flows.
- The lowest flows (downstream) from the lowest flow barrages present the largest volumetric errors in the model. These results tend to be for the downstream flow of barrages that divert most of the inflows such as Sidhnai, Balloki and Punjnad. Small or moderate errors in volume or daily correlation in upstream flows tend to be exacerbated in the modelled downstream flows.
- The Indus flows are consistently over until Guddu Barrage. This appears to be an issue associated with diversions down TP and CJ link canals amongst other issues.
    - The difference between u/s and d/S Taunsa is approximately 2.5 MAF which translates to a similar shortfall at Punjnad. As Punjnad demands are largely met this is effectively a different flow path for Indus flows i.e. TP link to Punjnad then back to the Indus confluence.
    - Flows downstream of Chashma are approximately 3 MAF too large and downstream of Trimmu are 2.5 MAF too small. This is caused by two potential problems. Firstly, we suspect that missing data in the CJ link was given a zero value which forced model calibration to not send flow down during these periods. Secondly, there is some inconsistency on CRBC withdrawals on whether they are combined Punjab and Khyber Pakhtunkhwa withdrawals or just Punjab withdrawals.
    - Future refinement of the IRSM could improve this distribution which would reduce most of the volumetric error to be less than 1 MAF, which is well within measurement error.
- The Indus flows are too low below Sukkur Barrage. We suspect this is due to canal diversions which is due in part to some confusion around whether Balochistan deliveries are included or not in Sindh withdrawals i.e. it is double counted. There are also similar issues in accounting for Karachi water supply from Kotri.
- In terms of total mean annual volume error, the low percentage errors in the high flow barrages result in far greater volumetric error than the low flow barrages and should be the subject of further model refinement.

Overall, the volumetric error could be considered within what might be expected of the flow measurement error and the correlation sufficiently high (Daily NSE >0.5) for most high flow sites over the full 10-year period. With these results, the model can be considered to be reasonably well calibrated.

4.2.1 Canal calibration performance

Mean annual flow volume results, volumetric error and daily correlation between modelled and measured flows for major canals are provided in Figure 80 to Figure 82.

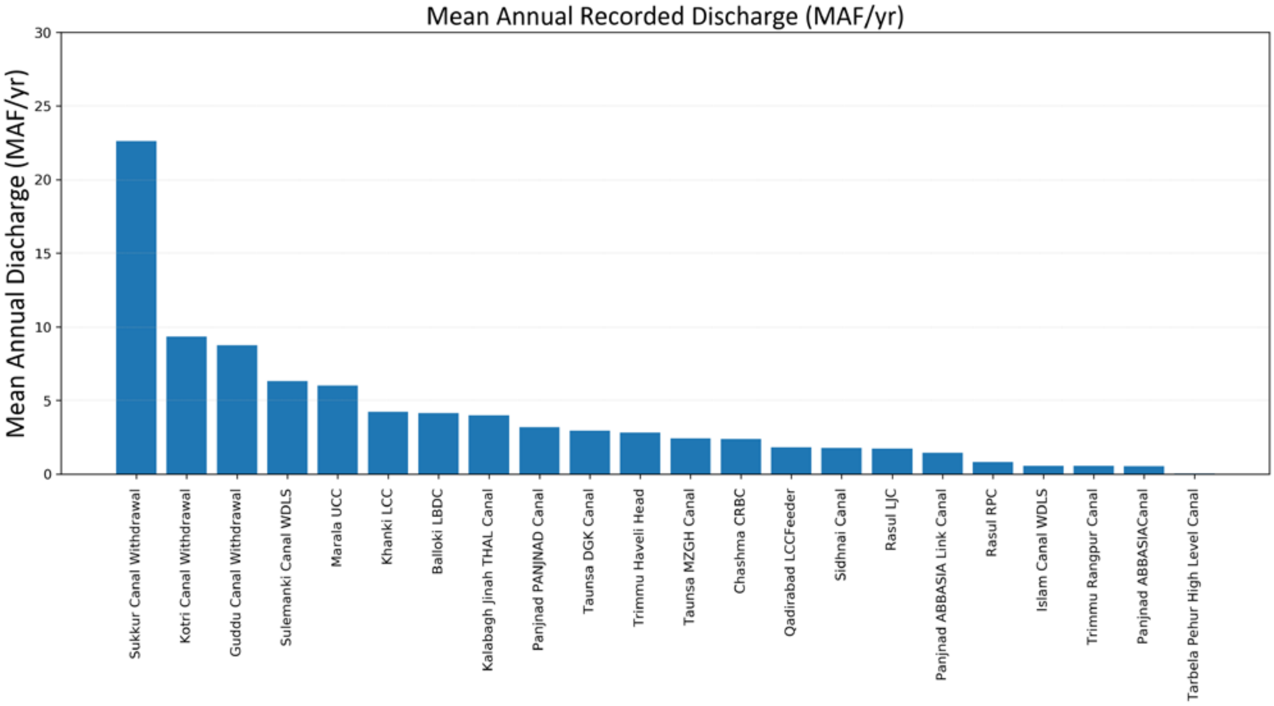


Figure 80 Mean annual discharge at canal locations

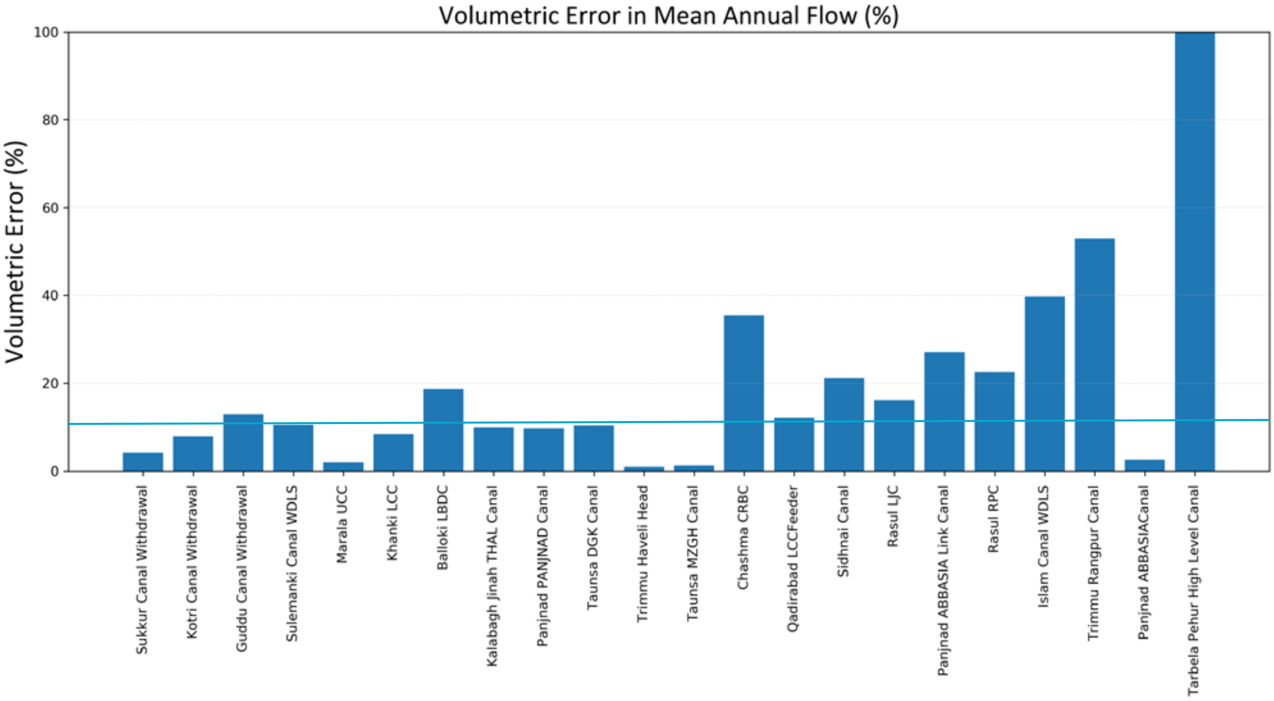


Figure 81 Mean annual modelled volumetric error (%) at canal locations

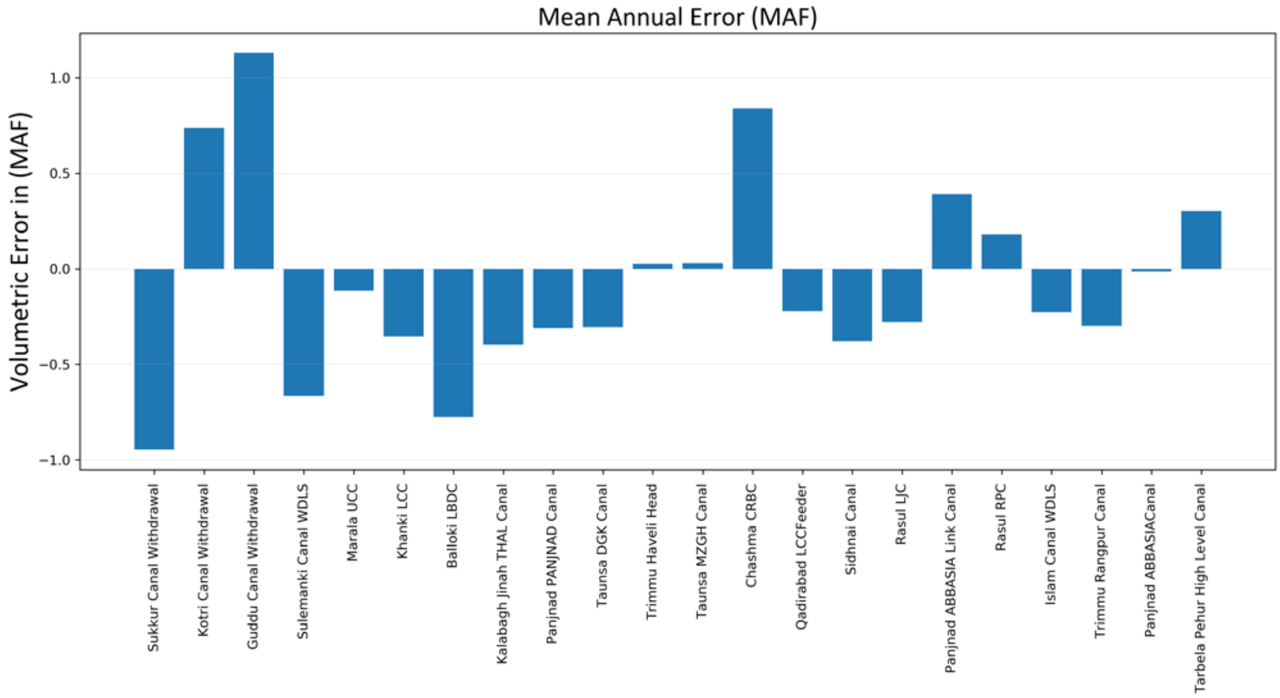


Figure 82 Mean annual modelled volumetric error at canal locations

The canal flow calibration results show:

- Canals with the highest flows are generally associated with low volumetric error – the notable exceptions are in Sindh. The observed data at each of these barrages is quite poor and consequently there are significant issues in achieving mass balance between the canals and the river. Some of the issues around this have been discussed previously. The issue around Chashma has also been discussed. All other sites are less than 1 MAF error with most sites less than 0.5 MAF, which is well within measurement error.
- Link Canals have the highest errors which was discussed previously. These require some further refinement.

Overall, the volumetric error at link canals needs further refinement and fine tuning to reduce model error.

4.2.2 Water forecasting and provincial allocation

Seasonal flow forecasting

The seasonal flow forecasting component of the IRSM performs extremely well against actual seasonal forecast volumes (Figure 83).

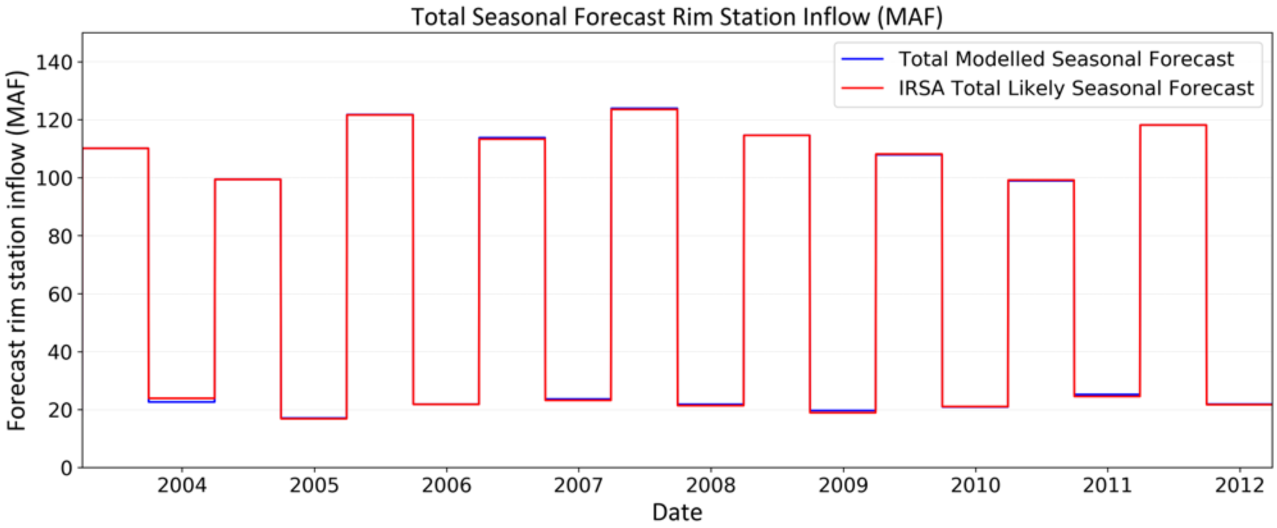


Figure 83 Modelled and observed likely seasonal flow forecast (IRSA) for rim station inflows (MAF)

The IRSM forecast seasonal flow volumes are almost identical to historic forecasts across both the calibration and validation period. Minor discrepancies in Rabi seasons 2004 and 2009 are produced by the model and are a result of IRSA using different probability tables as opposed to the fixed probability table in the model.

The close correlation between modelled and actual seasonal forecasts demonstrates that the model can capture this process of the water availability assessment component of the seasonal water resource assessment system.

Provincial allocation

Modelled system entitlements are provided in Figure 84 and Figure 85 and show that the IRSM replicates historic provincial entitlements reasonably well in terms of daily pattern of allocations and overall cumulative volume (2% volumetric error for combined Punjab and Sindh allocations vs withdrawals).

The provincial entitlements of Sindh and Punjab are also represented reasonably well. In the case of Sindh, most of the difference occurs in 2011 and 2012 (Figure 86 and Figure 87). The match in Punjab is much closer with the IRSM under-predicting particularly in 2011 and 2012 (Figure 88 and Figure 89). The small discrepancy in the modelled Punjab share that appears between 2006 and 2008 is responsible for the overall volumetric error for the modelled share in this province. Further IRSM refinements may be possible in the future to include mechanisms to replicate this behaviour.

These charts demonstrate that the IRSM can translate the seasonal forecasting results to provincial allocations in a reliable manner and can therefore now be used to extend the model period and test alternative water management scenarios.

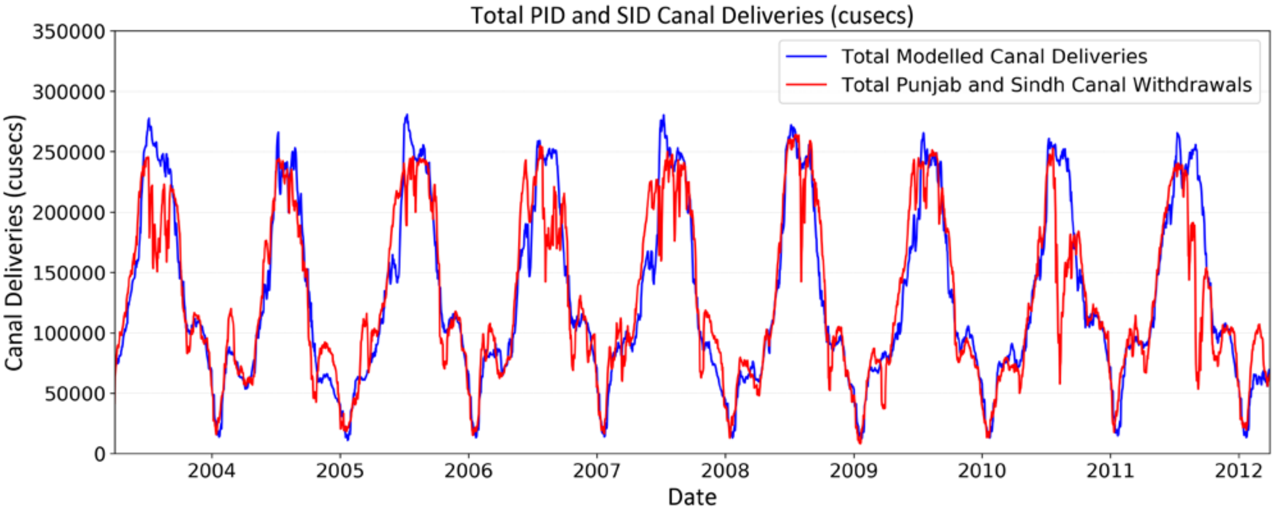


Figure 84 Modelled water entitlement and actual withdrawals

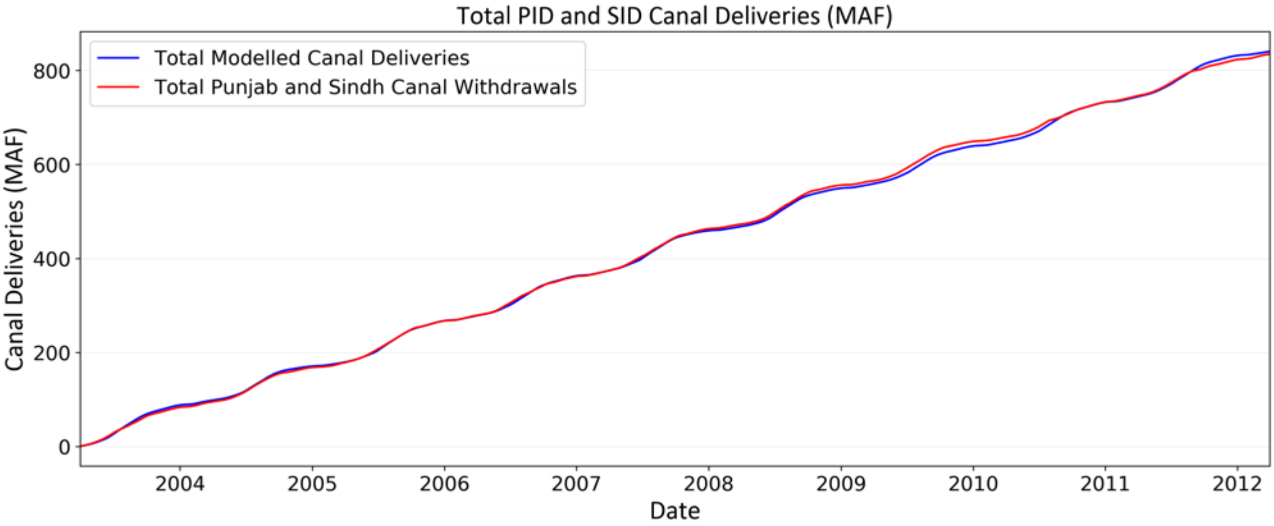


Figure 85 Cumulative modelled water entitlement and cumulative actual withdrawals

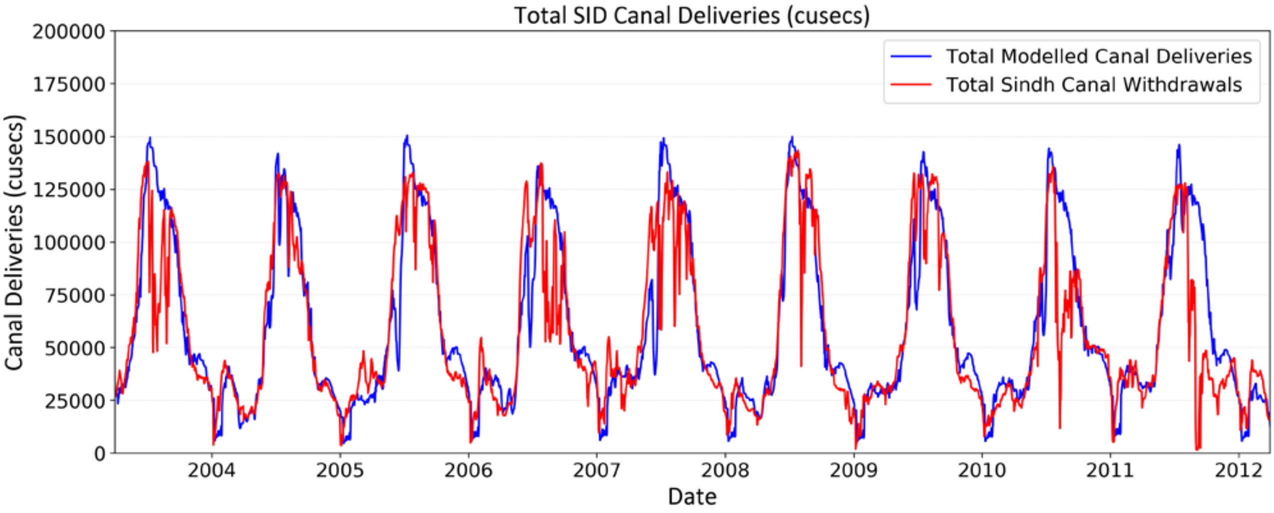


Figure 86 Modelled Sindh water entitlement and actual withdrawals

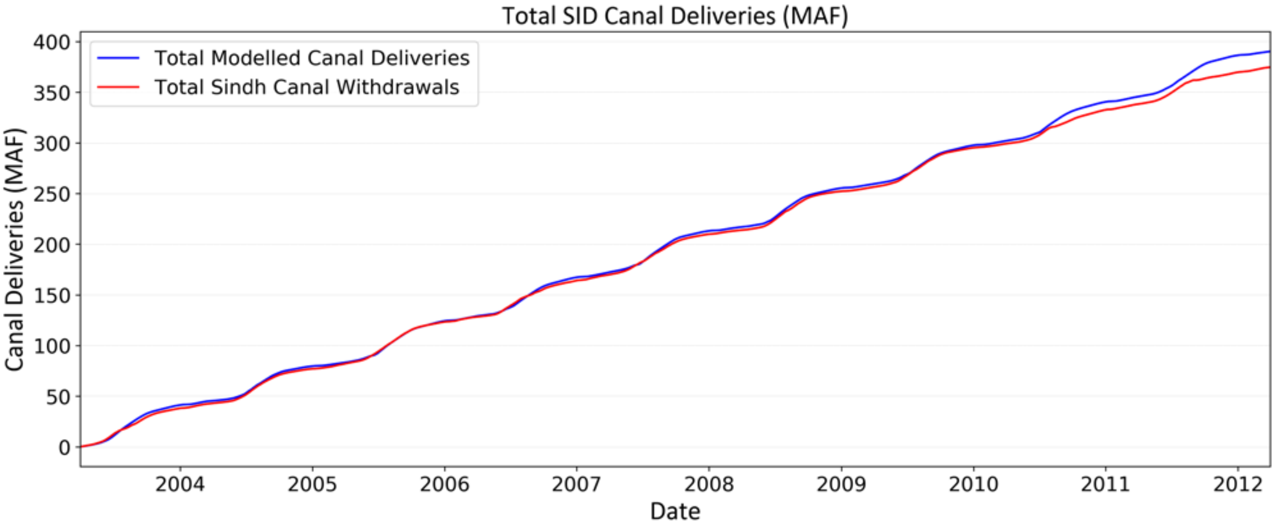


Figure 87 Cumulative modelled Sindh water entitlement and cumulative actual withdrawals

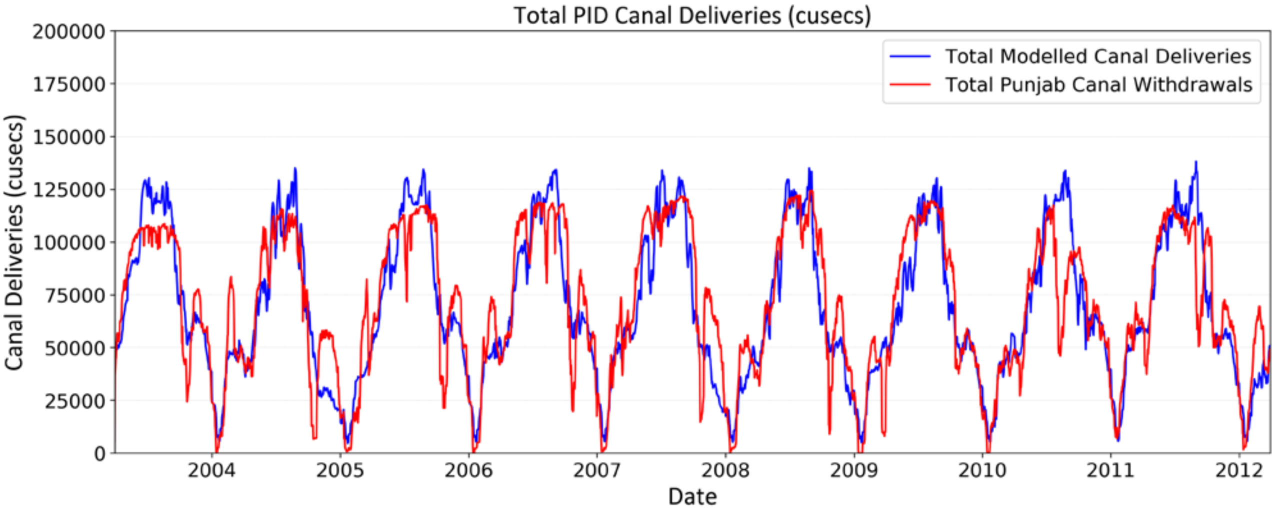


Figure 88 Modelled Punjab water entitlement and actual withdrawals

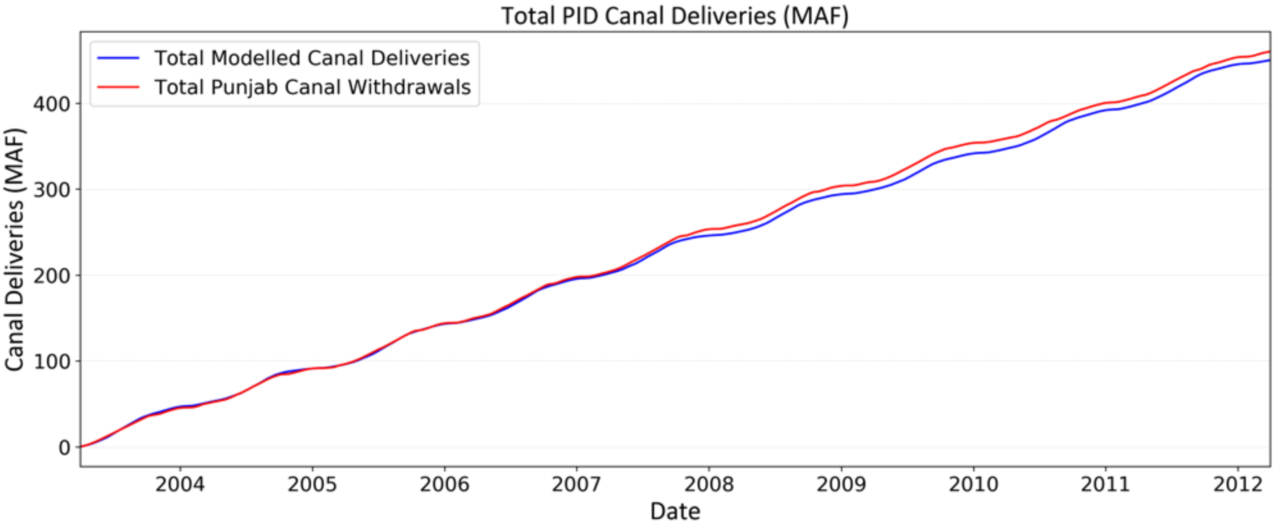


Figure 89 Cumulative modelled Punjab water entitlement and cumulative actual withdrawals

4.2.3 Major water storage behaviour at Tarbela and Mangla

The system is supplied from two major headwater storages Tarbela and Mangla. Moreover, these storages are used to supply two different allocation systems, Indus Zone and J-C Zone, noting that part of the J-C zone can only get water from Marala Barrage. The behaviour of these reservoirs reflects how well demands within these systems are met as well as how well orders and subsequent deliveries are balanced between the two reservoirs (i.e. replication of harmony operation behaviour). This can be best assessed by comparing the observed and simulated storage behaviour for Tarbela and Mangla reservoirs (Figure 90 and Figure 91).

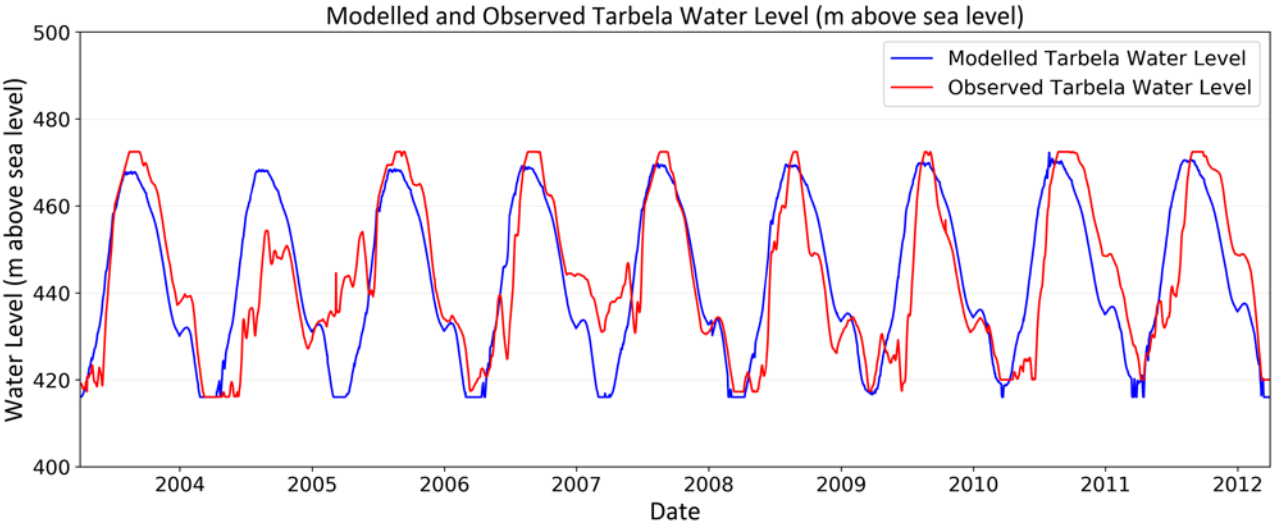


Figure 90 Comparison of observed and simulated storage level behaviour for Tarbela reservoir

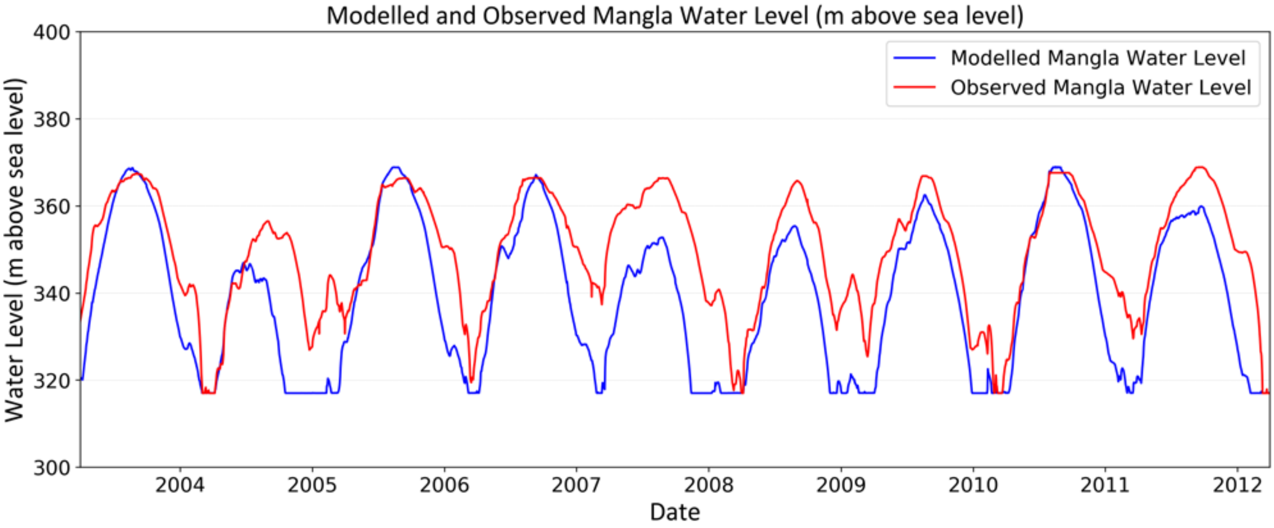


Figure 91 Comparison of observed and simulated storage level behaviour for Mangla reservoir

Whilst the overall storage behaviour has been broadly captured at Tarbela, the IRSM does not capture the season by season variation in the operational rule curve decisions that change how the storage operates. The IRSM tries to fit too closely to the designated, pre-calculated rule curves. In the case of Tarbela, the hydropower channel demand time series governs most of the release, ensuring that this storage behaves more closely to the observed water levels.

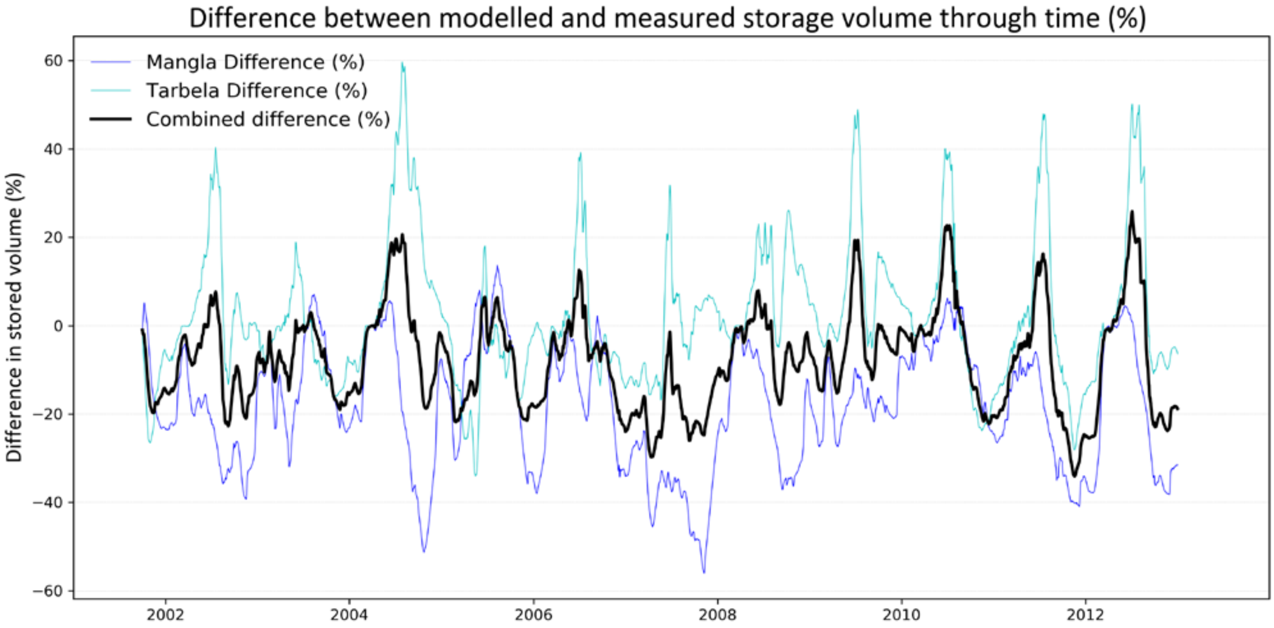


Figure 92 Volumetric difference between modelled and measured as % of storage volume

Figure 92 shows that the maximum volumetric errors in Tarbela and Mangla are as large as 60%. However, a positive error in Tarbela is offset by a negative error at Mangla. This demonstrates that the IRSM has balanced the two reservoirs differently to observed behaviour. The model consistently draws more water from Mangla and correspondingly less water from Tarbela. The combined trace shows much less error with the average of maximums at 13% and the average of minimums at -23%. This demonstrates that the IRSM has a bias towards extracting too much water from reservoirs. However, the storage capacities of the dams are considerably smaller than the mean annual inflow and when the volumetric error is compared against the mean annual inflow for Mangala, Tarbela and combined, the respective errors are 7%, 14% and 4%.

Overall the IRSM works the storage much harder than observed. This is due to several reasons:

- non-standard operations such as infrastructure maintenance and hydropower priorities;
- improved rule curves that better reflect typical operations;
- in balance in harmony operations;
- better representation of end of system flows: and
- orders not being reduced sufficiently by unregulated inflows.

The overall general behaviour is reasonably well represented for the scale of the modelling exercise but could be improved with some further model refinements. In particular, refinement of rule curves is required to better balance the water stored in Tarbela and Mangla as this could impact on the reliability of supply to water users in the JC system that can only access Mangla.

As part of the calibration process the IRSM was run with forced releases from Tarbela and Mangla and demand and distribution behaviour were significantly better. However, for running scenarios outside of history these releases must be calculated by the IRSM and consequently these results represent the compromise of allowing the model to manage the ordering and distribution of water and reflect the true performance of the model. Further refinements are possible, however specific behaviour outside of the IRSM's understanding will be much more difficult to represent without forcing behaviour, which is not desirable for future scenario analysis.

4.2.4 Model performance summary

The IRSM results provided in this Chapter are just a small selection of data that could be extracted from the model. The data presented above demonstrate three key aspects of IRSM performance, namely:

1. The seasonal forecasting and resultant provincial entitlements calculated by the IRSM replicate the current seasonal forecasting system with extremely well.
2. In translating the seasonal forecasts to provincial water entitlements, the model replicates the shares between provinces reasonably well.
3. When replicating the seasonal forecast and provincial shares, the IRSM then uses this information to drive the water requirements at barrages and canal commands. The IRSM reliably replicates the flow volumes and patterns at barrages and to canal commands with acceptable volumetric error and daily flow correlation. Link canals however are poorly correlated, indicating further refinement is needed in this area of the model. This means that the infrastructure, flow routing is appropriately parameterised within the IRSM. Further work should be undertaken to better define link canal operations and more flexible reservoir operating rules to improve IRSM's performance even more.
4. Further work is required to improve the individual and joint behaviour of Tarbela and Mangla, noting this is an area of diminishing returns for substantial calibration effort and that not all operations can and should be replicated.

5 Conclusions

The 2012 report from the Water Sector Task Force of the Friends of Democratic Pakistan highlighted five action areas to the water resources challenges faced by Pakistan. One of these solutions, under action area five, was to build knowledge and capacity with a specific focus on Australian water management culture and software tools.

In response to this report, the Australian Government engaged the CSIRO to contribute to the task of building capacity and sharing the Australian water management culture with Pakistan. This task has primarily been undertaken through the development of a river system simulation model of the Indus River System.

The model replicates the allocation and distribution of water resources in the Pakistan Indus Basin Irrigation System. Major components that are modelled include:

- Tarbela and Mangla supply storages
- Chashma balancing storage
- all barrages and link canals in the Indus and Jhelum-Chenab systems
- flow routing and unaccounted reach loss and gains
- seasonal flow forecasts (based on fixed probability tables)
- seasonal water sharing and allocation rules between provinces according to the 1991 Water Apportionment Accord
- daily distribution and delivery of water resource to command canals within provinces according to historic average delivery patterns.

Modelling of historic irrigated crop areas is also included. The productivity of the crops is considered based on the delivery of surface and groundwater resources where applicable.

Hydropower generation is also considered at major supply storages and barrages with hydropower generation capacity.

Model results for the period 2002-2012 show:

1. Simulated seasonal inflow forecasts match with historic forecasts resulting in provincial allocations that are also in agreement with historic water deliveries (cumulative difference <2%).
2. The subsequent water flows across barrages and deliveries to canal commands are also in agreement with recorded data (major barrages with an NSE 0.7 except Sukkur which is 0.6).

Replication of storage behaviour is reasonable but there is some scope for improvement. The average maximum volume error for Tarbela and Mangla are respectively 3% and 6%.

These model performance outcomes demonstrate that the IRSM is capable of simulating water sharing and allocation rules and the historic flow of water through the Indus River system. Based on this performance, the IRSM may now be used to investigate current and future water planning decisions at a basin scale by Pakistan water management agencies.

5.1 Initial recommendations for model enhancement and use

The IRSM developed for this project is intended to be used and updated by relevant agencies in Pakistan to provide support for decision making. To answer specific questions, it may require enhancement and amendment from time to time. Five key enhancements and project extensions have been identified by agencies in Pakistan and are included below as a series of recommendations that should be undertaken in the future to enhance IRSM's capability and use.

5.1.1 Enhanced model assessment

The model was built principally using 2007-2012 data. Extending the model from 2012 to 2017 and assessing the model against this more recent period will provide further verification of capability and confidence in the model. *We recommend that the IRSM now be extended and verified against the latest available flow and system planning data (up until 2018), particularly the IRSA seasonal forecasts.*

5.1.2 Model extension beyond canal command level

Making the IRSM more useful to provinces will involve extending it beyond the canal command level. This will aid the assessment of within province distribution decisions and options for management. *We recommend a pilot program to extend the IRSM beyond the canal command level to further engage the provinces and aid their province-based decision-making activities*.

5.1.3 Model enhancement for medium term (seasonal) operational assessments

The IRSM provides an assessment tool to investigate future long-term basin management options (new dams, climate change etc.). With some further enhancement, it can be made even more useful to agencies such as IRSA by adapting the model to more closely match the seasonal planning process and then assess seasonal operational planning decisions. *We recommend investigating the requirements to operationalise the IRSM to allow testing and reporting of seasonal plans, highlighting where potential seasonal shortages are more likely*.

5.1.4 Further capacity building

The IRSM makes extensive use of functions to simulate IRSA seasonal forecast calculations and provincial water distribution. Project partners in Pakistan have requested additional training in this integral component of the model to aid model acceptance and transparency. *We recommend undertaking enhanced IRSM function training for our partners in Pakistan to build further capacity and acceptance of its decision-making assessment capabilities.*.

5.1.5 Loss investigation

The IRSM provides a tool to assess reach-based distribution losses (15% of total flows in the system to the canal command level) for which there is considerable disagreement between agencies in Pakistan. *We recommend using the IRSM, in conjunction with the best available data, to analyse transmission losses for all river reaches in the IRSM to help build consensus and trust between agencies over the measurement of river flows*.

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Appendix A Conversion factors

Unit	Metric	Imperial	Conversion to metric
Distance	km	mile	1.60934
Area	ha	acre	0.404685642
Volume	m^3	ft^3	2.831685e-2
	ML	acre ft	1.23348185532
	MCM	MAF*	1.23348185532e3
	km^3	MAF	1.23348185532
Flow	m^3/s	ft^3/s	2.831685e-2
	m^3/s	ML/day	1.157407e-2
	m^3/s	kft^3/s	28.31685
	m^3/s	MAF/day	1.427641e-4
Temperature	C^o	F^0	(F0-32)*5/9

*MAF – million acre feet

Appendix B Location of key flow gauges locations in the Indus Basin Irrigation System of Pakistan

Table B-1 Location of key flow gauges

River	Country	Location	Lat	Long
Chenab	Pakistan	Khanki_Barrage	32.408078	73.969372
Chenab	Pakistan	Marala	32.672244	74.464494
Chenab	Pakistan	Punjnad_Barrage	29.345653	71.021358
Chenab	Pakistan	Qadirabad_Headworks	32.320897	73.685561
Chenab	Pakistan	Trimmu_Barrage	31.144686	72.146797
Gomal	Pakistan	Kot_Mutaza	32.149421	70.080452
Gomal	Pakistan	Gomal Zam Dam	32.098458	69.881339
Haro	Pakistan	Haro river at Garriala	33.748294	72.260934
Haro	Pakistan	KhanPur Dam	33.803000	72.929310
Indus	Pakistan	Besham_Qila	34.906242	72.866303
Indus	Pakistan	Chashma_Barrage_1971	32.435678	71.379886
Indus	Pakistan	Diamer-Basha_under_construction	35.541844	73.607217
Indus	Pakistan	Guddu_Barrage	28.418767	69.712981
Indus	Pakistan	Jinah_Barrage	32.918561	71.521800
Indus	Pakistan	Kotri_Barrage	25.442311	68.315833
Indus	Pakistan	Sukkur_Barrage	27.677200	68.846278
Indus	Pakistan	Tarbela_Dam_1976	34.088228	72.694200
Indus	Pakistan	Taunsa_Barrage	30.512883	70.849461
Jhelum	Pakistan	Mangla_Reservoir_1968	33.126378	73.644458
Jhelum	Pakistan	Rasul_Barrage	32.681267	73.519272
Kurram	Pakistan	Thal	33.355878	70.546669
Kurram	Pakistan	Daratang	32.609286	71.165599
Ravi	Pakistan	Balloki_Barrage	31.221122	73.859908
Ravi	Pakistan	Sidhnai_Barrage	30.572306	72.157681
Soan	Pakistan	Chirrah	33.657906	73.305031
Soan	Pakistan	Dhok_Pattan	33.130681	72.350772
Soan	Pakistan	Simly	33.720560	73.341940
Soan	Pakistan	Rawal Lake	33.693880	73.122960
Sutlej	Pakistan	Border_Ganda_Singh_Wala	30.992181	74.554639
Sutlej	Pakistan	Islam_Barrage	29.826039	72.549236
Sutlej	Pakistan	Sulemanki_Barrage	30.377769	73.866556

Appendix C Storage level-volume-area tables

Table C-1 Tarbela LVAs 1998-2001

1998 LVA			2000 LVA			2001 LVA		
Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)
0	0	0	0	0	0	0	0	0
1.524	1219297	18.47941	1.524	1034891	18.47941	1.524	1034891	18.47941
3.048	1270486	19.20441	3.048	1071896	19.20441	3.048	1071896	19.20441
4.572	1324759	19.92941	4.572	1110750	19.92941	4.572	1110134	19.92941
6.096	1379033	20.61438	6.096	1149605	20.61438	6.096	1148372	20.61438
7.62	1434539	21.26673	7.62	1189693	21.26673	7.62	1187843	21.26673
9.144	1490046	21.98432	9.144	1229781	21.98432	9.144	1227314	21.98432
10.668	1548020	22.6693	10.668	1271103	22.6693	10.668	1268019	22.6693
12.192	1605993	23.4195	12.192	1312425	23.4195	12.192	1308724	23.4195
13.716	1666434	24.13709	13.716	1355597	24.13709	13.716	1350663	24.13709
15.24	1726875	24.8873	15.24	1398768	24.8873	15.24	1391368	24.8873
16.764	1837888	25.63751	16.764	1511632	25.63751	16.764	1496213	25.63751
18.288	1948901	26.42033	18.288	1624496	26.42033	18.288	1601059	26.42033
19.812	2063615	27.23577	19.812	1741060	27.23577	19.812	1709606	27.23577
21.336	2178329	29.16022	21.336	1857624	29.16022	21.336	1818152	29.16022
22.86	2297360	31.08466	22.86	1978505	31.08466	22.86	1930399	31.08466
24.384	2416391	33.07434	24.384	2099386	33.07434	24.384	2042646	33.07434
25.908	2540973	35.06402	25.908	2225818	35.06402	25.908	2159827	35.06402
27.432	2665554	37.11893	27.432	2352250	37.11893	27.432	2277007	37.11893
28.956	2796303	39.17385	28.956	2484849	39.17385	28.956	2400356	39.17385
30.48	2927052	41.32662	30.48	2617448	41.32662	30.48	2522470	41.32662
32.004	3123176	43.47938	32.004	2815422	43.47938	32.004	2718594	43.47938
33.528	3319300	45.73	33.528	3013396	45.73	33.528	2913484	45.73
35.052	3522824	48.01324	35.052	3218154	48.01324	35.052	3117009	48.01324
36.576	3726349	52.71019	36.576	3422912	52.71019	36.576	3319300	52.71019
38.1	3936041	57.43975	38.1	3633838	57.43975	38.1	3528992	57.43975
39.624	4145814	62.29979	39.624	3844763	62.29979	39.624	3737450	62.29979
41.148	4364675	67.19244	41.148	4064939	67.19244	41.148	3955776	67.19244
42.672	4583619	72.21557	42.672	4285116	72.21557	42.672	4172869	72.21557
44.196	4813046	77.23869	44.196	4515777	77.23869	44.196	4402297	77.23869
45.72	5042474	82.45752	45.72	4746438	82.45752	45.72	4630491	82.45752
47.244	5301505	87.70897	47.244	5006086	87.70897	47.244	4890755	87.70897
48.768	5560536	93.22136	48.768	5265734	93.22136	48.768	5149787	93.22136
50.292	5828818	98.70113	50.292	5535250	98.70113	50.292	5418686	98.70113
51.816	6097101	105.5509	51.816	5804766	105.5509	51.816	5687585	105.5509
53.34	6372167	112.4006	53.34	6081065	112.4006	53.34	5963885	112.4006
54.864	6647234	119.5112	54.864	6357365	119.5112	54.864	6238951	119.5112
56.388	6932785	126.5893	56.388	6644150	126.5893	56.388	6525119	126.5893
57.912	7218336	133.863	57.912	6930934	133.863	57.912	6811287	133.863
59.436	7514988	141.1368	59.436	7229437	141.1368	59.436	7109789	141.1368

1998 LVA			2000 LVA			2001 LVA		
Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)
60.96	7811640	148.6714	60.96	7527940	148.6714	60.96	7407058	148.6714
62.484	8116311	156.2387	62.484	7832610	156.2387	62.484	7711728	156.2387
64.008	8420981	164.067	64.008	8137280	164.067	64.008	8015165	164.067
65.532	8736752	171.9279	65.532	8453051	171.9279	65.532	8330936	171.9279
67.056	9052523	179.9844	67.056	8768822	179.9844	67.056	8646708	179.9844
68.58	9381246	188.0084	68.58	9097545	188.0084	68.58	8976047	188.0084
70.104	9709969	196.3585	70.104	9426268	196.3585	70.104	9304154	196.3585
71.628	10053494	204.7086	71.628	9769793	204.7086	71.628	9648295	204.7086
73.152	10397018	213.3849	73.152	10113318	213.3849	73.152	9991203	213.3849
74.676	10756578	222.0939	74.676	10472878	222.0939	74.676	10350146	222.0939
76.2	11116138	231.1942	76.2	10832438	231.1942	76.2	10709089	231.1942

Table C-2 Tarbela LVAs 2002-2004

2002 LVA			2003 LVA			2004 LVA		
Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)
0	0	0	0	0	0	0	0	0
1.524	1031807.559	18.47940957	1.524	993569.6221	18.47940957	1.524	955948.426	18.47940957
3.048	1066961.792	19.20440957	3.048	1027490.373	19.20440957	3.048	986785.472	19.20440957
4.572	1103966.247	19.92940957	4.572	1062644.605	19.92940957	4.572	1020089.482	19.92940957
6.096	1140970.702	20.61438109	6.096	1097798.838	20.61438109	6.096	1053393.491	20.61438109
7.62	1179208.639	21.26673492	7.62	1134803.293	21.26673492	7.62	1087930.983	21.26673492
9.144	1217446.576	21.98432414	9.144	1171807.748	21.98432414	9.144	1122468.474	21.98432414
10.668	1256917.995	22.66929566	10.668	1210045.685	22.66929566	10.668	1158239.448	22.66929566
12.192	1296389.414	23.41950257	12.192	1248283.622	23.41950257	12.192	1194010.421	23.41950257
13.716	1337094.315	24.13709178	13.716	1288988.523	24.13709178	13.716	1232248.358	24.13709178
15.24	1377799.215	24.88729869	15.24	1329693.424	24.88729869	15.24	1269252.813	24.88729869
16.764	1475244.281	25.6375056	16.764	1420354.339	25.6375056	16.764	1356830.024	25.6375056
18.288	1572689.346	26.4203302	18.288	1511015.254	26.4203302	18.288	1444407.235	26.4203302
19.812	1673218.116	27.23577249	19.812	1605376.615	27.23577249	19.812	1535684.891	27.23577249
21.336	1773746.886	29.16021629	21.336	1699737.976	29.16021629	21.336	1625729.065	29.16021629
22.86	1877976.101	31.08466009	22.86	1797799.782	31.08466009	22.86	1720707.167	31.08466009
24.384	1982205.317	33.07433928	24.384	1895861.588	33.07433928	24.384	1814451.787	33.07433928
25.908	2091368.46	35.06401847	25.908	1998240.581	35.06401847	25.908	1913130.334	35.06401847
27.432	2200531.603	37.11893304	27.432	2100619.574	37.11893304	27.432	2010575.399	37.11893304
28.956	2315245.414	39.17384761	28.956	2208549.235	39.17384761	28.956	2114187.874	39.17384761
30.48	2429959.225	41.32661526	30.48	2316478.896	41.32661526	30.48	2217800.348	41.32661526
32.004	2622999.133	43.4793829	32.004	2509518.803	43.4793829	32.004	2411456.997	43.4793829
33.528	2816039.041	45.73000362	33.528	2702558.711	45.73000362	33.528	2603880.164	45.73000362
35.052	3015863.099	48.01324204	35.052	2902382.77	48.01324204	35.052	2803704.222	48.01324204
36.576	3215687.157	52.71018963	36.576	3102206.828	52.71018963	36.576	3003528.28	52.71018963
38.1	3421678.624	57.43975491	38.1	3308198.295	57.43975491	38.1	3209519.748	57.43975491
39.624	3627670.091	62.29979096	39.624	3514189.762	62.29979096	39.624	3415511.215	62.29979096
41.148	3842912.673	67.1924447	41.148	3728198.861	67.1924447	41.148	3630137.055	67.1924447
42.672	4058155.254	72.2155692	42.672	3942207.961	72.2155692	42.672	3844762.895	72.2155692

2002 LVA			2003 LVA			2004 LVA		
Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)
44.196	4283265.689	77.23869371	44.196	4167318.396	77.23869371	44.196	4070490.072	77.23869371
45.72	4508376.125	82.45752436	45.72	4392428.832	82.45752436	45.72	4296217.249	82.45752436
47.244	4768024.053	87.70897271	47.244	4652076.76	87.70897271	47.244	4556481.917	87.70897271
48.768	5027671.98	93.22136259	48.768	4911724.687	93.22136259	48.768	4816746.585	93.22136259
50.292	5296571.021	98.70113478	50.292	5181240.469	98.70113478	50.292	5086879.108	98.70113478
51.816	5565470.062	105.55085	51.816	5450756.251	105.55085	51.816	5355778.149	105.55085
53.34	5841153.253	112.4005653	53.34	5727056.183	112.4005653	53.34	5632078.081	112.4005653
54.864	6116836.445	119.511222	54.864	6003356.115	119.511222	54.864	5908378.014	119.511222
56.388	6403620.972	126.5892611	56.388	6290140.643	126.5892611	56.388	6195779.282	126.5892611
57.912	6690405.5	133.8630063	57.912	6576925.171	133.8630063	57.912	6481947.069	133.8630063
59.436	6988908.105	141.1367516	59.436	6875427.776	141.1367516	59.436	6781683.156	141.1367516
60.96	7287410.711	148.6714383	60.96	7173930.381	148.6714383	60.96	7080185.762	148.6714383
62.484	7592080.725	156.2387428	62.484	7478600.396	156.2387428	62.484	7384855.776	156.2387428
64.008	7896750.74	164.0669887	64.008	7783270.41	164.0669887	64.008	7690759.272	164.0669887
65.532	8213138.832	171.9278524	65.532	8099658.502	171.9278524	65.532	8006530.623	171.9278524
67.056	8529526.924	179.9844222	67.056	8416046.594	179.9844222	67.056	8323535.456	179.9844222
68.58	8858249.834	188.0083744	68.58	8744769.505	188.0083744	68.58	8651641.626	188.0083744
70.104	9186972.744	196.3585034	70.104	9073492.415	196.3585034	70.104	8980981.277	196.3585034
71.628	9530497.437	204.7086325	71.628	9417017.107	204.7086325	71.628	9323889.229	204.7086325
73.152	9874022.129	213.3849384	73.152	9760541.8	213.3849384	73.152	9668030.662	213.3849384
74.676	10232348.6	222.0938621	74.676	10120101.76	222.0938621	74.676	10026973.88	222.0938621
76.2	10590675.08	231.1941981	76.2	10479661.71	231.1941981	76.2	10387150.57	231.1941981

Table C-3 Tarbela LVAs 2005-2008

2005 LVA			2007 LVA			2008 LVA		
Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)	Level (m)	Volume (ML)	Surface Area (km²)
0	0	0	0	0	0	0	0	0
1.524	951631.2396	18.47940957	1.524	912776.5616	18.47940957	1.524	838767.6512	18.47940957
3.048	983085.0265	19.20440957	3.048	943613.6076	19.20440957	3.048	867137.7335	19.20440957
4.572	1016389.036	19.92940957	4.572	975684.1354	19.92940957	4.572	896741.2977	19.92940957
6.096	1049693.046	20.61438109	6.096	1007754.663	20.61438109	6.096	926344.8618	20.61438109
7.62	1084230.537	21.26673492	7.62	1041058.673	21.26673492	7.62	957181.9078	21.26673492
9.144	1118768.029	21.98432414	9.144	1074362.683	21.98432414	9.144	988018.9538	21.98432414
10.668	1154539.002	22.66929566	10.668	1108900.174	22.66929566	10.668	1020089.482	22.66929566
12.192	1190309.976	23.41950257	12.192	1143437.666	23.41950257	12.192	1052160.01	23.41950257
13.716	1227314.431	24.13709178	13.716	1179825.38	24.13709178	13.716	1085464.019	24.13709178
15.24	1264318.886	24.88729869	15.24	1216213.094	24.88729869	15.24	1118768.029	24.88729869
16.764	1350662.615	25.6375056	16.764	1292688.968	25.6375056	16.764	1193393.68	25.6375056
18.288	1437006.344	26.4203302	18.288	1369164.842	26.4203302	18.288	1268019.332	26.4203302
19.812	1526433.777	27.23577249	19.812	1448724.421	27.23577249	19.812	1345728.687	27.23577249
21.336	1615861.21	29.16021629	21.336	1528284	29.16021629	21.336	1423438.043	29.16021629
22.86	1708372.348	31.08466009	22.86	1610310.542	31.08466009	22.86	1503614.363	31.08466009
24.384	1800883.486	33.07433928	24.384	1692337.084	33.07433928	24.384	1583790.683	33.07433928
25.908	1897711.811	35.06401847	25.908	1778064.072	35.06401847	25.908	1667667.448	35.06401847

2005 LVA			2007 LVA			2008 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)
27.432	1994540.135	37.11893304	27.432	1863791.06	37.11893304	27.432	1751544.213	37.11893304
28.956	2096302.387	39.17384761	28.956	1954451.975	39.17384761	28.956	1839738.164	39.17384761
30.48	2198064.639	41.32661526	30.48	2082117.346	41.32661526	30.48	1927932.116	41.32661526
32.004	2385553.879	43.4793829	32.004	2216566.866	43.4793829	32.004	2103086.537	43.4793829
33.528	2573043.118	45.73000362	33.528	2388020.842	45.73000362	33.528	2278240.958	45.73000362
35.052	2767316.508	48.01324204	35.052	2565642.227	48.01324204	35.052	2458946.048	48.01324204
36.576	2961589.898	52.71018963	36.576	2743263.612	52.71018963	36.576	2639651.138	52.71018963
38.1	3162030.697	57.43975491	38.1	2926435.665	57.43975491	38.1	2825906.895	57.43975491
39.624	3362471.496	62.29979096	39.624	3109607.719	62.29979096	39.624	3012162.653	62.29979096
41.148	3571546.668	67.1924447	41.148	3300180.663	67.1924447	41.148	3206436.043	67.1924447
42.672	3780621.84	72.2155692	42.672	3490753.607	72.2155692	42.672	3400709.433	72.2155692
44.196	3999564.866	77.23869371	44.196	3691194.406	77.23869371	44.196	3604233.936	77.23869371
45.72	4218507.893	82.45752436	45.72	3891635.205	82.45752436	45.72	3807758.44	82.45752436
47.244	4476922.338	87.70897271	47.244	4149432.91	87.70897271	47.244	4064322.663	87.70897271
48.768	4735336.784	93.22136259	48.768	4407230.614	93.22136259	48.768	4320886.886	93.22136259
50.292	5003002.343	98.70113478	50.292	4674279.433	98.70113478	50.292	4586702.222	98.70113478
51.816	5270667.902	105.55085	51.816	4941328.251	105.55085	51.816	4852517.559	105.55085
53.34	5545117.612	112.4005653	53.34	5215161.22	112.4005653	53.34	5125117.045	112.4005653
54.864	5819567.321	119.511222	54.864	5488994.188	119.511222	54.864	5397716.532	119.511222
56.388	6104501.626	126.5892611	56.388	5773928.493	126.5892611	56.388	5681417.355	126.5892611
57.912	6389435.931	133.8630063	57.912	6058862.798	133.8630063	57.912	5965118.178	133.8630063
59.436	6686088.314	141.1367516	59.436	6355515.181	141.1367516	59.436	6259920.338	141.1367516
60.96	6982740.696	148.6714383	60.96	6652167.563	148.6714383	60.96	6554722.498	148.6714383
62.484	7287410.711	156.2387428	62.484	6956220.837	156.2387428	62.484	6858775.771	156.2387428
64.008	7592080.725	164.0669887	64.008	7260274.11	164.0669887	64.008	7162829.045	164.0669887
65.532	7907852.076	171.9278524	65.532	7576045.461	171.9278524	65.532	7478600.396	171.9278524
67.056	8223623.427	179.9844222	67.056	7891816.812	179.9844222	67.056	7794371.747	179.9844222
68.58	8552346.338	188.0083744	68.58	8220539.723	188.0083744	68.58	8123094.657	188.0083744
70.104	8881069.248	196.3585034	70.104	8549262.633	196.3585034	70.104	8451817.568	196.3585034
71.628	9225210.681	204.7086325	71.628	8892170.585	204.7086325	71.628	8795342.26	204.7086325
73.152	9569352.115	213.3849384	73.152	9235078.536	213.3849384	73.152	9138866.953	213.3849384
74.676	9928295.33	222.0938621	74.676	9592788.27	222.0938621	74.676	9497193.427	222.0938621
76.2	10287238.55	231.1941981	76.2	9950498.003	231.1941981	76.2	9855519.902	231.1941981

Table C-4 Tarbela LVAs 2009-2012

2009 LVA			2011 LVA			2012 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)
0	0	0	0	0	0	0	0	0
1.524	778943.8	18.47941	1.524	748723.5	18.47941	1.524	740705.8	18.47941
3.048	804230.2	19.20441	3.048	770926.2	19.20441	3.048	762291.8	19.20441
4.572	830750	19.92941	4.572	794362.3	19.92941	4.572	785111.2	19.92941
6.096	857269.9	20.61438	6.096	817798.5	20.61438	6.096	807930.6	20.61438
7.62	885023.2	21.26673	7.62	841851.4	21.26673	7.62	831366.8	21.26673
9.144	912776.6	21.98432	9.144	865904.3	21.98432	9.144	854802.9	21.98432

2009 LVA			2011 LVA			2012 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)
10.668	941146.6	22.6693	10.668	891190.6	22.6693	10.668	879472.6	22.6693
12.192	969516.7	23.4195	12.192	916477	23.4195	12.192	904142.2	23.4195
13.716	999737	24.13709	13.716	942996.9	24.13709	13.716	941886.7	24.13709
15.24	1029957	24.8873	15.24	969516.7	24.8873	15.24	954714.9	24.8873
16.764	1102733	25.63751	16.764	1037975	25.63751	16.764	1019473	25.63751
18.288	1175508	26.42033	18.288	1106433	26.42033	18.288	1084231	26.42033
19.812	1250751	27.23577	19.812	1177358	27.23577	19.812	1151455	27.23577
21.336	1325993	29.16022	21.336	1248284	29.16022	21.336	1218680	29.16022
22.86	1403702	31.08466	22.86	1321676	31.08466	22.86	1288495	31.08466
24.384	1481412	33.07434	24.384	1395068	33.07434	24.384	1358064	33.07434
25.908	1562821	35.06402	25.908	1472777	35.06402	25.908	1431579	35.06402
27.432	1644231	37.11893	27.432	1550487	37.11893	27.432	1504848	37.11893
28.956	1729958	39.17385	28.956	1631280	39.17385	28.956	1581324	39.17385
30.48	1815685	41.32662	30.48	1712073	41.32662	30.48	1657800	41.32662
32.004	1993923	43.47938	32.004	1882910	43.47938	32.004	1818152	43.47938
33.528	2172162	45.73	33.528	2053747	45.73	33.528	1978505	45.73
35.052	2356567	48.01324	35.052	2230752	48.01324	35.052	2144532	48.01324
36.576	2540973	52.71019	36.576	2407757	52.71019	36.576	2310311	52.71019
38.1	2730929	57.43975	38.1	2590312	57.43975	38.1	2481765	57.43975
39.624	2920885	62.29979	39.624	2772867	62.29979	39.624	2653219	62.29979
41.148	3118859	67.19244	41.148	2964057	67.19244	41.148	2832814	67.19244
42.672	3316833	72.21557	42.672	3155247	72.21557	42.672	3009696	72.21557
44.196	3524798	77.23869	44.196	3355071	77.23869	44.196	3197185	77.23869
45.72	3732516	82.45752	45.72	3554895	82.45752	45.72	3384674	82.45752
47.244	3991547	87.70897	47.244	3810225	87.70897	47.244	3643705	87.70897
48.768	4250578	93.22136	48.768	4065556	93.22136	48.768	3902737	93.22136
50.292	4518984	98.70113	50.292	4329521	98.70113	50.292	4171636	98.70113
51.816	4787143	105.5509	51.816	4593486	105.5509	51.816	4440535	105.5509
53.34	5062209	112.4006	53.34	4864236	112.4006	53.34	4716218	112.4006
54.864	5337276	119.5112	54.864	5134985	119.5112	54.864	4991901	119.5112
56.388	5622950	126.5893	56.388	5416219	126.5893	56.388	5278069	126.5893
57.912	5908378	133.863	57.912	5697453	133.863	57.912	5564237	133.863
59.436	6205030	141.1368	59.436	5990405	141.1368	59.436	5862122	141.1368
60.96	6501683	148.6714	60.96	6283356	148.6714	60.96	6160008	148.6714
62.484	6805736	156.2387	62.484	6583093	156.2387	62.484	6460361	156.2387
64.008	7109789	164.067	64.008	6882829	164.067	64.008	6760714	164.067
65.532	7425561	171.9279	65.532	7194283	171.9279	65.532	7072168	171.9279
67.056	7741332	179.9844	67.056	7505737	179.9844	67.056	7383622	179.9844
68.58	8070055	188.0084	68.58	7829526	188.0084	68.58	7708028	188.0084
70.104	8398778	196.3585	70.104	8153315	196.3585	70.104	8032434	196.3585
71.628	8742303	204.7086	71.628	8491906	204.7086	71.628	8371641	204.7086
73.152	9085827	213.3849	73.152	8830496	213.3849	73.152	8710849	213.3849
74.676	9455872	222.0939	74.676	9183889	222.0939	74.676	9064241	222.0939
76.2	9801247	231.1942	76.2	9537282	231.1942	76.2	9417634	231.1942

Table C-5 Tarbela LVAs 2013

2013 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)
0	0	0
1.524	666696.9	18.47941
3.048	684582.4	19.20441
4.572	703701.4	19.92941
6.096	722820.4	20.61438
7.62	742556.1	21.26673
9.144	762291.8	21.98432
10.668	782644.2	22.6693
12.192	802996.7	23.4195
13.716	823965.9	24.13709
15.24	844935.1	24.8873
16.764	909076.1	25.63751
18.288	973217.2	26.42033
19.812	1039825	27.23577
21.336	1106433	29.16022
22.86	1175508	31.08466
24.384	1244583	33.07434
25.908	1316742	35.06402
27.432	1388901	37.11893
28.956	1465376	39.17385
30.48	1541852	41.32662
32.004	1704672	43.47938
33.528	1867492	45.73
35.052	2035862	48.01324
36.576	2204232	52.71019
38.1	2378153	57.43975
39.624	2552074	62.29979
41.148	2733396	67.19244
42.672	2914718	72.21557
44.196	3105291	77.23869
45.72	3295863	82.45752
47.244	3555511	87.70897
48.768	3815159	93.22136
50.292	4084058	98.70113
51.816	4352957	105.5509
53.34	4629257	112.4006
54.864	4905557	119.5112
56.388	5192342	126.5893
57.912	5479126	133.863
59.436	5777629	141.1368
60.96	6076132	148.6714
62.484	6376484	156.2387
64.008	6676837	164.067
65.532	6988908	171.9279
67.056	7300979	179.9844

2013 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)
68.58	7625385	188.0084
70.104	7949790	196.3585
71.628	8288998	204.7086
73.152	8628205	213.3849
74.676	8981598	222.0939
76.2	9334991	231.1942

Table C-6 Mangla LVAs 1993-2003

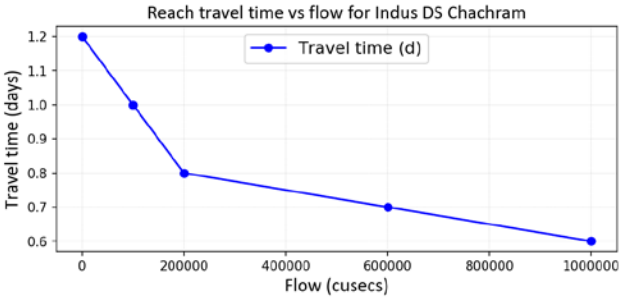
1993 LVA			1997 LVA			2003 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)
0	265301	0	0	189586.2	0	0	0	0
3.048	340640.8	749.9965	3.048	230537.8	749.9965	3.048	168098.9	749.9965
6.096	425966.9	1045.45	6.096	284811	1045.45	6.096	286932.5	1045.45
9.144	510428.4	1426.13	9.144	350555.5	1426.13	9.144	352652.5	1426.13
12.192	617297.2	1920.446	12.192	441216.5	1920.446	12.192	442548.6	1920.446
15.24	743636.6	2613.624	15.24	560740.8	2613.624	15.24	564157.6	2613.624
18.288	887860.2	3460.211	18.288	712705.8	3460.211	18.288	694351.6	3460.211
18.5928	907441.8	3561.915	18.5928	731701.4	3561.915	18.5928	715579.8	3561.915
21.336	1086176	4477.252	21.336	902662	4477.252	21.336	910371.3	4477.252
24.384	1330030	5647.701	24.384	1136530	5647.701	24.384	1143894	5647.701
27.432	1624683	7022.694	27.432	1402839	7022.694	27.432	1407181	7022.694
30.48	1966549	8630.641	30.48	1733042	8630.641	30.48	1732857	8630.641
33.528	2367322	10477.22	33.528	2167844	10477.22	33.528	2167585	10477.22
36.576	2829430	12568.12	36.576	2633730	12568.12	36.576	2633459	12568.12
39.624	3348981	14857.88	39.624	3174489	14857.88	39.624	3174304	14857.88
42.672	3914627	17357.87	42.672	3746084	17357.87	42.672	3745875	17357.87
45.72	4533220	20045.36	45.72	4383918	20045.36	45.72	4371398	20045.36
48.768	5213649	22880.57	48.768	5058386	22880.57	48.768	5022590	22880.57
51.816	5955094	25897.61	51.816	5797611	25897.61	51.816	5650630	25897.61
52.4256	6115646	26752.48	52.4256	5948590	26752.48	52.4256	5797759	26752.48
54.864	6636177	29533.95	54.864	6594934	29533.95	54.864	6444203	29533.95
57.912	7432207	33494.16	57.912	7454794	33494.16	57.912	7303976	33494.16
60.96	8276366	37681.64	60.96	8181932	37681.64	60.96	8212966	37681.64
64.008	9168655	42114.37	64.008	9097056	42114.37	64.008	9169766	42114.37
64.6176	9352889	43046.72	64.6176	9286374	43046.72	64.6176	9370589	43046.72
64.9224	9445727	43517.53	64.9224	9381790	43517.53	64.9224	9470994	43517.53
71.9328	11713853	55200.62	71.9328	11715509	55200.62	71.9328	11894650	55200.62

Table C-7 Mangla LVAs 2004-2011

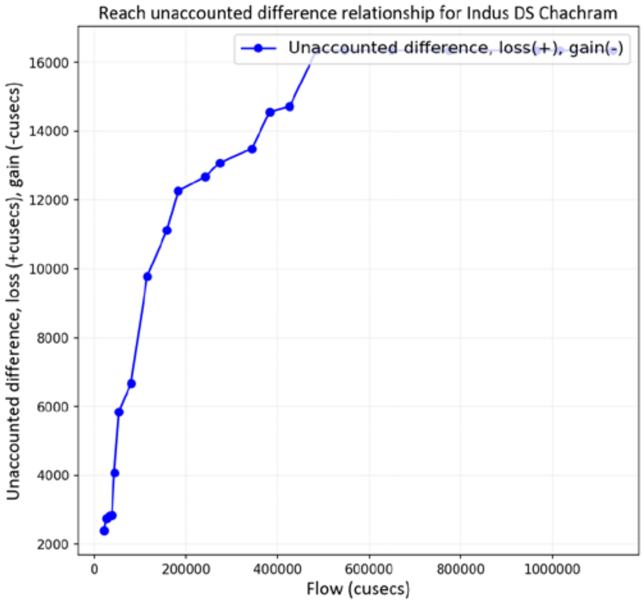
2004 LVA			2011 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)
0	0	0	0	0	0
3.048	173797.6	749.9965	3.048	120881.2	749.9965
6.096	237198.6	1045.45	6.096	181321.8	1045.45
9.144	318608.4	1426.13	9.144	263965.1	1426.13

2004 LVA			2011 LVA		
Level (m)	Volume (ML)	Surface Area (km^2)	Level (m)	Volume (ML)	Surface Area (km^2)
12.192	426044.6	1920.446	12.192	367577.6	1920.446
15.24	576406.1	2613.624	15.24	502027.1	2613.624
18.288	761921.7	3460.211	18.288	666080.2	3460.211
18.5928	782397.5	3561.915	18.5928	685815.9	3561.915
21.336	983331.7	4477.252	21.336	867137.7	4477.252
24.384	1240019	5647.701	24.384	1112601	5647.701
27.432	1542592	7022.694	27.432	1398768	7022.694
30.48	1895368	8630.641	30.48	1740443	8630.641
33.528	2258382	10477.22	33.528	2127756	10477.22
36.576	2759916	12568.12	36.576	2563175	12568.12
39.624	3263546	14857.88	39.624	3051634	14857.88
42.672	3812569	17357.87	42.672	3586965	17357.87
45.72	4402297	20045.36	45.72	4169169	20045.36
48.768	5025698	22880.57	48.768	4815513	22880.57
51.816	5688572	25897.61	51.816	5513664	25897.61
52.4256	5832642	26752.48	52.4256	5677717	26752.48
54.864	6385119	29533.95	54.864	6231550	29533.95
57.912	7107939	33494.16	57.912	7171463	33494.16
60.96	7857773	37681.64	60.96	8080540	37681.64
64.008	8874097	42114.37	64.008	9037721	42114.37
64.6176	9048611	43046.72	64.6176	9238779	43046.72
64.9224	9136522	43517.53	64.9224	9338691	43517.53
71.9328	11278649	55200.62	71.9328	11762483	55200.62

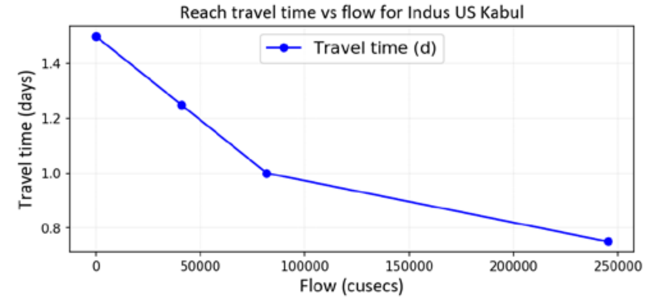
Appendix D Reach routing and loss parameters


Reach travel time vs flow for Indus DS Chachram

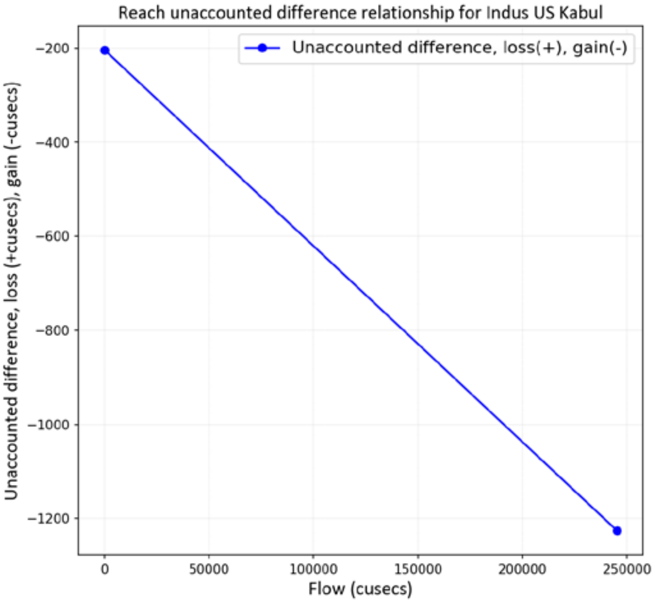
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.2
100000.0	244658.0	1.0
200000.0	489315.0	0.8
600000.0	1467945.0	0.7
1000000.0	2446576.0	0.6


Reach unaccounted difference relationship for Indus DS Chachram

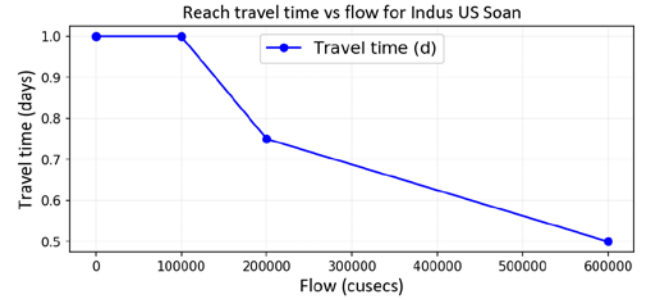
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
20356.0	2393.0	49802.0	5854.0
25584.0	2756.0	62593.0	6743.0
33248.0	2818.0	81344.0	6894.0
38116.0	2845.0	93254.0	6961.0
43162.0	4079.0	105599.0	9980.0
53365.0	5855.0	130562.0	14324.0
79647.0	6669.0	194862.0	16317.0
115238.0	9783.0	281938.0	23935.0
158054.0	11117.0	386691.0	27198.0
182808.0	12262.0	447254.0	30000.0
241090.0	12671.0	589845.0	31000.0
273749.0	13080.0	669747.0	32000.0
343658.0	13488.0	840786.0	33000.0
382357.0	14557.0	935464.0	35615.0
426130.0	14714.0	1042559.0	36000.0
484772.0	16349.0	1186032.0	40000.0
546094.0	16349.0	1336060.0	40000.0
648815.0	16349.0	1587375.0	40000.0
773847.0	16349.0	1893274.0	40000.0
964382.0	16349.0	2359434.0	40000.0
1015708.0	16349.0	2485006.0	40000.0
1132095.0	16349.0	2769756.0	40000.0


Reach travel time vs flow for Indus US Kabul

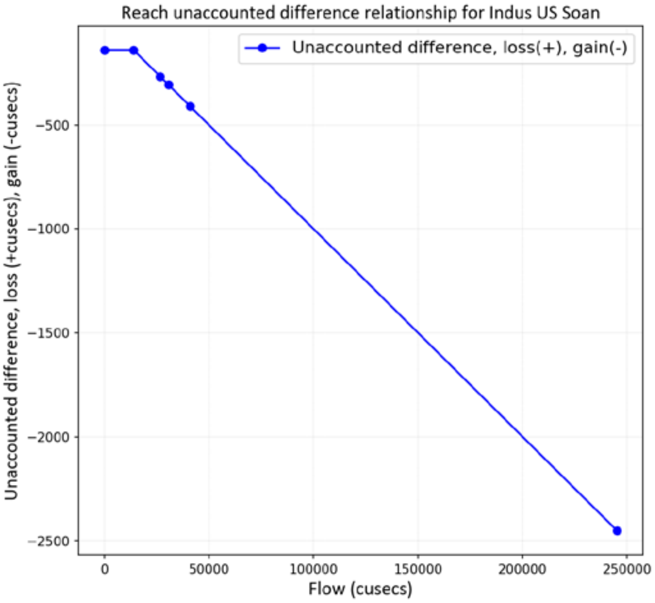
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.5
40873.0	100000.0	1.25
81747.0	200000.0	1.0
245241.0	600000.0	0.75


Reach unaccounted difference relationship for Indus US Kabul

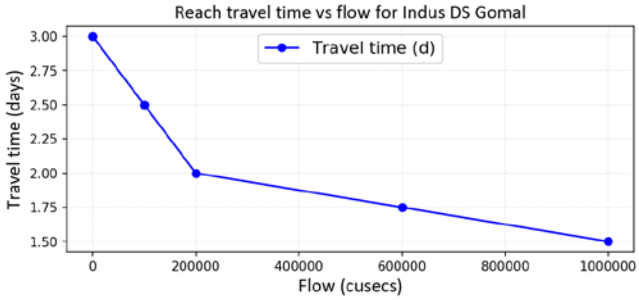
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	-204.0	0.0	-500.0
245241.0	-1226.0	600000.0	-3000.0


Reach travel time vs flow for Indus US Soan

Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.0
100000.0	244658.0	1.0
200000.0	489315.0	0.75
600000.0	1467945.0	0.5

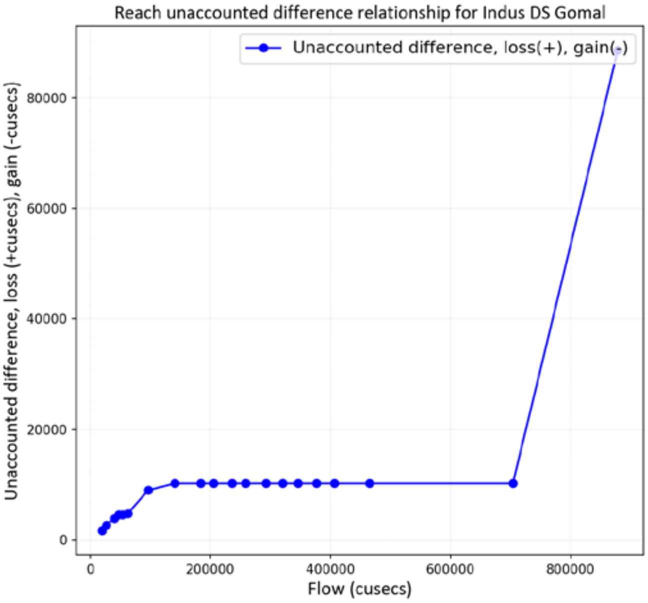

Reach unaccounted difference relationship for Indus US Soan

Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	-139.0	0.0	-340.0
13897.0	-139.0	34000.0	-340.0
26568.0	-266.0	65000.0	-650.0
30655.0	-307.0	75000.0	-750.0
40873.0	-409.0	100000.0	-1000.0
245241.0	-2452.0	600000.0	-6000.0



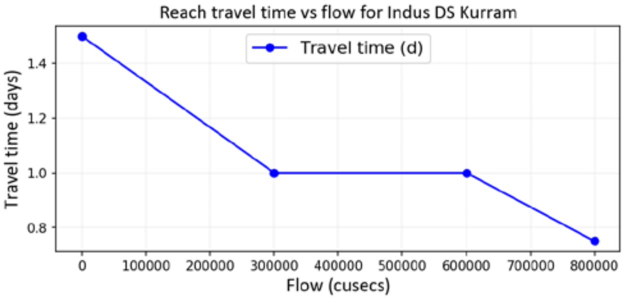
Reach travel time vs flow for Indus DS Gomal

Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	3.0
100000.0	244658.0	2.5
200000.0	489315.0	2.0
600000.0	1467945.0	1.75
1000000.0	2446576.0	1.5



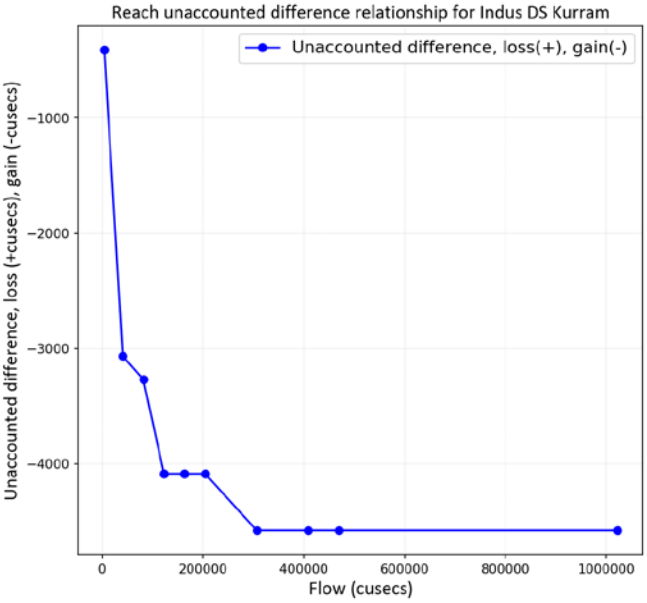
Reach unaccounted difference relationship for Indus DS Gomal

Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
19869.0	1665.0	48610.0	4074.0
27343.0	2706.0	66897.0	6620.0
40000.0	3920.0	97863.0	9590.0
47085.0	4538.0	115198.0	11103.0
53096.0	4617.0	129903.0	11297.0
63095.0	4812.0	154367.0	11773.0
96827.0	8995.0	236895.0	22006.0
141111.0	10218.0	345238.0	25000.0
183520.0	10218.0	448996.0	25000.0
205313.0	10218.0	502313.0	25000.0
236224.0	10218.0	577939.0	25000.0
258442.0	10218.0	632298.0	25000.0
292182.0	10218.0	714846.0	25000.0
320316.0	10218.0	783677.0	25000.0
346375.0	10218.0	847432.0	25000.0
376465.0	10218.0	921051.0	25000.0
406933.0	10218.0	995593.0	25000.0
464659.0	10218.0	1136823.0	25000.0
704000.0	10218.0	1722389.0	25000.0
878898.0	88657.0	2150289.0	216907.0



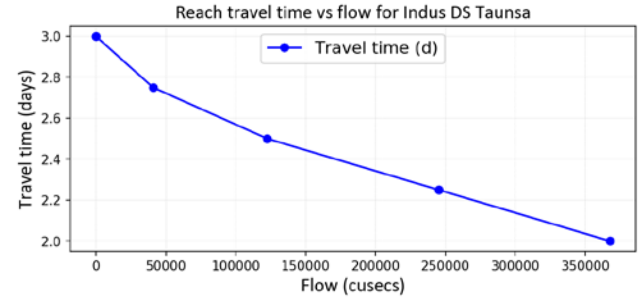
Reach travel time vs flow for Indus DS Kurram

Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.5
300000.0	733973.0	1.0
600000.0	1467945.0	1.0
800000.0	1957260.0	0.75

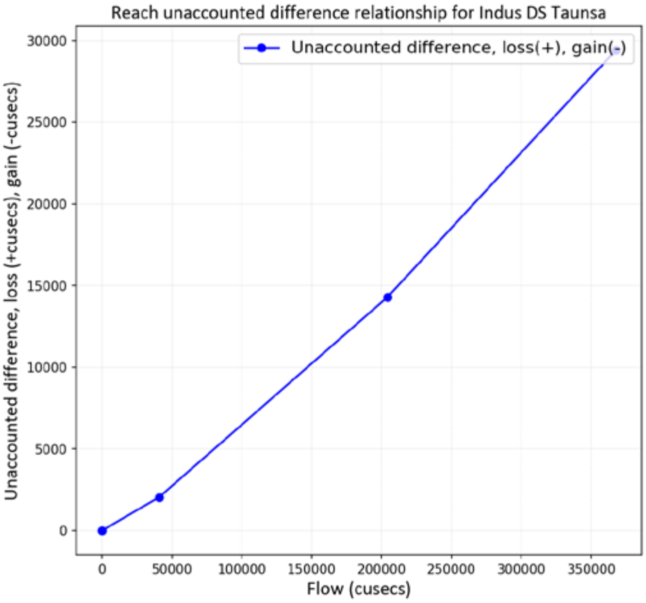


Reach unaccounted difference relationship for Indus DS Kurram

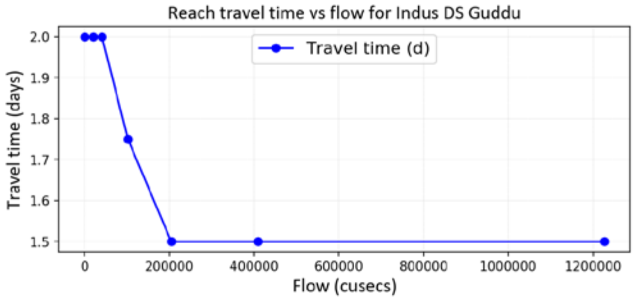
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
4087.0	-409.0	10000.0	-1000.0
40873.0	-3066.0	100000.0	-7500.0
81747.0	-3270.0	200000.0	-8000.0
122620.0	-4087.0	300000.0	-10000.0
163494.0	-4087.0	400000.0	-10000.0
204367.0	-4087.0	500000.0	-10000.0
306551.0	-4578.0	750000.0	-11200.0
408735.0	-4578.0	1000000.0	-11200.0
470045.0	-4578.0	1150000.0	-11200.0
1021836.0	-4578.0	2500000.0	-11200.0



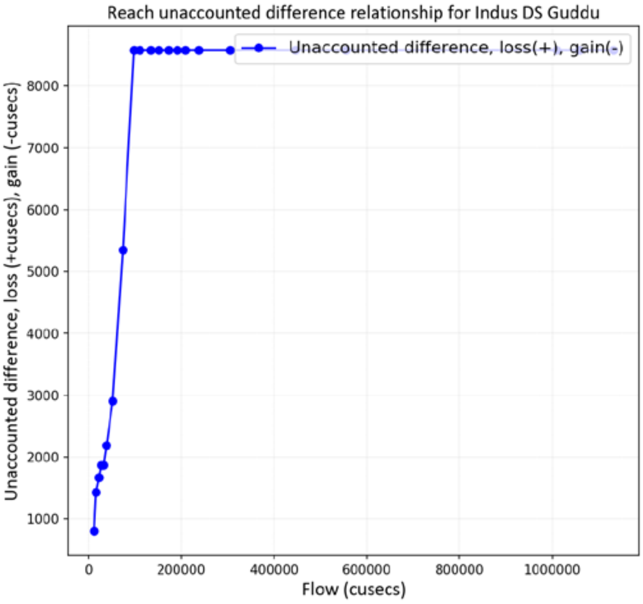
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	3.0
40873.0	100000.0	2.75
122620.0	300000.0	2.5
245241.0	600000.0	2.25
367861.0	900000.0	2.0



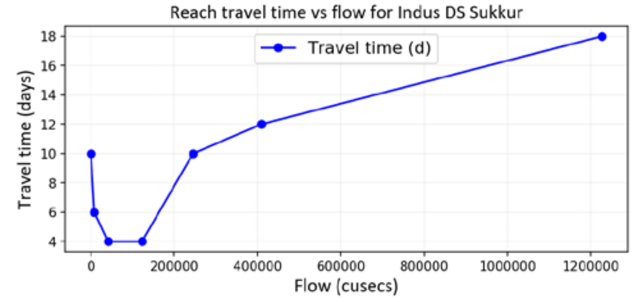
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	0.0	0.0	0.0
40873.0	2044.0	100000.0	5000.0
204367.0	14306.0	500000.0	35000.0
367861.0	29429.0	900000.0	72000.0



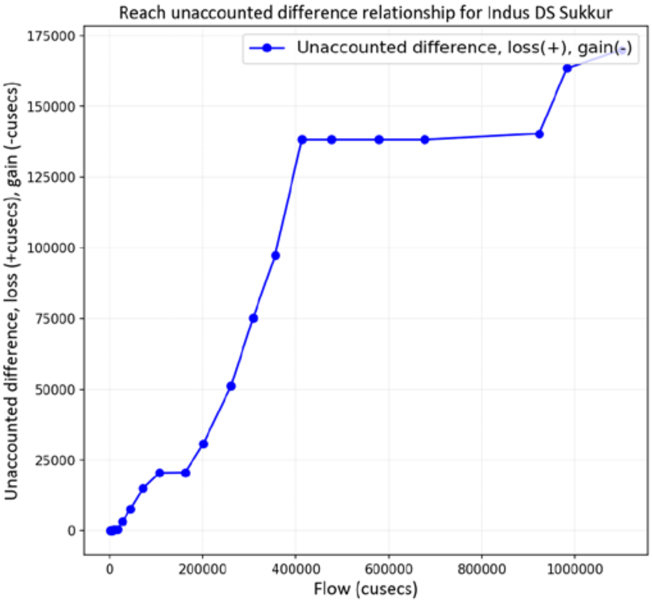
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	2.0
20437.0	50000.0	2.0
40873.0	100000.0	2.0
102184.0	250000.0	1.75
204367.0	500000.0	1.5
408735.0	1000000.0	1.5
1226204.0	3000000.0	1.5



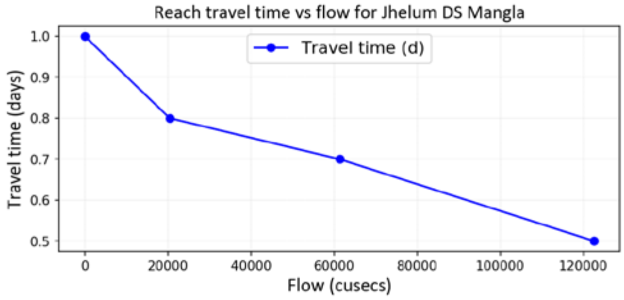
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
11992.0	801.0	29340.0	1960.0
16220.0	1426.0	39683.0	3489.0
22841.0	1669.0	55883.0	4084.0
27591.0	1865.0	67503.0	4563.0
32114.0	1865.0	78569.0	4563.0
38744.0	2184.0	94789.0	5344.0
52014.0	2903.0	127257.0	7102.0
74005.0	5350.0	181059.0	13089.0
98045.0	8583.0	239875.0	21000.0
110204.0	8583.0	269622.0	21000.0
134576.0	8583.0	329251.0	21000.0
150712.0	8583.0	368728.0	21000.0
173016.0	8583.0	423296.0	21000.0
190866.0	8583.0	466969.0	21000.0
208778.0	8583.0	510792.0	21000.0
237351.0	8583.0	580696.0	21000.0
304705.0	8583.0	745484.0	21000.0
446507.0	8583.0	1092412.0	21000.0
555599.0	8583.0	1359316.0	21000.0
1009481.0	8583.0	2469771.0	21000.0
1059013.0	8583.0	2590956.0	21000.0
1130995.0	8583.0	2767065.0	21000.0



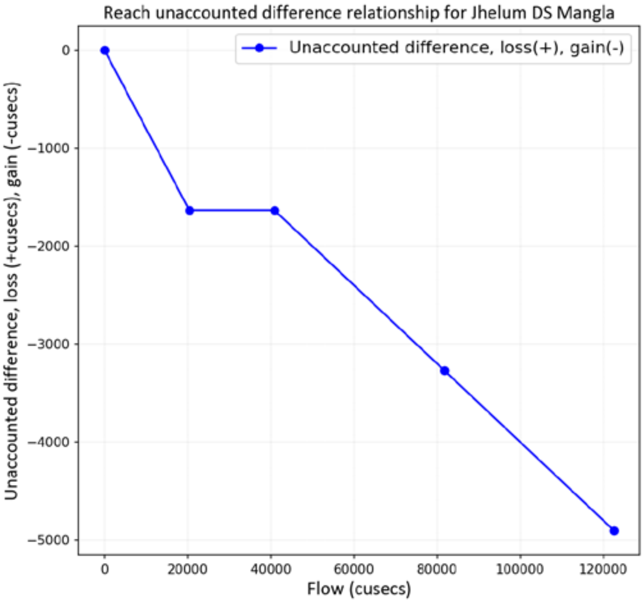
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	10.0
8175.0	20000.0	6.0
40873.0	100000.0	4.0
122620.0	300000.0	4.0
245241.0	600000.0	10.0
408735.0	1000000.0	12.0
1226204.0	3000000.0	18.0



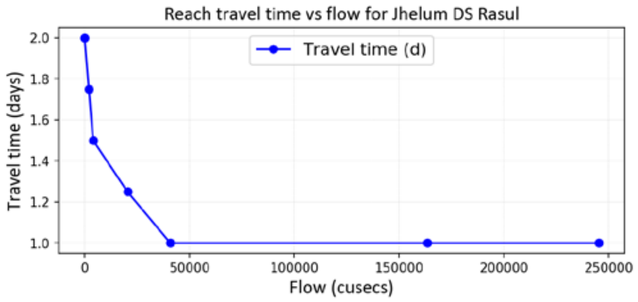
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
742.0	0.0	1816.0	0.0
2083.0	0.0	5096.0	0.0
4236.0	0.0	10363.0	0.0
6329.0	0.0	15485.0	0.0
10206.0	409.0	24970.0	1000.0
16889.0	541.0	41321.0	1324.0
27589.0	3229.0	67499.0	7900.0
44466.0	7612.0	108789.0	18623.0
71625.0	14953.0	175235.0	36585.0
106352.0	20437.0	260198.0	50000.0
162099.0	20546.0	396588.0	50268.0
201002.0	30689.0	491765.0	75083.0
260832.0	51183.0	638144.0	125224.0
308186.0	75261.0	754001.0	184132.0
355635.0	97403.0	870089.0	238304.0
412616.0	138221.0	1009495.0	338168.0
476071.0	138221.0	1164744.0	338168.0
577885.0	138221.0	1413839.0	338168.0
676824.0	138221.0	1655902.0	338168.0
922987.0	140361.0	2258158.0	343404.0
982464.0	163494.0	2403672.0	400000.0
1100616.0	169953.0	2692740.0	415803.0



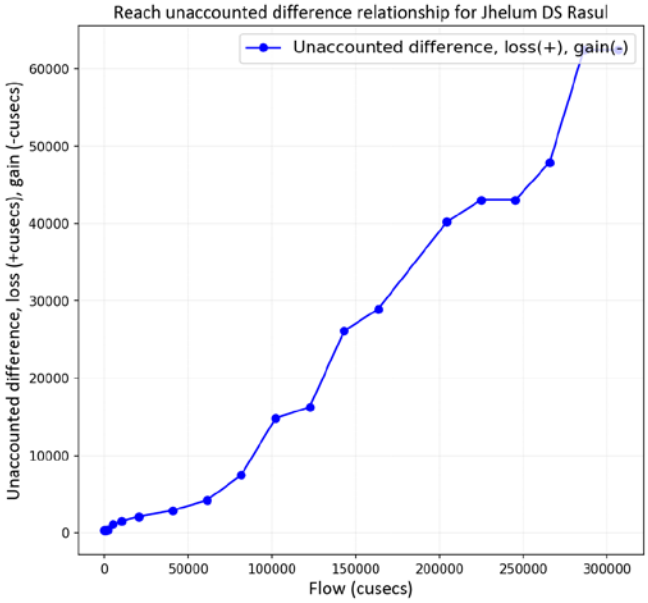
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.0
20437.0	50000.0	0.8
61310.0	150000.0	0.7
122620.0	300000.0	0.5



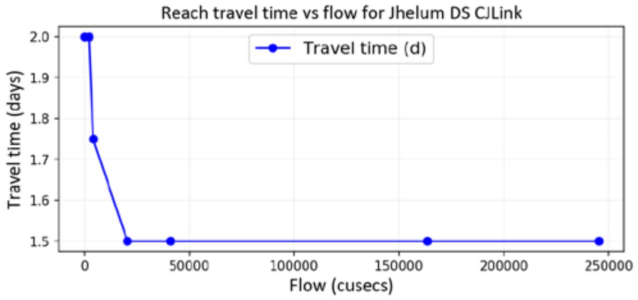
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	0.0	0.0	0.0
20437.0	-1635.0	50000.0	-4000.0
40873.0	-1635.0	100000.0	-4000.0
81747.0	-3270.0	200000.0	-8000.0
122620.0	-4905.0	300000.0	-12000.0


Reach travel time vs flow for Jhelum DS Rasul

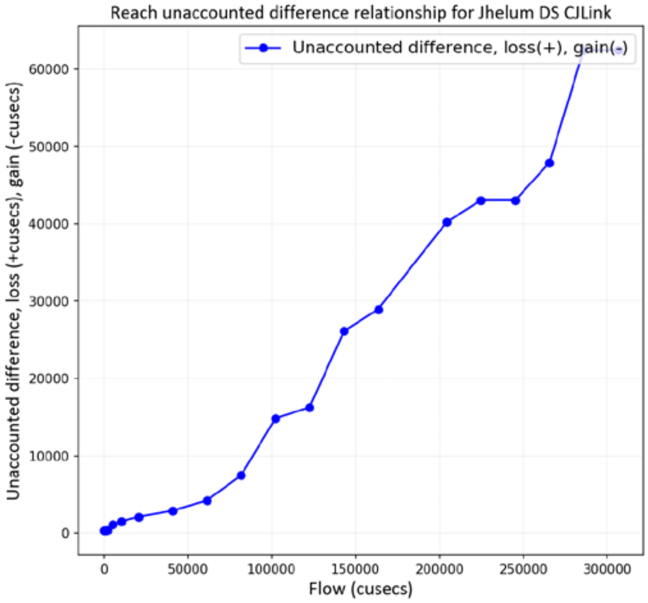
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	2.0
2044.0	5000.0	1.75
4087.0	10000.0	1.5
20437.0	50000.0	1.25
40873.0	100000.0	1.0
163494.0	400000.0	1.0
245241.0	600000.0	1.0


Reach unaccounted difference relationship for Jhelum DS Rasul

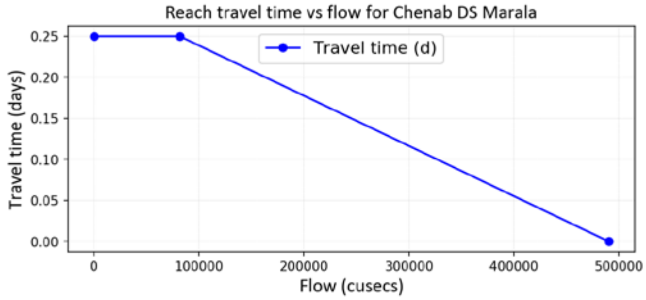
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	327.0	0.0	800.0
511.0	327.0	1250.0	800.0
1022.0	327.0	2500.0	800.0
2044.0	376.0	5000.0	919.0
5109.0	1146.0	12500.0	2804.0
10218.0	1544.0	25000.0	3777.0
20437.0	2111.0	50000.0	5165.0
40873.0	2910.0	100000.0	7120.0
61310.0	4238.0	150000.0	10369.0
81747.0	7470.0	200000.0	18275.0
102184.0	14833.0	250000.0	36289.0
122620.0	16278.0	300000.0	39826.0
143057.0	26103.0	350000.0	63863.0
163494.0	28958.0	400000.0	70847.0
204367.0	40206.0	500000.0	98368.0
224804.0	43037.0	550000.0	105294.0
245241.0	43037.0	600000.0	105294.0
265677.0	47899.0	650000.0	117189.0
286114.0	62464.0	700000.0	152823.0
306551.0	62464.0	750000.0	152823.0


Reach travel time vs flow for Jhelum DS CJLink

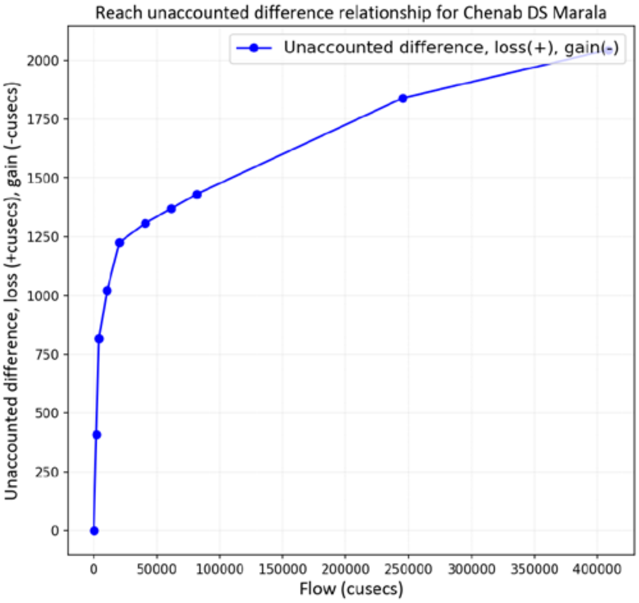
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	2.0
2044.0	5000.0	2.0
4087.0	10000.0	1.75
20437.0	50000.0	1.5
40873.0	100000.0	1.5
163494.0	400000.0	1.5
245241.0	600000.0	1.5


Reach unaccounted difference relationship for Jhelum DS CJLink

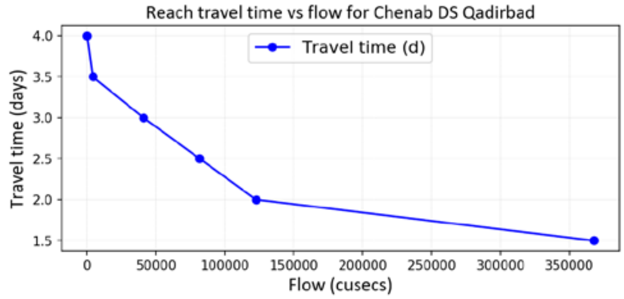
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	327.0	0.0	800.0
511.0	327.0	1250.0	800.0
1022.0	327.0	2500.0	800.0
2044.0	376.0	5000.0	919.0
5109.0	1146.0	12500.0	2804.0
10218.0	1544.0	25000.0	3777.0
20437.0	2111.0	50000.0	5165.0
40873.0	2910.0	100000.0	7120.0
61310.0	4238.0	150000.0	10369.0
81747.0	7470.0	200000.0	18275.0
102184.0	14833.0	250000.0	36289.0
122620.0	16278.0	300000.0	39826.0
143057.0	26103.0	350000.0	63863.0
163494.0	28958.0	400000.0	70847.0
204367.0	40206.0	500000.0	98368.0
224804.0	43037.0	550000.0	105294.0
245241.0	43037.0	600000.0	105294.0
265677.0	47899.0	650000.0	117189.0
286114.0	62464.0	700000.0	152823.0
306551.0	62464.0	750000.0	152823.0


Reach travel time vs flow for Chenab DS Marala

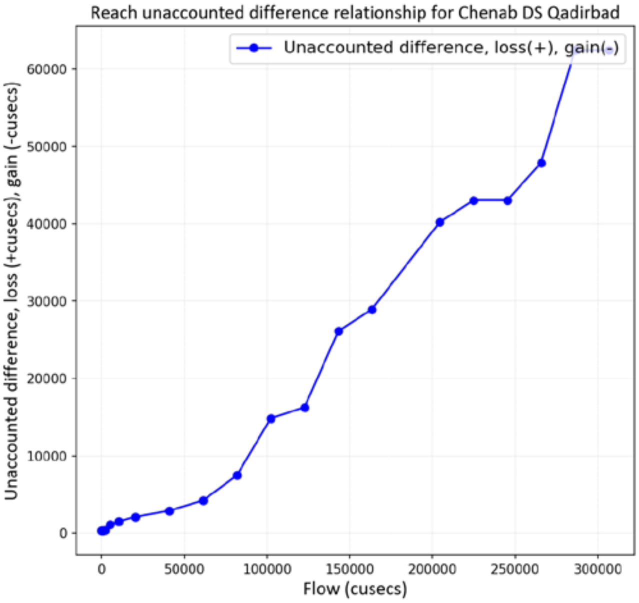
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	0.25
81747.0	200000.0	0.25
490481.0	1200000.0	0.0


Reach unaccounted difference relationship for Chenab DS Marala

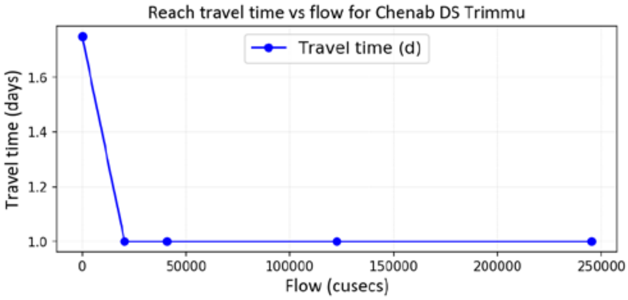
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	0.0	0.0	0.0
2044.0	409.0	5000.0	1000.0
4087.0	817.0	10000.0	2000.0
10627.0	1022.0	26000.0	2500.0
20437.0	1226.0	50000.0	3000.0
40873.0	1308.0	100000.0	3200.0
61310.0	1369.0	150000.0	3350.0
81747.0	1431.0	200000.0	3500.0
245241.0	1839.0	600000.0	4500.0
408735.0	2044.0	1000000.0	5000.0


Reach travel time vs flow for Chenab DS Qadirbad

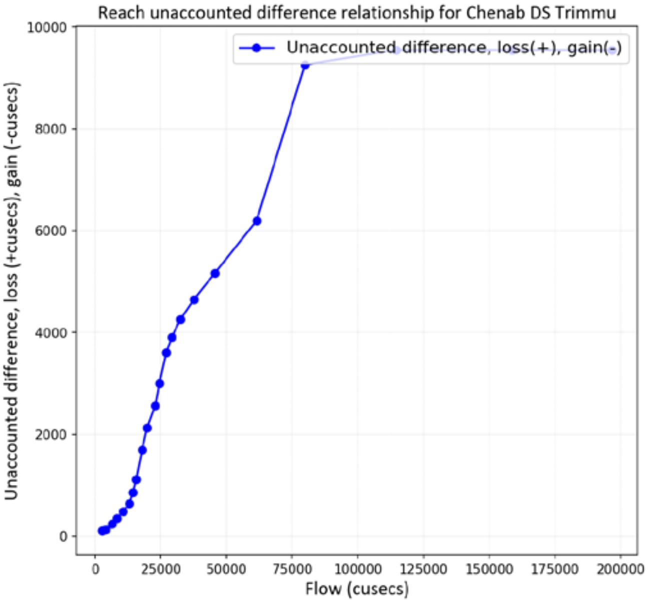
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	4.0
4087.0	10000.0	3.5
40873.0	100000.0	3.0
81747.0	200000.0	2.5
122620.0	300000.0	2.0
367861.0	900000.0	1.5


Reach unaccounted difference relationship for Chenab DS Qadirbad

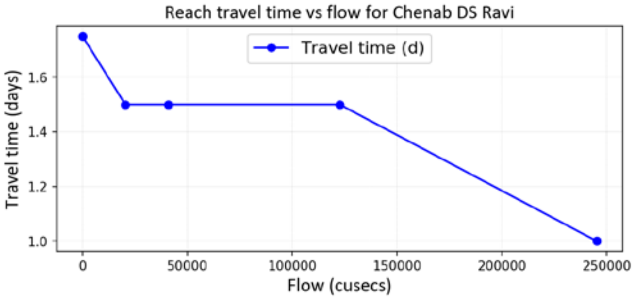
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	327.0	0.0	800.0
511.0	327.0	1250.0	800.0
1022.0	327.0	2500.0	800.0
2044.0	376.0	5000.0	919.0
5109.0	1146.0	12500.0	2804.0
10218.0	1544.0	25000.0	3777.0
20437.0	2111.0	50000.0	5165.0
40873.0	2910.0	100000.0	7120.0
61310.0	4238.0	150000.0	10369.0
81747.0	7470.0	200000.0	18275.0
102184.0	14833.0	250000.0	36289.0
122620.0	16278.0	300000.0	39826.0
143057.0	26103.0	350000.0	63863.0
163494.0	28958.0	400000.0	70847.0
204367.0	40206.0	500000.0	98368.0
224804.0	43037.0	550000.0	105294.0
245241.0	43037.0	600000.0	105294.0
265677.0	47899.0	650000.0	117189.0
286114.0	62464.0	700000.0	152823.0
306551.0	62464.0	750000.0	152823.0



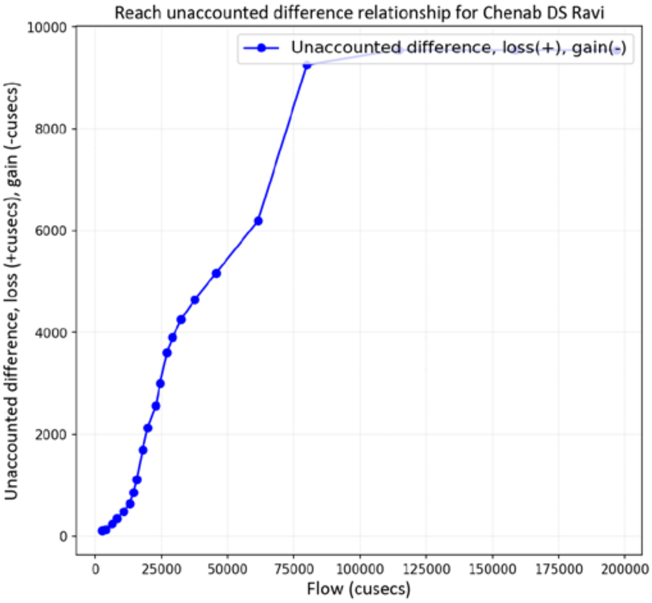
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.75
20437.0	50000.0	1.0
40873.0	100000.0	1.0
122620.0	300000.0	1.0
245241.0	600000.0	1.0



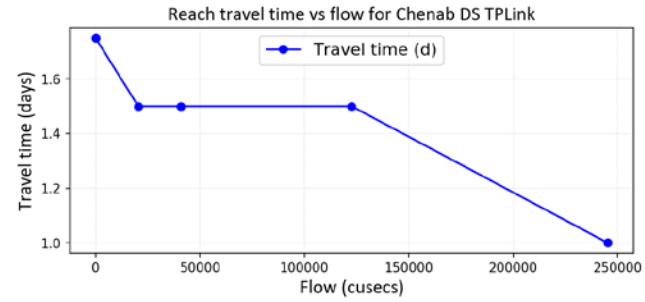
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
2500.0	110.0	6116.0	270.0
4000.0	135.0	9786.0	331.0
6300.0	249.0	15413.0	608.0
8194.0	356.0	20047.0	870.0
10595.0	486.0	25921.0	1190.0
13005.0	642.0	31818.0	1570.0
14380.0	864.0	35182.0	2115.0
15560.0	1109.0	38069.0	2712.0
17820.0	1695.0	43598.0	4147.0
19708.0	2127.0	48217.0	5203.0
22857.0	2567.0	55921.0	6280.0
24420.0	3006.0	59745.0	7354.0
27050.0	3601.0	66180.0	8810.0
29163.0	3910.0	71349.0	9565.0
32361.0	4255.0	79174.0	10409.0
37513.0	4646.0	91778.0	11367.0
45560.0	5167.0	111466.0	12640.0
61443.0	6197.0	150325.0	15162.0
79813.0	9257.0	195269.0	22648.0
114550.0	9547.0	280254.0	23356.0
158554.0	9547.0	387915.0	23356.0
196652.0	9547.0	481125.0	23356.0



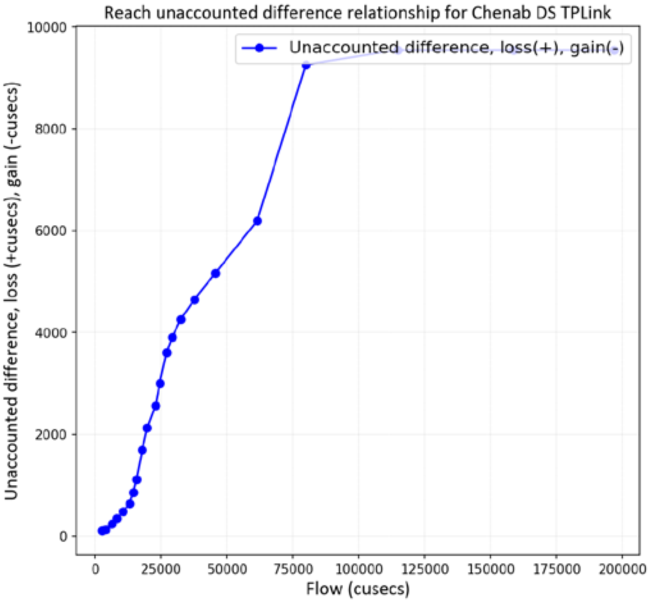
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.75
20437.0	50000.0	1.5
40873.0	100000.0	1.5
122620.0	300000.0	1.5
245241.0	600000.0	1.0



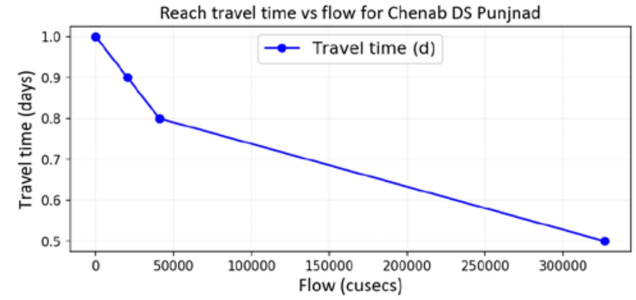
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
2500.0	110.0	6116.0	270.0
4000.0	135.0	9786.0	331.0
6300.0	249.0	15413.0	608.0
8194.0	356.0	20047.0	870.0
10595.0	486.0	25921.0	1190.0
13005.0	642.0	31818.0	1570.0
14380.0	864.0	35182.0	2115.0
15560.0	1109.0	38069.0	2712.0
17820.0	1695.0	43598.0	4147.0
19708.0	2127.0	48217.0	5203.0
22857.0	2567.0	55921.0	6280.0
24420.0	3006.0	59745.0	7354.0
27050.0	3601.0	66180.0	8810.0
29163.0	3910.0	71349.0	9565.0
32361.0	4255.0	79174.0	10409.0
37513.0	4646.0	91778.0	11367.0
45560.0	5167.0	111466.0	12640.0
61443.0	6197.0	150325.0	15162.0
79813.0	9257.0	195269.0	22648.0
114550.0	9547.0	280254.0	23356.0
158554.0	9547.0	387915.0	23356.0
196652.0	9547.0	481125.0	23356.0



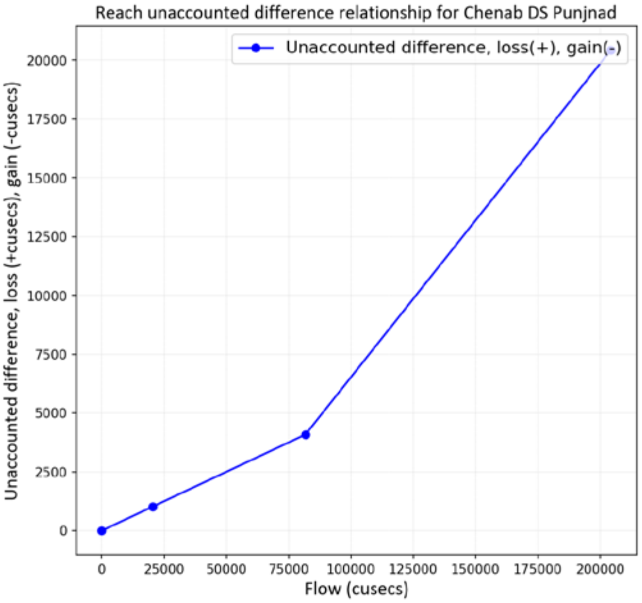
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.75
20437.0	50000.0	1.5
40873.0	100000.0	1.5
122620.0	300000.0	1.5
245241.0	600000.0	1.0



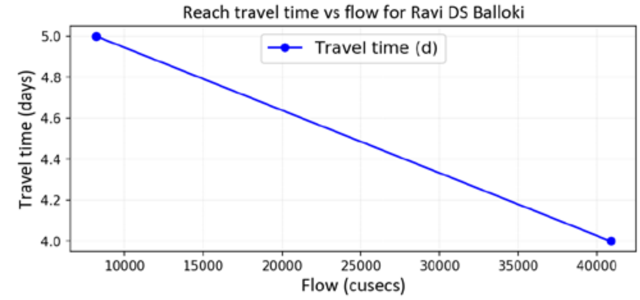
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
2500.0	110.0	6116.0	270.0
4000.0	135.0	9786.0	331.0
6300.0	249.0	15413.0	608.0
8194.0	356.0	20047.0	870.0
10595.0	486.0	25921.0	1190.0
13005.0	642.0	31818.0	1570.0
14380.0	864.0	35182.0	2115.0
15560.0	1109.0	38069.0	2712.0
17820.0	1695.0	43598.0	4147.0
19708.0	2127.0	48217.0	5203.0
22857.0	2567.0	55921.0	6280.0
24420.0	3006.0	59745.0	7354.0
27050.0	3601.0	66180.0	8810.0
29163.0	3910.0	71349.0	9565.0
32361.0	4255.0	79174.0	10409.0
37513.0	4646.0	91778.0	11367.0
45560.0	5167.0	111466.0	12640.0
61443.0	6197.0	150325.0	15162.0
79813.0	9257.0	195269.0	22648.0
114550.0	9547.0	280254.0	23356.0
158554.0	9547.0	387915.0	23356.0
196652.0	9547.0	481125.0	23356.0



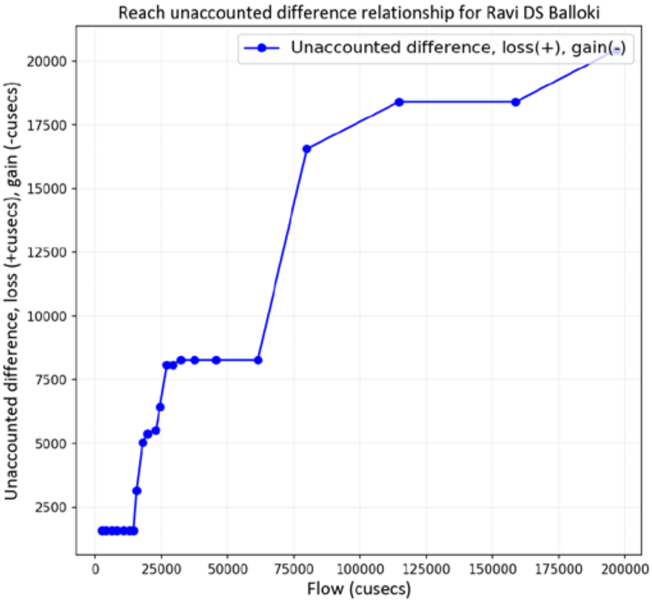
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.0
20437.0	50000.0	0.9
40873.0	100000.0	0.8
326988.0	800000.0	0.5



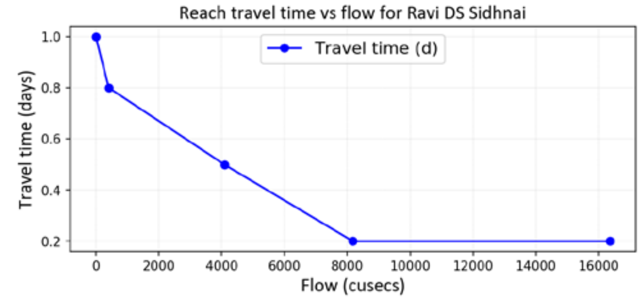
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	0.0	0.0	0.0
20437.0	1022.0	50000.0	2500.0
81747.0	4087.0	200000.0	10000.0
204367.0	20437.0	500000.0	50000.0


Reach travel time vs flow for Ravi DS Balloki

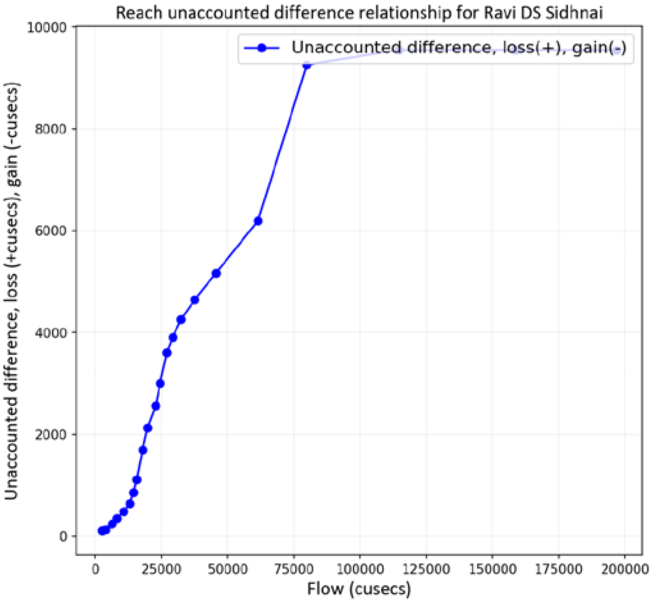
Flow (cusecs)	flow(ML/d)	Travel Time (d)
8175.0	20000.0	5.0
40873.0	100000.0	4.0


Reach unaccounted difference relationship for Ravi DS Balloki

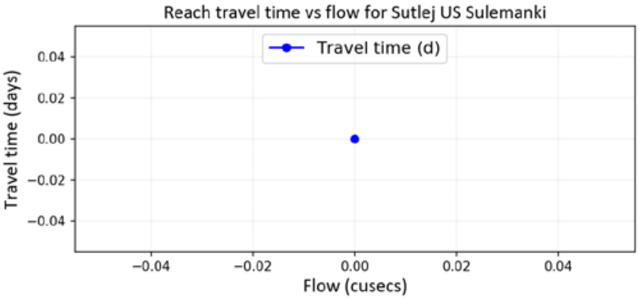
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
2500.0	1574.0	6116.0	3850.0
4000.0	1574.0	9786.0	3850.0
6300.0	1574.0	15413.0	3850.0
8194.0	1574.0	20047.0	3850.0
10595.0	1574.0	25921.0	3850.0
13005.0	1574.0	31818.0	3850.0
14380.0	1582.0	35182.0	3872.0
15560.0	3153.0	38069.0	7713.0
17820.0	5027.0	43598.0	12299.0
19708.0	5370.0	48217.0	13137.0
22857.0	5515.0	55921.0	13492.0
24420.0	6437.0	59745.0	15749.0
27050.0	8087.0	66180.0	19785.0
29163.0	8087.0	71349.0	19785.0
32361.0	8277.0	79174.0	20250.0
37513.0	8277.0	91778.0	20250.0
45560.0	8277.0	111466.0	20250.0
61443.0	8277.0	150325.0	20250.0
79813.0	16554.0	195269.0	40500.0
114550.0	18393.0	280254.0	45000.0
158554.0	18393.0	387915.0	45000.0
196652.0	20437.0	481125.0	50000.0


Reach travel time vs flow for Ravi DS Sidhnai

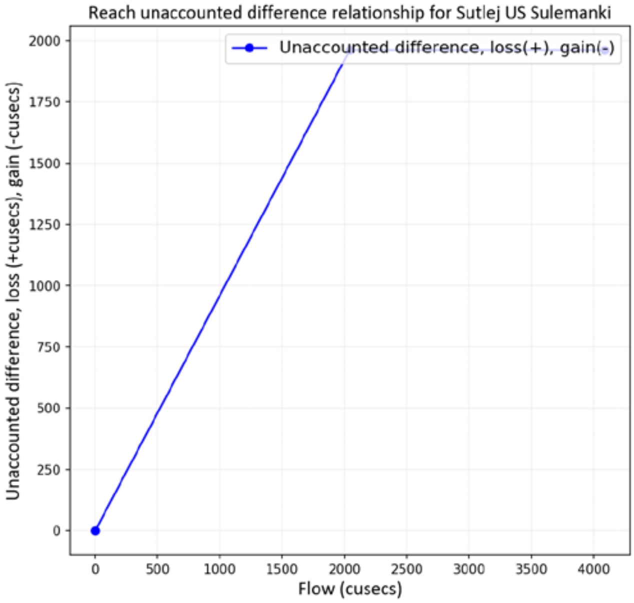
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	1.0
409.0	1000.0	0.8
4087.0	10000.0	0.5
8175.0	20000.0	0.2
16349.0	40000.0	0.2


Reach unaccounted difference relationship for Ravi DS Sidhnai

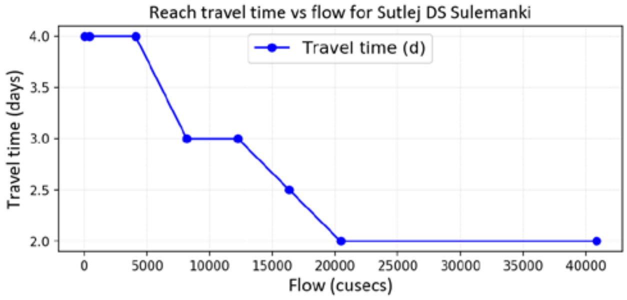
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
2500.0	110.0	6116.0	270.0
4000.0	135.0	9786.0	331.0
6300.0	249.0	15413.0	608.0
8194.0	356.0	20047.0	870.0
10595.0	486.0	25921.0	1190.0
13005.0	642.0	31818.0	1570.0
14380.0	864.0	35182.0	2115.0
15560.0	1109.0	38069.0	2712.0
17820.0	1695.0	43598.0	4147.0
19708.0	2127.0	48217.0	5203.0
22857.0	2567.0	55921.0	6280.0
24420.0	3006.0	59745.0	7354.0
27050.0	3601.0	66180.0	8810.0
29163.0	3910.0	71349.0	9565.0
32361.0	4255.0	79174.0	10409.0
37513.0	4646.0	91778.0	11367.0
45560.0	5167.0	111466.0	12640.0
61443.0	6197.0	150325.0	15162.0
79813.0	9257.0	195269.0	22648.0
114550.0	9547.0	280254.0	23356.0
158554.0	9547.0	387915.0	23356.0
196652.0	9547.0	481125.0	23356.0



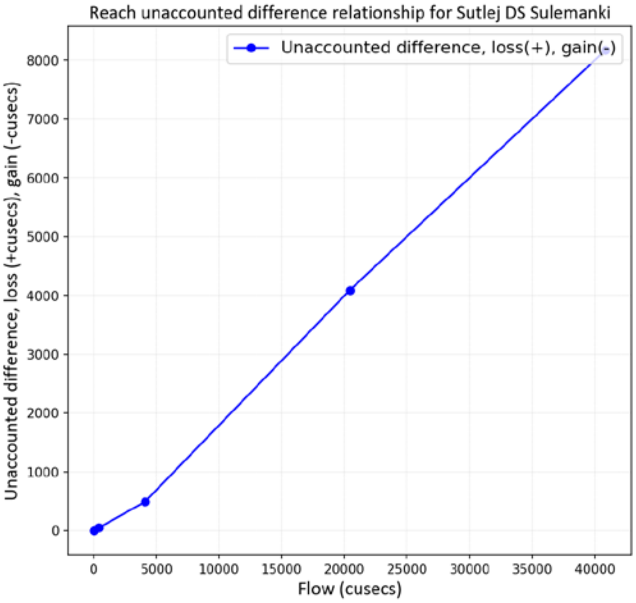
Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	0.0



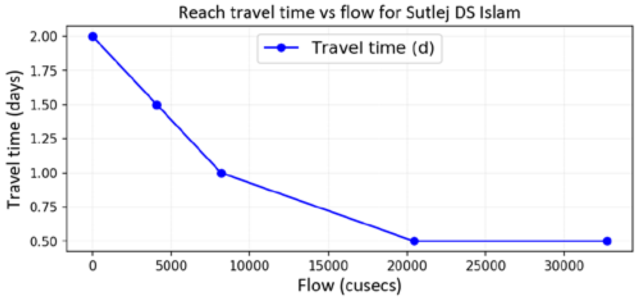
Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	0.0	0.0	0.0
2044.0	1962.0	5000.0	4800.0
4087.0	1962.0	10000.0	4800.0

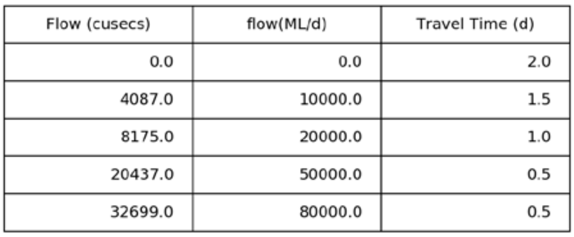


Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	4.0
409.0	1000.0	4.0
4087.0	10000.0	4.0
8175.0	20000.0	3.0
12262.0	30000.0	3.0
16349.0	40000.0	2.5
20437.0	50000.0	2.0
40873.0	100000.0	2.0

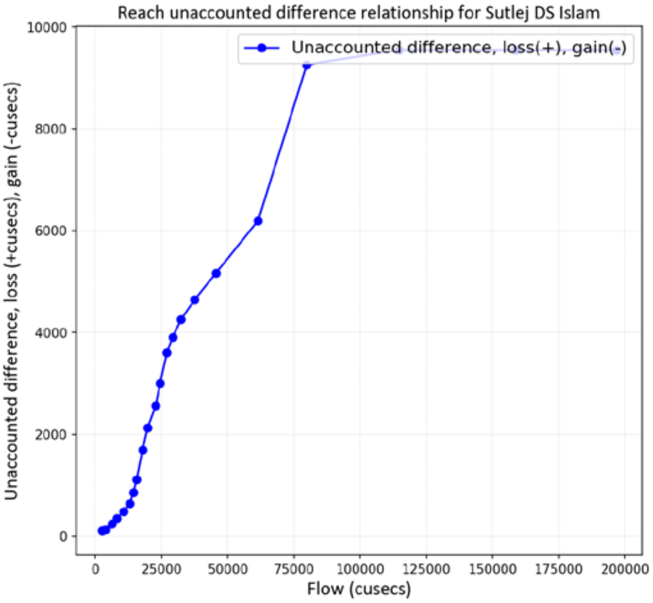


Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
0.0	0.0	0.0	0.0
41.0	5.0	100.0	12.0
409.0	49.0	1000.0	120.0
4087.0	490.0	10000.0	1200.0
20437.0	4087.0	50000.0	10000.0
40873.0	8175.0	100000.0	20000.0





Flow (cusecs)	flow(ML/d)	Travel Time (d)
0.0	0.0	2.0
4087.0	10000.0	1.5
8175.0	20000.0	1.0
20437.0	50000.0	0.5
32699.0	80000.0	0.5



Flow (cusecs)	unacc. diff. (cusecs)	flow(ML/d)	Loss/gain (ML/d)
2500.0	110.0	6116.0	270.0
4000.0	135.0	9786.0	331.0
6300.0	249.0	15413.0	608.0
8194.0	356.0	20047.0	870.0
10595.0	486.0	25921.0	1190.0
13005.0	642.0	31818.0	1570.0
14380.0	864.0	35182.0	2115.0
15560.0	1109.0	38069.0	2712.0
17820.0	1695.0	43598.0	4147.0
19708.0	2127.0	48217.0	5203.0
22857.0	2567.0	55921.0	6280.0
24420.0	3006.0	59745.0	7354.0
27050.0	3601.0	66180.0	8810.0
29163.0	3910.0	71349.0	9565.0
32361.0	4255.0	79174.0	10409.0
37513.0	4646.0	91778.0	11367.0
45560.0	5167.0	111466.0	12640.0
61443.0	6197.0	150325.0	15162.0
79813.0	9257.0	195269.0	22648.0
114550.0	9547.0	280254.0	23356.0
158554.0	9547.0	387915.0	23356.0
196652.0	9547.0	481125.0	23356.0

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