Development of a Regional Groundwater model for the Indus Basin Irrigation System of Pakistan

Status Report

W Schmid, JF Punthakey, G Hodgson, M Kirby, M Ahmad, G Podger, J Stewart, M Basharat, Z Khero, HU Bodla

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¹CSIRO Land & Water, Canberra ACT
²Ecoseal Developments Pty Ltd, PO Box 496 Roseville NSW 2069 Australia
³CSIRO Land & Water, Floreat WA
⁴IWASRI, WAPDA
⁵Sindh Irrigation Department
⁶Punjab Irrigation Department

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## Abbreviations

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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>(A)MSL</td>
<td>(Above) mean sea level</td>
</tr>
<tr>
<td>(G)WEM</td>
<td>(Ground)water extraction mechanism</td>
</tr>
<tr>
<td>ACIAR</td>
<td>Australian Centre for International Agricultural Research</td>
</tr>
<tr>
<td>ACZ</td>
<td>Agro-climatic zone</td>
</tr>
<tr>
<td>ALOS</td>
<td>Advanced Land Observing Satellite</td>
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<tr>
<td>CGE</td>
<td>Computable General Equilibrium (model)</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DFAT</td>
<td>Department of Foreign Affairs and Trade (Australia)</td>
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<tr>
<td>DTW</td>
<td>Depth to water</td>
</tr>
<tr>
<td>EA</td>
<td>Executing Agency</td>
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<tr>
<td>EC</td>
<td>Electrical conductivity (1 mS/cm = 1dS/m = 1000 µS/cm)</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>Environmental Satellite</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>GoP</td>
<td>Government of Pakistan</td>
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<tr>
<td>GW</td>
<td>Groundwater</td>
</tr>
<tr>
<td>ha</td>
<td>hectare</td>
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<tr>
<td>HSU</td>
<td>Hydrologically Similar Unit</td>
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<tr>
<td>IA</td>
<td>Implementing Agency</td>
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<tr>
<td>IBIS</td>
<td>Indus Basin Irrigation System</td>
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<tr>
<td>IBMR</td>
<td>Indus Basin Model Revised (of World Bank)</td>
</tr>
<tr>
<td>IRSA</td>
<td>Indus River System Authority</td>
</tr>
<tr>
<td>IWMI</td>
<td>International Water Management Institute</td>
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<tr>
<td>LBDC</td>
<td>Lower Bari Doab Canal</td>
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<tr>
<td>LBOD &amp; RBOD</td>
<td>Left &amp; Right Bank Outfall Drains</td>
</tr>
<tr>
<td>LCC</td>
<td>Lower Chenab Canal</td>
</tr>
<tr>
<td>MAF</td>
<td>Million Acre-feet</td>
</tr>
<tr>
<td>MAR</td>
<td>Managed Aquifer Recharge</td>
</tr>
<tr>
<td>MERIS</td>
<td>Medium Resolution Imaging Spectrometer</td>
</tr>
<tr>
<td>Mha</td>
<td>Million hectares</td>
</tr>
<tr>
<td>MoWP</td>
<td>Ministry of Water and Power</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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<tr>
<td>NDVI</td>
<td>Normalized difference vegetation index</td>
</tr>
<tr>
<td>PID</td>
<td>Punjab Irrigation Department</td>
</tr>
<tr>
<td>PIDA</td>
<td>Punjab Irrigation and Drainage Authority</td>
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<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>QB</td>
<td>Qadirabad Bulloki</td>
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<tr>
<td>SCARP</td>
<td>Salinity Control and Reclamation Project</td>
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<td>SDIP</td>
<td>Sustainable Development Investment Portfolio</td>
</tr>
<tr>
<td>SID</td>
<td>Sindh Irrigation Department</td>
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<tr>
<td>SW</td>
<td>Surface water</td>
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<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
</tr>
<tr>
<td>TMR</td>
<td>Telescopic Mesh Refinement</td>
</tr>
<tr>
<td>UF</td>
<td>University of Faisalabad</td>
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Summary

Food insecurity is a sensitive issue in Pakistan, Bangladesh and India where it affects about 25% of the population – equivalent to over 300 million people or one third of the globally food insecure population. In the Indus Basin Irrigation System (IBIS) in Pakistan, the area under irrigation has expanded greatly over the past five decades enhancing agricultural production to meet increased food and fibre demands. The water demand associated with increased population and subsequent increases in irrigation areas has been met through increased groundwater usage for irrigation mainly from tubewells. As a result, in areas of fresh groundwater quality, almost half of the irrigation supplies come from groundwater. However, since the 1980s, pumping of groundwater for supplementary irrigation has reduced groundwater levels significantly in some areas. Increased groundwater use had induced leakage from rivers and canals to groundwater, which has become the predominant form of surface water and groundwater interaction. Surface and groundwater are highly connected due to the sandy nature of the alluvial aquifer of the Indus Basin Irrigation System (IBIS) of Pakistan. In areas of fresh groundwater, levels continue to drop while in saline areas there are issues of waterlogging and expansion of saline areas.

To help sustainably manage this resource, a new regional 5km-resolution groundwater model has been built for entire IBIS in Pakistan in conjunction with the ongoing development of an integrated river system model of Pakistan. This integrated modelling framework considers physical interactions and conjunctive use of surface and groundwater. The interaction between both models can assist Pakistan in developing an overall integrated water resource model of the Indus basin. The groundwater model serves as a foundation to better understand groundwater dynamics and groundwater budgets on a regional and sub-regional scale, surface-groundwater interaction, assess the impact of development on fresh and saline groundwater areas on multiple scales (e.g., future solute-transport child models), help mitigate the response of water demand/supply to external changes (e.g., in climate, land-use, and water policy), as well as help build a national water resource plan for the IBIS of Pakistan.

The need for a basin-wide groundwater model was also corroborated through a review of previous models, which largely are fit-for-purpose models at local or sub-regional scales. However, many of these models assumed vertical-flux domination and no horizontal groundwater flows across no-flow boundaries formed by doab-bounding rivers. In contrast, a regional model can simulate horizontal groundwater flow across doab-bounding rivers induced by excessive groundwater extraction for irrigation and urban water in neighbouring doabs/areas. This transition from initial vertical-flux domination to ever increasing horizontal boundary flows is best addressed by a regional parent model, or, in the case of potential future doab-level child models, by dynamic parent-child boundary conditions. The function of those boundary conditions is not just to simulate historic cross-boundary flows as components of a groundwater mass balance, but also to allow future scenario perturbations of groundwater overdraft in highly stressed aquifers to interact with such model boundaries. Areas surrounding the regional model domain of the IBIS may influence lateral boundary flows, such as irrigated areas across the border to India, urban areas near the boundary such as the city of Lahore, the Indus delta, and mountain-front recharge from the Himalayas. Such external inflows may be driven by Global Climate Model scenarios that factor in population growth and increasing irrigation and urban water demand across the boundary.
Prior to constructing the numerical model, data on climate, water levels, geohydrology, and river and canal network have been gathered from multiple sources (WAPDA, PID, SID), which has resulted in a compendium of hydrologic data as part of this study. (A) Spatially and temporally distributed climate data were retrieved from gridded daily data covering the entire Indus basin and Pakistan. For this study, precipitation and evapotranspiration data were needed to formulate sources and sinks into and out of the groundwater, such as groundwater pumping, diffuse recharge, and evapotranspiration from groundwater specified or simulated by Well, Recharge, and Evapotranspiration Packages of MODFLOW. (B) Water level data were organised in a common georeferenced database and can now be used for water level trend analysis (e.g., in areas of groundwater overdraft or near the international border), contour maps, initial heads for the groundwater model, and the calibration of simulated heads to observations. (C) A geohydrologic framework was created based on digitized and georeferenced borelog lithology. This framework allows for the delineation of the base of the alluvial aquifer and the association of major lithologic component with typical ranges of hydraulic parameters. A separate database of observed hydraulic parameters was compiled and georeferenced. (D) A simplified river system was developed for input into MODFLOW that covers the major rivers and upstream major tributaries. A canal conveyance network from the Indus River System Authority (IRSA) was also generalized to just Main Canals, Link Canals, Feeders and Branch Canals (>500 cfs). Drains were not considered in this study, except the Left Bank and Right Bank Outfall drains (LBOD and RBOD) that prevent waterlogging in southern Sindh.

The groundwater model extends horizontally across the entire irrigated Indus basin of Pakistan and beyond encompassing the entire quaternary alluvial basin as well as surrounding areas that may influence boundary flows, such as metropolitan water users, the Indus delta, and mountain-front recharge from the Himalayas. It is limited vertically to the alluvial aquifer of the Indus basin as the primary focus is surface-groundwater interaction and, as such, does not extend into the tertiary highland areas. External model boundaries are represented by no flow from hard-rock formations west and north of basin. Groundwater underflow occurs as inflows and outflows from the landward eastern and offshore southern boundaries.

The model domain consists of a finite difference grid discretised into 228 rows and 184 columns and spatial resolution of 5000 x 5000 m. A temporal discretization of 264 monthly stress periods was specified for a total of 22 years from October 1990 (beginning of Rabi 1990) to September 2012 (end of Kharif 2012). The vertical discretization is defined by the surface topography derived from a 90 meter Digital Elevation Model and by three numerical layers, with the assumption that groundwater pumping would occur from the first two layers. In the Indus Basin water quality declines with depth. Thus the third and deepest layer with relatively higher salinity needs to be differentiated from the pumping layers. The bottom of the third layer extends to the top of the bottom layer encountered in the borehole if of low permeability or in some cases to bedrock where bores have been drilled to a sufficient depth. The upper layer is unconfined and the remaining layers are confined, but convertible to unconfined if dewatered. A geohydrologic framework derived from nearly 1500 borelogs was used to associate various major and minor lithologic components with typical values of hydraulic parameters, that is, hydraulic conductivity, specific yield, specific storage and porosity. Observations of aquifer properties will be used as bounds for refining the initial estimates during sensitivity analysis and calibration.

By extending the external model boundaries to the edges of the basin, internal river boundaries will no longer be used as external boundaries of doabs, but – along with the canal network – as internal sources or sinks of stream seepage into the aquifer or groundwater discharge into streams. The
calculated stream-aquifer interaction will also allow for a future linkage to the SOURCE river system model (CSIRO 2016c). This opens the door for future scenarios that help formulate constraints on streamflow, such as Global Climate Models and related changes in river streamflow. Other internal boundary conditions, such as diffuse-rainfall and irrigation recharge into groundwater, evapotranspiration from groundwater are also considered. Mountain-front recharge and supplemental groundwater pumping are defined using injection and extraction wells.

In this model, groundwater pumping requirements and groundwater pumping are synonymous. That is, groundwater pumping is not constrained by maximum well capacities or groundwater allotments. However, we do cap pumping with an assumed maximum limit in saline groundwater areas. The groundwater requirement for each MODFLOW cell equals the remainder of total irrigation delivery requirement not satisfied by the delivery of surface-water supply to the cell. The total delivery requirement is determined as crop irrigation requirement (crop water demand not satisfied by precipitation) increased sufficiently to compensate for inefficient use from irrigation with respect to plant consumption. The crop water demand is represented by district-wide, temporally variable potential crop evapotranspiration depths equal to the product of spatially and temporally distributed potential or reference evapotranspiration and a crop coefficient.

At the current status of the IBIS groundwater model, the parameterization of several stress packages and external boundary conditions in Groundwater Vistas has not yet been fully completed. This includes recharge, canal and drain seepage, as well as general head boundaries. This report describes the current status of the model development without discussion of any results. After finalizing the model construction, the next step is to run, debug, and calibrate the model, test its sensitivity, and analyse the model results. This insures that the model is robust enough for future scenarios. The second step is the quantification of surface water-groundwater interaction internal to the MODFLOW groundwater model and between coupled MODFLOW groundwater and SOURCE rivers system models (CSIRO 2016c). This step entails a number of model scenarios to improve understanding of the water balance and sustainability of groundwater extractions. The final step is the selection and creation of child models in areas of local or provincial relevance and their coupling to the coarser resolution parent model. The purpose would be defined by local and provincial stakeholder, e.g., to assess storage potentials of individual doabs or canal command areas, better represent the distribution of crop water use, or for focused salinity analyses.

CSIRO has been and continues to work closely with key stakeholders in Pakistan throughout the process of building this model (e.g., Pakistan Water and Power Development Authority - WAPDA, Punjab Irrigation Department - PID, Sindh Irrigation Department - SID). This collaborative approach has ensured that the model is designed to meet Pakistan’s specific needs, capacity in groundwater modelling is built, and stakeholders in Pakistan have a common modelling platform and the skills to use and maintain this model into the future.

The Government of Pakistan has already recognised the importance of groundwater management. This study adds value to the already ongoing monitoring program for water levels and water quality parameters from several hundred piezometers and tubewells in the Punjab. However, in Sindh there is a lack of systematic groundwater monitoring in place at present, which needs to be improved for the parameterization of this MODFLOW groundwater model and in order to keep future updates current. The duality of basin-wide management tools, such as this model, and groundwater monitoring will serve the Government of Pakistan’s interest in addressing the growing exploitation of groundwater and the increased scarcity of water that Pakistan is facing. Water scarcity in the country is projected to increase further as the impacts of climate change accelerate beyond 2050.
1 Introduction

1.1 Global Food-Agriculture-Water Crisis

The Food and Agriculture Organisation of the United Nations (FAO) projections suggest that by 2050 agricultural production must increase by 70% globally, and by almost 100% in developing countries in order to meet food demand (Alexandratos and Bruinsma 2012). Food insecurity is a chronic and sensitive issue in Pakistan, Bangladesh and India where it affects about 25% of the population – equivalent to over 300 million people or one-third of the globally food-insecure population. Of the estimated 1.4 billion ha of crop land worldwide, around 20% is irrigated and produces 40% of global agricultural output and significantly 60% of grain production. Thus increasing productivity of irrigated agriculture offers a significant opportunity to produce more food, use water wisely and judiciously, and to meet the challenge of improving livelihoods and poverty alleviation in South Asia.

About 70% of the world’s fresh water is used for irrigation with a substantial contribution from groundwater resources. Most of the 750-800 billion m$^3$/yr of global groundwater withdrawals are used for agriculture (Shah et al. 2000). During the last 30 years, there has been a significant increase in the utilisation of groundwater resources for irrigated agriculture. In countries facing increasing water insecurity, the low development cost for individual bores has resulted in widespread distribution. This has not been restricted to semi-arid regions, but has also occurred in more humid areas to provide a greater intensity as well as more reliable supplies for existing cultivated areas. Groundwater has been the heart of the green revolution in agriculture across many Asian nations, and has permitted cultivation of high value crops in various arid to semi-arid regions.

At the same time, global water scarcity forms a major constraint on sustaining and enhancing agricultural productivity. Between 1900 and 1995, the demand for freshwater increased sixfold, which was twice the rate of population growth (Gleick 1998). Just two decades ago, most serious water supply problems were confined to manageable pockets of the world. Today, they exist on every continent and are spreading rapidly. It is estimated that by the year 2025, two thirds of the world population will be living in areas facing water stressed conditions. In Bangladesh, groundwater already represents 35% of total annual water withdrawals, in India it is 32%, Pakistan 30%, and China 11%. In some of the most populous and poverty stricken regions of the world, particularly in south Asia, groundwater use has emerged at the centre of the food agriculture economy. For example, in India 60% of the irrigated food grain production depends on irrigation from groundwater wells (Janakarajan 2000). Across vast areas, farmers are pumping groundwater faster than nature is replenishing it, causing a continuous drop in water levels. As a consequence, the situation is deteriorating; as the demand for water increases, its availability is diminishing.

Irrigated agricultural has helped meet rapidly rising demand for food, and has contributed to the growth of farm profitability and poverty reduction as well as to regional development and environmental protection. After several decades of publicly funded surface irrigation, and more recently of privately developed groundwater irrigation, remaining opportunities to harness new resources for agriculture are fewer and more expensive. Investment is increasingly focused on rehabilitating and improving the existing systems. However, water productivity remains generally low, and returns to public investment generally disappointing, especially in large scale irrigation. New solutions are needed, based on new management options and widely available technologies.
1.2 The Water Challenge in the Indus Basin of Pakistan

The Indus Basin is one of the world’s major food baskets and the heartland for irrigated agriculture in Pakistan. It is one of the largest contiguous irrigation network in the world with more than 16 million ha of irrigable land and 128 billion m$^3$ of annual canal diversions since the construction of the Tarbela dam in 1975 (Randhawa 2002; Bastiaanssen, et al. 2002; Government of Pakistan 2009a and 2009b). Its agriculture feeds about 250 million people who live in the basin in Pakistan, India and Afghanistan. Pakistan’s economy is predominantly agricultural – the agricultural sector comprises about 26% of gross domestic product (GDP). Moreover, agriculture provides livelihoods for over 70% of the population.

On the down side, Pakistan is one of the world’s most arid countries, with an average rainfall of under 240 mm a year and distinct high rainfall and flows in July and August and little rain from November to April. The population and the economy are heavily dependent on about 180 billion m$^3$ of water annual flows into the Indus, Jhelum, Chenab Ravi, Beas and Sutlej rivers which comprise the Indus river system (Briscoe and Qamar 2005). The headwaters of these rivers are in India and China and are mostly derived from snowmelt in the Himalayas. Through the ages, the people of the Indus Basin have adapted to the low and poorly distributed rainfall by either living along river banks or by careful conservation and management of local water resources.

Given the increasing dimensions of poverty, food insecurity, and water scarcity in Pakistan, this project aims to make a contribution towards improving the present understanding of the available groundwater resources in the Indus Basin of Pakistan. A regional groundwater model of the Indus Basin will provide improved understanding for surface and groundwater interaction, which will improve water management and planning in the Indus Basin. The Government of Pakistan (GoP) requires an improved understanding of surface and groundwater use in the Indus Basin so that resources are utilised on a sustainable basis and accurate information on the status of surface and groundwater resources can be provide to Resource Managers and to assist in policy development. This study initially models water quantity and future plans include modelling solute transport so that management changes are based on an informed approach using the best available data.

1.2.1 History

In the Indus Basin of Pakistan, groundwater – once deep and highly saline – has risen to shallow levels and even water logging over the last 120 years following the introduction of regulated rivers and canals by the British (Figure 1.1). The advent of large scale irrigation in the 19th century made the Indus irrigation system the largest contiguous irrigation system in the world. Surface salinization from shallow groundwater led to systematic groundwater monitoring, installation of deep drainage pumps, and subsidies for private groundwater pumping, as a result of which today’s fresh groundwater resources are in decline again. Yet, today, river and irrigation systems are still strongly connected with the groundwater system both in terms of surface-groundwater interaction and conjunctive use of surface water and groundwater. The supplemental use of fresh groundwater has become unsustainable for the alluvial Indus Basin aquifer in terms of storage depletion or increased salinity. Urban/domestic groundwater pumping poses an additional stress on the alluvial aquifer. The groundwater depletion has implications for Pakistan’s provincial and national economies, leads to ever increasing river losses, which, so far, are neither shared nor quantified, and increases the risk to salinization of rivers and areas of previously fresh groundwater.
The Indus Waters Treaty gave Pakistan rights in perpetuity to the waters of the Indus, Jhelum and Chenab rivers, which comprise 75% of the flow of the entire Indus system. However, under the provisions of the Treaty waters of the Ravi, Beas and Sutlej rivers were severed from the irrigated heartland of Punjab in the east. Additionally the Treaty made no provision for minimal environmental flows for the Ravi, Beas and Sutlej rivers. The pressure to bring water from the western rivers to the east was accomplished by building Tarbela dam and several major link canals. This massive transfer of water via link canals resulted in enhanced leakage from canals to the groundwater system. Vast quantities of water were used to irrigate desert lands where the underlying groundwater was of oceanic origin and highly saline. The advent of large scale canal irrigation resulted in excessive recharge from irrigation and unlined canals to the naturally deep aquifers of Punjab. Over time groundwater levels have risen and resulted in waterlogging and secondary salinity by the 1960s.

The World Bank country water resources assistance strategy report (Briscoe and Qamar 2005) claims the solution to this crisis was not the obvious one of lining canals and putting less water on the land but of increasing the use of groundwater, which may have temporarily relieved the symptoms of waterlogging and salinity in Punjab. Groundwater use in Pakistan started to accelerate from the 1960’s when public tubewells were installed to control rising watertables in waterlogged areas under the first Salinity Control and Reclamation Project (SCARP) scheme, and to encourage agricultural production in areas with good quality groundwater by promoting private tubewells. Under the SCARP scheme 16,700 public tubewells were installed in waterlogged areas during the 1960s (Bhutta and Smedema, 2007). Additionally, the government policy encouraged the installation of private tubewells in fresh groundwater areas through subsidies on electricity, diesel, drilling services and free pump sets (Johnson 1989). The rapid uptake and growth of private tubewells has resulted in a dramatic increase in groundwater usage and this presents a policy challenge for the Government of Pakistan. In the 1980s a 227% increase in electric tubewells caused the government to remove the subsidy of electricity and introduce a flat rate tariff on electricity for tubewells. This change made electric tubewells less favourable and many farmers started using diesel pumps for tubewell irrigation. The lower installation costs for diesel tubewells coupled with lower energy costs caused many farmers to adopt diesel engines for tubewell irrigation. Between 1990 and 1995 there was a two-fold increase in tubewell numbers (Qureshi et al. 2010). As indicated by Watto (2015) neither customary law nor government policy has provided the impetus for finding a balance between recharge and groundwater extraction as shown in Figure 1.2.
The World Bank report touted, that tubewell and diesel engine, as a decentralized “on demand” source of water, enabled farmers to greatly increase their crop yields and incomes. The on-demand nature of groundwater use can greatly help in applying the right amount of water at the right time and some farmers may have benefitted by increasing crop yields. However, yields in Pakistan Punjab are consistently lower than in Indian Punjab. Access to groundwater has filled a gap brought on by increased cropping intensity but it is not a universal remedy for Pakistan farmers. The uncontrolled use of groundwater for irrigation has now resulted in additional problems.

### 1.2.2 Current Issues

Water resources in the Indus Basin are amongst the most stretched in the world (Briscoe and Qamar 2005). Several studies have highlighted the growing water stress and crises in Pakistan (Mustafa et al. 2013; Condon et al. 2014, Kirby and Ahmad 2014). Projections indicate that beyond 2035 Pakistan is likely to face water scarcity (<1000 m³/capita/year). Some of the challenges facing Pakistan are:

1. **Further decline of surface and groundwater availability** as a result of continued population growth, no new water sources to develop, and comparatively lower land and water productivity in agriculture (compared to neighbouring countries).

2. **Excessive groundwater depletion:** The Indus river plain aquifer is considered by some authors ‘THE’ area with the highest groundwater depletion in the world (Figure 1.3) (Wada et al. 2010). Overexploitation of and excessive depletion of groundwater resources results in falling groundwater tables in many places (particularly evident in the Eastern doabs of Punjab) and causes the following consequences:
a. Unsustainable fresh groundwater usage is mainly caused by the conjunctive use of surface water and groundwater for irrigation, where, at least in Punjab, up to up to 50% of irrigation supplies come from groundwater pumpage. The irrigation water demand from groundwater increases, because a surface water system designed for cropping intensity of 67% is now expected to provide water for cropping intensities over 150%.

b. Urban and domestic water supplies also come from groundwater pumpage.

c. Groundwater withdrawals are in excess of the rate of renewal/recharge.

d. Excessive use of groundwater increases the following risks of groundwater salinization:
   i. Up-coning of deeper saline groundwater,
   ii. Lateral intrusion from neighbouring saline aquifers, and
   iii. Seawater intrusion of saline water into freshwater aquifers (in parts of the Punjab), which would increase salinity and render groundwater not suitable for irrigation. In the coastal areas of Sindh Province, over exploitation of groundwater has led to seawater intrusion into coastal agricultural areas inland up to 100 km north of the Arabian Sea and has impacted 10 million acres in the Indus delta (Shah et al. 2000; Qureshi et al. 2009).

e. Environmental risks that follow groundwater depletion:
   i. Strong connection between groundwater and rivers and irrigation system, where groundwater usage could affect river streamflow (stream capture). The river losses are increasing but neither shared nor quantified.
   ii. Small lakes and wetlands (groundwater dependent ecosystems), which are connected to shallow groundwater systems, have dried out due declining groundwater levels and also from prolonged droughts (Watto 2015).
   iii. Loss of vegetation due to lack of uptake from groundwater: Access to shallow groundwater is vital for sparse vegetation cover in arid and semi-
arid plains. Phreatophytes are most commonly affected by declining groundwater level. For instance date palms in many regions have wilted due to decreasing watertables.

iv. Land subsidence resulting storage depletion.

f. Excessive pumping of groundwater in the Indus basin using electric and diesel pumps is causing shortage of energy in the country.

3. **Canal seepage, water logging and salinization:** Continuous seepage from the canal network along with over irrigation caused watertables, which originally were 20 to 30m deep, to rise close to the soil surface causing widespread waterlogging and salinity, which remain intractable issues in Sindh and in parts of Punjab. Researchers estimate 15 million tons of salt accumulate in the Indus Basin annually (Briscoe and Qamar 2005).

4. **Soil salinisation and soil sodicity** can occur from over-irrigation, use of poor or marginal quality groundwater, lack of drainage and/or by rising groundwater levels (Kijne 1999; Kahlown and Azam 2002; Ahmad et al. 2002). Punjab has 1.6% of land strongly affected by salinity whereas in Sindh the area affected is 20%. Additionally, in Punjab 23% of groundwater is saline, whereas in Sindh has 78% poor groundwater quality.
   a. Lack of drainage: The introduction of large scale irrigation in the Indus Basin without the requisite drainage system changed the hydrological balance in the basin. In some areas such as in the mid portions of doabs, tubewells are discharging water which is high in sodicity.
   b. Poor groundwater quality: Irrigation of crops with groundwater of high salinity and sodicity leads to a deterioration of soil structure and accumulation of salts in the root zone, which is causing salinity and sodicity of agricultural land and decreases crop productivity. Furthermore once soils are salinized farmers do not have the means to reclaim these soils.

5. **Loss of crops and arable land due to salinity:** Studies by Kahlown and Azam (2002), Bhutta and Smedema (2007) and others indicate that salinity remains a major threat to the sustainability of irrigated agriculture in the Indus basin. Current estimates indicate 6.3 million ha are affected by salinity and sodicity, and about 1.4 million ha of agricultural land is not cultivable. Moreover, crop losses due to salinity amount to US$1.5 billion annually which equated to 0.6% of Pakistan’s GDP in 2004 (Corbishley and Pearce 2007).

6. **Degradation of water quality** due to salinity build up in surface and groundwater and water pollution. Intensive agriculture is resulting in widespread use of large quantities of fertilizers and pesticides and pollution loads from rapidly growing cities and industry.

7. **Increased risk of flooding and drainage problems** in the lower Indus basin due to the raised riverbed levels resulting from sedimentation.

8. **Delta degradation** in the lower reaches of the Indus due to low flows and low silt loads, impacting subsistence coastal communities, coastal vegetation (mangroves) and biodiversity.

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1 Phreatophytes are plants that depend for their water supply upon ground water that lies within reach of their roots.
9. **Impact of climate change** is likely to exacerbate the severity of floods and prolonged droughts. Climate change is beginning to affecting glacier melt in the Western Himalayas. Present estimates indicate that glacial retreat will continue for the next 50 years which will increase river flows and flooding, after which will follow decreases in river flows between 30 and 40% in a hundred years.

10. **Transboundary groundwater issues**: An emerging issue is the over-exploitation of groundwater and expanding groundwater depletion in western India along the eastern border of Pakistan. In these areas the impact of excessive depletion of groundwater has resulted in declining groundwater levels along the western region of India as shown by the large dark red zones in Figure 1.4. The dark red zones indicate areas where groundwater levels have fallen below 14.6 m. Similarly, results of groundwater depletion estimates based on GRACE satellite observations show a zone of depression in India expanding into Pakistan (Figure 1.5). The area affected by declining groundwater levels is extensive, stretching from the north near Amritsar towards the south near Palanpur which extends along the eastern border of Pakistan. This expanding zone of groundwater level decline is likely to have an impact on groundwater availability and access in Pakistan as groundwater levels decline further. It is likely that in the very near future, transboundary issues will go beyond the current focus on surface water resources as groundwater depletion is likely to impact on the aquifer in Pakistan as shown in Figure 1.4 and Figure 1.5.

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**Figure 1.4** The impact of groundwater over-extraction in India particularly along its western region bordering Pakistan showing the extent of decline in water levels (Shiao et al. 2015; after www.indiawatertool.in)

**Figure 1.5** Cumulative total freshwater losses in South Asia from 2002 to 2015 (in inches) observed by NASA’s Gravity Recovery and Climate Experiment (GRACE) mission. Image by NASA’s Jet Propulsion Laboratory (Rodell et al. 2009)

1.2.3 Socio-economic aspects of groundwater in the Indus Basin

Groundwater demand in the Indus Basin is regionally disparate. Groundwater now accounts for more than half of all irrigation requirements in the Punjab surpassing a groundwater development potential of around 43 million acre-feet (MAF). In contrast, groundwater accounts for only 10% of all irrigation requirements in Sindh, where only about 4 MAF of groundwater is being pumped annually (Amin, M. 2005; Basharat et al. 2014).

Groundwater depletion also causes social inequities in the Indus Basin as smallholder farmers are the most economically vulnerable: The ‘on-demand’ nature of groundwater and the widespread use of tubewells in Pakistan has led to declining water levels, which resulted in a significant cost increase of tubewell drilling and installation, groundwater extraction and irrigation in many parts of Pakistan (Qureshi et al. 2003). This is likely to have the greatest impact on smallholder farmers as they do not have the resources to deepen wells, when shallow tubewells fall dry. Wattoo and Mugera (2013) found that irrigation costs per acre of cotton were 23.5% more in Lodhran district compared to Jhang district for tubewell owners. For farmers who had to buy water from tubewell owners, their irrigation costs were estimated at 30.1% higher in Lodhran district compared to water buyers in Jhang district. As indicated by Watto (2015), the implications of these spatial cost differences is that some smallholder farmers are leaving farming either by selling their lands or leasing their lands to farmers that have more cost effective access to groundwater. As a consequence, farm size is already shrinking in Pakistan and the number of landless farmers is increasing (Mustafa et al. 2013). In summary, in a regime where groundwater levels are declining and where policies and regulations for managing groundwater are lacking, groundwater extraction continues until the marginal cost of groundwater extraction begins to exceed the value of pumped water for agricultural production. At this point farmers have a choice: reduce crop production, or implement more efficient irrigation technologies, or switch to higher value crops. A benefit cost analysis of groundwater pumping would need to account for wider impacts of environmental, social and economic aspects of groundwater use. However, there is not enough research to facilitate the estimation of the costs of groundwater depletion in the Indus Basin.

The use of groundwater for irrigation has an economic value to Pakistan. The long term value and benefit of this project lies in understanding the importance of groundwater to the economy in Pakistan. Determining the size of the groundwater economy can be undertaken by estimating the economic value of groundwater used in Pakistan. In South Asia and in the North China Plain an active market exists for groundwater irrigation services in which tubewell owners sell irrigation water to their neighbours at a cost that often exceeds the marginal cost of pumping. This price offers a surrogate market valuation of groundwater use in irrigation. A comparison of the groundwater economy in India, Pakistan, Bangladesh, Nepal Terai and North China Plain is shown in Table 1.1. The total size of the groundwater economy in this region was estimated at US$10 to 12 billion per annum by Mukherji and Shah (2005), while the indirect benefits derived by the farmers in the form of higher crop yields and cropping intensity and livelihood benefits are much higher. By far the largest groundwater economy is in India estimated at US$8.6 billion, which is an indicator of the extent of groundwater exploitation in the country. Specifically, in the case of Pakistan Punjab the value of groundwater used is US$1.1 billion per year. Interestingly these figures (pre 2005 data) suggest the total number of tubewells in Pakistan Punjab are 0.5 million. However current estimates by Punjab Irrigation Department indicate the number of tubewells in Punjab to be in excess of 1 million (Government of Punjab 2017). The estimated groundwater use shown in the table below, though is consistent with current estimates of 50 km$^3$/year for Punjab and 5 km$^3$/year for Sindh. This
puts the value of groundwater used for irrigation in Punjab at US$1 billion and in Sindh at US$100 million/year.

Table 1.1 The size of agricultural groundwater economy in South Asia and China (Source: Mukerji and Shah 2005)

<table>
<thead>
<tr>
<th></th>
<th>INDIA</th>
<th>PAKISTAN</th>
<th>BANGLADESH</th>
<th>NEPAL TERAI</th>
<th>NORTH CHINA PLAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Total number of irrigation GWEMs (million)(^b)</td>
<td>26</td>
<td>0.5</td>
<td>0.8</td>
<td>0.06</td>
<td>3.5</td>
</tr>
<tr>
<td>B Average output of groundwater structures (m(^3)/h)(^c)</td>
<td>25</td>
<td>100</td>
<td>30</td>
<td>30</td>
<td>41(^d)</td>
</tr>
<tr>
<td>C Average hours of operation/well/year(^e)</td>
<td>330</td>
<td>1090</td>
<td>1300</td>
<td>205</td>
<td>1134</td>
</tr>
<tr>
<td>D Price at which pump irrigation from standard size pump sells (US $/hr)</td>
<td>1</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>0.96</td>
</tr>
<tr>
<td>E Estimated groundwater used (km(^3))</td>
<td>(\frac{(A<em>B</em>C)}{1000000000})</td>
<td>215</td>
<td>54.5</td>
<td>31.2</td>
<td>0.37</td>
</tr>
<tr>
<td>F Imputed value of groundwater used/year in US billion $ (E/B<em>D) or (\frac{(D</em>C*A)}{1000})</td>
<td>8.6</td>
<td>1.1</td>
<td>1.6</td>
<td>0.02</td>
<td>2.5</td>
</tr>
</tbody>
</table>

\(^a\) Estimate for Pakistan includes only that of Pakistan Punjab, which has almost 90% of groundwater structures in the country.

\(^b\) Total number of groundwater structures have been estimated for India based on MI Census 1986 and 1993, for Bangladesh based on MI Census 1996 97 and that of Pakistan based on estimates provided by Punjab Private Sector Development Project 2001. GWEMs = Groundwater extraction mechanisms.

\(^c\) Average output of groundwater structures (m\(^3\)/hr) will depend among other things on average HP of pumps and depths to watertable. In Pakistan, average HP is almost two or three times that of India. Pakistan Punjab has high watertables due to canal recharge. In Bangladesh, though pump HP is comparable with that of India, the watertable is very near to the surface and WEMs pump water from an average depth of 5 8 m in most places. So, average output of WEM in Bangladesh is assumed to be marginally higher than that of India, and that of Pakistan is 4 times that of India.


\(^e\) Average hours of operation (hr/well/year) and price at which water sells is based on primary data generated through survey conducted by IWMI in 2002 and published in Mukherji and Shah (2004).

Although these figures are estimates, they offer policy makers and resource managers an overall assessment of the contribution of groundwater to the national economy. Furthermore, as Mukerji and Shah (2005) have indicated there are significant indirect benefits derived by farmers in the form of higher crop yields, allowing farmers to increase cropping intensity and generation of additional income which benefits rural livelihoods. And added to this is the large number of small holder farmers who are benefitting directly from the availability and access to groundwater resources. Thus protecting groundwater resources and ensuring sustainability for supply for the millions of small holder farmers who rely on this resource makes it even more important for the Government of Pakistan to develop the right policies and to develop in country capacity to manage this valuable resource.

1.2.4 Groundwater Governance and Management

Reduced supplies from lower river flows and overexploited groundwater aquifers are unable to meet an increasing demand for water from all sectors of society, agriculture, industry and potable use. Improved food security for Pakistan’s burgeoning population and is the key driver for the increase in irrigation water demand and cropping intensity. Declining groundwater levels economically
disadvantage farmers by raising their cost of production particularly in the absence of the right policies and regulatory framework for managing groundwater. The need for judicious use of water for irrigation has largely been bypassed in favour of expanding the canal network or seeking out new sources of water. The use, distribution, and accessibility of both surface water and groundwater for irrigation needs to be efficient, sustainable, fair and equitable. Pakistan will begin to manage its water scarcity challenge, if surface and groundwater use and management is improved at each level, from the basin to the canal command level, to the distributary and farm scale.

Creating the knowledge base, awareness of groundwater issues, the need for management of groundwater resources for economic and resource sustainability and for improving equity issues amongst farmers in Pakistan is at the forefront of progressive thinking in Pakistan. There is an urgent need to strengthen institutional capacity to manage groundwater and to develop socially acceptable approaches and policies for addressing the imbalance between water withdrawals and recharge. Since much of the groundwater recharge is from canal leakage and irrigation application, conjunctive use strategies and management needs to be put in place. However, neither governments nor major donors are strategically funding to cater for these needs.

Studies undertaken by Briscoe and Qamar (2005), Mustafa et al. (2013), Condon et al. (2014), Kirby and Ahmad (2014), Kirby et al. (2017), and CSIRO (2016a) have proposed solutions to the water crisis which include constructing new dams and related infrastructure, improved water productivity in agriculture, and improved institutions governing water allocation and use. Construction of new dams in Pakistan is a highly contentious issue. Although this may increase the supply of surface water it will not solve the underlying problems of low land and water productivity and the need for institutions to promote good governance of water. To build these capabilities, a greater focus is needed on managing water, building capacity of irrigation departments and institutions, and the building of a good knowledge base to improve water governance. An improvement of the understanding and knowledge base of the basin’s water resources (surface and groundwater), linkages and dependencies between different uses is needed to manage resources and to develop effective policies. Kirby and Ahmad (2014) indicate that several previous studies have proposed that improved knowledge, and in particular modelling of the hydrology of the Indus Basin is necessary to support overall water resources management. Significant gaps in groundwater modelling at the basin scale have been identified by Kirby and Ahmad (2014). They showed that the groundwater models developed thus far are designed largely to address local to doab-scale groundwater management issues with no regional understanding.

The CSIRO DFAT Indus Sustainable Development Investment Program (SDIP) aims to address this knowledge and technical gap by developing a regional groundwater model of the alluvial areas of the Indus Basin, to integrate the management of surface and groundwater resources at the basin scale, and, in the future, to expand this to the doab and canal command scale. Additionally, the project has a significant capacity development program which will benefit researchers and resource managers’ in country. CSIRO has been working and continues to work closely with key stakeholders in Pakistan throughout the process of building this model (e.g., Pakistan Water and Power Development Authority – WAPDA, Punjab Irrigation Department - PID, Sindh Irrigation Department - SID). This collaborative approach ensures that the model is designed to meet Pakistan’s specific needs and that there are skilled people within Pakistan to use and maintain this model into the future.
1.3 Purpose and Outputs of the IBIS Groundwater Model

In the Indus Basin Irrigation System (IBIS) in Pakistan, the area under irrigation has expanded greatly over the past five decades enhancing agricultural production to meet food and fibre demands. However, one of the key drivers for the expansion is a massive increase in groundwater use for irrigation. As a result, in areas of fresh groundwater quality, almost half of the irrigation supplies come from groundwater. There is a strong linkage between the surface and groundwater resources. Hence, due to the increasing demand from increased population and subsequent increases in irrigation areas the associated water demands have been met through increased groundwater usage, which in turn has impacted surface water losses. In areas of fresh groundwater, levels continue to drop while in saline areas there are issues of water logging and expansion of saline areas. There is a need to sustainably manage the conjunctive management of surface and groundwater resources in the IBIS. To be able to do this effectively, a model is needed to assess availability of groundwater resources and the interaction between surface and groundwater systems and to take into account the constraints by seasonally variable surface water flows, groundwater recharge, quality and storage and climatic variability. To date there is no such regional scale groundwater flow model that fulfils this objective and covers the entire IBIS.

To address this need, a new regional 5km coarse-resolution MODFLOW model for the IBIS will be built by CSIRO in collaboration with partners from Pakistan (WAPDA, PID, SID). While the groundwater model extends horizontally across the entire Indus basin of Pakistan, it will be limited vertically to the quaternary, alluvial aquifer of the Indus basin as the primary focus is interaction between surface water and shallow groundwater. The groundwater model will provide a better understanding of groundwater dynamics and of groundwater budgets on a regional and sub-regional scale. The simulated surface-groundwater interaction will allow for a visualisation of areas where groundwater usage could affect river streamflow (capture analysis).

It will also provide boundary conditions for finer resolution flow and solute-transport child models (e.g., doab or command areas) within the coarser scale regional groundwater model to better represent the distribution of crop water use between surface and groundwater resources and to assess the impact of development on fresh and saline groundwater areas on multiple scales.

When complete, it will be linked to an integrated river system model of Pakistan that is currently being constructed by CSIRO as part of the SDIP Indus Basin Project (CSIRO 2016c). This integrated modelling framework considers physical interactions and spatially and temporally variable conjunctive use and availability of both surface and groundwater. The interaction between both models would assist Pakistan in developing an overall integrated water resource model of the Indus basin. This framework will allow for scenario analysis to understand the impacts of groundwater pumping and climate change, for instance, the risks of long duration droughts for the Indus Basin to existing groundwater supplies. It will help mitigate the response of water demand/supply to external changes (e.g., in climate, land-use, and water policy), as well as help build a national water resource plan for the IBIS of Pakistan.
1.4 Current Arrangements, Funding, and Ownership

CSIRO has been building the groundwater model for the Indus Basin of Pakistan described herein in partnership with Pakistani stakeholders in conjunction with the ongoing development of an integrated river and irrigation system model of Pakistan in order to assist Pakistan in developing an integrated water resource assessment tool of the Indus basin. Work on the IBIS groundwater model has commenced in August 2015. Funding for this activity has been provided by the Department of Foreign Affairs and Trade (DFAT) under the Sustainable Development Investment Portfolio (SDIP). This funding has covered data gathering/compilation, most of the model construction and parameterization, but not running, debugging, calibrating and analysing the model (see chapter 5, ‘Future Tasks and Outlook’).

CSIRO has been and continues to work closely with key stakeholders in Pakistan throughout the process of building this model (e.g., Pakistan Water and Power Development Authority - WAPDA, Punjab Irrigation Department - PID, Sindh Irrigation Department - SID). This collaborative approach has ensured a model design to meet Pakistan’s specific needs and capacity building in groundwater modelling though stakeholder input, participation in the model development, and through training seminars and workshops.

This collaboration between CSIRO and Pakistan has been formalised through a Subsidiary Arrangement between the Governments of Pakistan and Australia. This arrangement identifies the Ministry of Water and Power (MoWP) as the managing agency within Pakistan and has been endorsed by federal and all provincial water jurisdictions. It provides the mandate to work within Pakistan and provides the required access to key datasets with Pakistan government departments. Under the agreement cleaned and quality assured data sets are provided back to custodians and course resolution groundwater model that is under development will handed back to MoWP for Pakistan for continued development and use.
2 Previous modelling studies in the Indus Basin

This chapter contains a review of the previous modelling studies that have been undertaken in the Indus Basin. There are very few modelling studies that cover the entire basin. The most well-known is an economic optimization but not groundwater model of the Indus Basin model by the World Bank (Yu et al. 2013). The other groundwater modelling studies documented in this review are either at the doab scale, or at the canal command level, or focus on specific issues on a much smaller scale. The purpose of this review is to document that most previous models were generally fit for purpose, yet did not address the need to capture cross boundary flows that follow from a transition of vertical irrigation-flux domination to groundwater overdraft induced horizontal flows crossing boundaries of canal command, doabs and even provinces. Furthermore, none of the previous models captures external boundary flows into the entire irrigated Indus basin of Pakistan, such as mountain-front recharge from the Himalayas. In addition the review also demonstrates regional inequalities with a number of models in the eastern doabs of Punjab, but there deficiencies in model coverage in southern and western Punjab, and no models covering Sindh.

Disclaimer: The most recent MODFLOW groundwater model for Punjab was published after completion of this literature review and, hence, is not yet included herein (Khan et al. 2016).

2.1 The World Bank IBMR

The World Bank model IBMR (Indus Basin Model Revised) by Yu et al. (2013) combines a hydro economic optimization model with a general equilibrium (CGE) model for the Pakistan macro economy. The economic optimisation model utilises agronomic information, irrigation system data, and water inflows to generate optimal crop production across the provinces in the Indus Basin monthly. The integrated models were used to illustrate how changes in climate may impact the macro economy and different household groups through the agriculture sector.

The IBMR model derives a water balance for each agro climatic zone (ACZ). The model uses a network of nodes and arcs to simulate the flows throughout the Indus rivers and link canals. At each node, a water flow decision is made and the water balance for each month is calculated. The IBMR has 47 nodes that represent reservoirs, inflow stations, barrages, confluences of rivers, and the terminus of the Arabian Sea. Forty nine sink nodes represent diversions to irrigation canals and 110 arcs represent river reaches and link canals between nodes. Flows along these river reaches are simulated with losses and gains from river bank storage. The IBMR also considers the efficiency of canals and watercourses for irrigation purposes. In the groundwater context, stream recharge to groundwater is computed as river seepage and treated as a loss from surface water. The canal water diversion efficiency and watercourse diversion efficiency are considered losses from surface water and as additions to groundwater. In the IBMR the residual moisture in the root zone is represented as a potential source of water for crops. Thus, crop water needs are met from precipitation, canals, groundwater wells, and the moisture in the root zone available for crop use. The IBMR assumes that 60% of the evaporation from groundwater can be absorbed by crops. Fresh and saline groundwater areas are treated separately with tubewell pumping occurring in fresh groundwater zones but not in areas where the groundwater is saline. The IBMR model is a useful planning tool for GoP agencies and provides a monthly water budget for each ACZ, however, it is not a groundwater model. It does
not explicitly model groundwater flow nor does it model salinity transport. Hence, it is not able to
answer questions of surface water/groundwater interaction, such as stream capture by groundwater
overdraft, questions of groundwater availability, and to address focussed salinity analyses in local
hotspots of salinisation.

2.2 Groundwater models in Indus Basin

A number of groundwater models have been developed in the Indus basin over the years. Most of
these models cover a doab or smaller regions within the basin. Of these the most recent work covers
the Rechna Doab model developed by CSIRO and IWMI (Khan et al. 2003), the Upper Chaj Doab
model (Ashraf and Ahmad 2008), Lower Bari Doab (Basharat 2012), Lower Bari Doab (Lahmeyer
International 2013), and the revised Rechna Doab model developed in conjunction with UAAR and
PID with Australian financing (Punthakey et al. 2015).

2.2.1 Upper Chaj Doab model

A 3D finite element model (Feflow) has been used for regional groundwater flow modelling of
Upper Chaj Doab in Indus Basin, Pakistan (Ashraf and Ahmad 2008). The groundwater flow model
was used to analyse the regional groundwater flow of Upper Chaj Doab area in the Indus basin and
to estimate the groundwater budget of the aquifer. Modelling results show a gradual decline in
watertable from year 1999 onward. The persistent dry condition and high withdrawal rates have
resulted in lowering groundwater levels. Different scenarios were developed to study the impact of
extreme climatic conditions (drought/flood) and variable groundwater abstraction on the regional
groundwater system.

2.2.2 Rechna Doab models and studies

Water balance model for Rechna Doab

An early study was the development of a water balance model for Rechna Doab by Hassan and
Bhutta (1995). A regional lumped water balance model and using the specific yield method was
applied to estimate recharge for Rechna Doab on a seasonal basis for a period of 31 years (1960–
1990). Both methods were in good agreement. The average value of net groundwater recharge
during Kharif (April to September) season was estimated at 60 mm, whilst for Rabi (October to
March) there was no recharge, rather there was depletion of the groundwater reservoir during the
winter months. Long term average annual depletion of the groundwater reservoir was found to be
greater than corresponding value of annual recharge. Their study concluded that regional
groundwater levels in Rechna Doab had declined by 2.3 m over a 31 year period from 1960 to 1990,
or in other words an average decline of 74 mm/year.

CSIRO IWMI Rechna Doab model

The Rechna Doab CSIRO IWMI model (Khan et al. 2003) was developed to address problems of
sustainable use of groundwater and surface water as well as the response of groundwater quantity
and quality from changes in recharge and groundwater pumping rates. The study aimed at
identifying a combination of institutional and technical strategies to manage surface and
groundwater at the regional scale to promote environmental sustainability and maximize
agricultural water productivity (‘crop per drop’). This was to be achieved by development and
calibration of a flow and solute transport model to describe the surface water–groundwater interactions in the Rechna Doab, and the spatial and temporal impact of future surface water and groundwater use scenarios. An internal review was undertaken of this model by CSIRO and a number of areas for modifying the modelling approach were identified. A review of this model undertaken by CSIRO (Schmid 2015) summarised the following:

- conclusions of ‘very high water yields and transmission’ and ‘tremendous water storage’ are vague and based on unreferenced assumptions for aquifer parameters
- findings of >15 meters of groundwater depressions are questionable if simulated near inflexible ‘river’ no flow boundary condition
- limitation to two stress periods of Kharif (summer) and Rabi (winter) prevents farm management at shorter time scales versus a long term protection of the resource and peak seasons of recharge and crop water demand cannot be distinguished
- water balance issues: Boundary outflows are ignored and groundwater pumping estimate does not take into account beneficial uptake from groundwater
- the correlation of increased groundwater pumping with degrading water quality in the lower doab seems to be a model result not corroborated by observations. That is, the transport model is uncalibrated and observed salinity is not a calibration target
- the scenario and suggestion of more surface water supply, reduced groundwater pumping, and increased recharge in the lower doab will allow the recovery of groundwater levels, but will eventually lead to waterlogging and salt build up (not simulated), if drainage pumping (also not simulated) is not maintained.

The following scenarios undertaken by the CSIRO IWMI model are briefly discussed:

Scenario 1: The statement about high salinisation risk "due to vertical up coning and lateral movement of highly saline groundwater into the fresh shallow aquifers" not founded as majority of doab experiences a decline in salinity compared to the year 2000 baseline.

Scenario 2: Shifting to more surface-water supply, reducing groundwater pumping, and increasing recharge in the lower Doab would naturally elevate water levels as correctly mentioned yet this would allow ET from groundwater when water levels reach the ET extinction depths. This in turn would increase salinity not decrease it as stated for the lower Doab. The only way surface water dominated irrigation districts prevent this is by drainage pumping, which, however, was not done/simulated. In fact, groundwater pumping was reduced!

Scenario 3: Conclusion of RIV leakage diluting the groundwater salinity possible but highly speculative and conclusion of upconing from deeper saline groundwater seems unfounded as deeper layers actually seem to be less saline than layer 1.

The concept of Rechna Doab as water storage through river recharge and recovery by farm wells rests on the assumption in the model that there is no capture of groundwater through groundwater irrigation agriculture in other areas of the Punjab surrounding the Rechna Doab, especially across the border to India, and by metropolitan water use such as the city of Lahore just across the border.

The statement that “the groundwater is a valuable but vulnerable resource that requires management at a regional or national scale” is correct, yet cannot be concluded from this model.
ACIAR Rechna Doab groundwater and solute transport model

Additionally, a review was also undertaken for ACIAR and it was recommended in conjunction with PID to redevelop the model using PID’s extensive data set on water levels and salinity which have been monitored since 2008. Additionally, the monitoring of salinity from several hundred tubewells undertaken by PID staff in Rechna Doab provided a valuable data set for calibration of the salinity transport model. The Rechna Doab model was redeveloped with ACIAR funding to develop a tool which was suitable for use by PID (Punthakey et al. 2015). The main areas where the latest Rechna Doab model differs from the previous model is shown in Table 2.1.

Table 2.1 Enhancements in model approach for Rechna Doab (Punthakey et al. 2015)

<table>
<thead>
<tr>
<th>Previous Rechna Model (Khan et al. 2003)</th>
<th>New Rechna Model (Punthakey et al. 2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kharif and Rabi periods only</td>
<td>Monthly stress periods</td>
</tr>
<tr>
<td>Four layers: 7, 21, 30 m, and variable depth to bedrock</td>
<td>Four layers: first 3 layers 30 m each, lower layer variable depth to bedrock</td>
</tr>
<tr>
<td>Recharge going to very deep layers</td>
<td>Recharge only into top layer</td>
</tr>
<tr>
<td>Different conductances for Kharif and Rabi</td>
<td>River and Canal Conductance stays constant</td>
</tr>
<tr>
<td>2 heads varied cyclically for Kharif and Rabi</td>
<td>River and canal stage variable and simulated for each grid cell along reach for each month</td>
</tr>
<tr>
<td>SCARP data</td>
<td>PID monitoring wells from 2008 to 2013 (not SCARP (restricted to waterlogged areas?))</td>
</tr>
<tr>
<td>Traditional approach using rainfall stations. Recharge 20% of rainfall and 15% of SW delivered to field. Spatially lumped ET, constant extinction depth.</td>
<td>Spatial and temporal distribution of rainfall and ETa is used for each month using remote sensing (NDVI)</td>
</tr>
<tr>
<td>Pumping calculated as difference between monthly water supplies (from 3 nodal networks of channel reaches and demand nodes) and crop demand volumes</td>
<td>Pumping calculated spatially as a difference between actual evapotranspiration and recharge from rainfall and irrigation</td>
</tr>
<tr>
<td>Calibration for top two layers (for Kn, Sm) or four layers (for Ks). No calibration for transport</td>
<td>Calibration is undertaken for top two layers where most of the data is available.</td>
</tr>
</tbody>
</table>

Both Rechna Doab models are fit for purpose models at the scale of a single doab. In those models, doab bounding rivers formed no flow boundaries in the sense of a groundwater divide assuming that horizontal flow across these boundaries is negligible and vertical fluxes are dominant. However, different boundary conditions are needed to simulate boundary flows into the entire irrigated Indus basin of Pakistan and into doabs/areas not bounded by two major rivers. In addition, even for river bounded doabs, horizontal groundwater flow across those ‘river’ boundaries cannot be neglected when simulating increasing groundwater overdraft on either side of doab bounded rivers over historic periods or in future scenarios. Additionally, the deeper aquifer layers also require boundary conditions to simulate flows occurring across doab boundaries.

The recent Rechna Doab model development by Ecoseal Developments (Punthakey et al. 2015) is a regional flow and solute transport model which was developed to assess availability of groundwater resources and interaction of surface and groundwater in the Rechna Doab. Spatial and temporal assessment of groundwater use, availability of surface water supplies, and climatic variability were modelled to assess the quantity and quality of groundwater resources. The study found the major components of the water balance are recharge from rainfall, river leakage, canal leakage and
irrigation recharge which accounts for 93% of inputs to the system. The model was used to assess the sustainable yields from the system. Based on the calibration period from 2008 to 2013, the recommend pumping from Rechna Doab should be managed around 11,000 ± 1000 GL/yr depending on the need for pumping in response to drought and or lack of surface water supplies. When surface water supplies are plentiful pumping levels should be decreased so that the groundwater system gets recharged with freshwater. The reduction in pumping during years when surface water supplies are plentiful is also important for replenishing the aquifer and minimising salinity increase due to groundwater pumping which enhances lateral inflows and upconing of saline groundwater from deeper layers.

The findings from scenario analysis show that improved controls on pumping will achieve greater water savings. Thus Punjab Irrigation Department (PID) will need to focus effort on significantly enhancing the level of groundwater management. The study will allow improved understanding of the sustainability of groundwater usage in Rechna Doab and to improve the management of surface and groundwater in the doab.

2.2.3 The Lower Chenab Canal Command sub model

In addition a sub model comprising the Lower Chenab Canal (LCC) East region was extracted from the regional Rechna Doab model using a detailed grid structure compared to the coarse grid used for the regional Rechna Doab model (Punthakey et al. 2015). The sub model for LCC East was constructed using the Telescopic Mesh Refinement method of MODFLOW (TMR; Leake and Claar 1999). It required additional calibration as the distribution and coverage of the river and canal network had changed. Thus the spread of river cells in the LCC East sub model are much less than in the regional Rechna Doab model. The preferred course of action for future enhancements of the LCC East sub model would be to incorporate the distributaries and important minors which would also allow a more realistic spread of canal losses in the model and allow improved assessment of canal losses and groundwater quantity and quality.

It is recommended that future work with the LCC sub model re-evaluate the pumping which would also entail reworking the spatial estimates of reference and actual evapotranspiration at a fine spatial scale of 500x500 m. Moreover, our assessment is that the approach used in this study to estimate pumping works best where groundwater availability is not constrained by salinity. Where salinity of the groundwater is high farmers may only use groundwater when forced to due to lack of surface water supplies, thus there is a high probability that in areas with poor quality groundwater the estimation of pumping by this method is likely to be overestimated.

2.2.4 Conjunctive use model for Qadirabad Bulloki Link Upper Chenab subarea

A FEFLOW model covering an area of 38,100 ha between the Qadirabad Bulloki Link canal and Upper Chenab canal in the Rechna Doab was developed by Sarwar and Eggers (2006) to evaluate alternative management options for surface and groundwater resources. The study site is shown in Figure 2.1.

A simple water balance approach was used to estimate net recharge to the aquifer. A groundwater model using FEFLOW and the net recharge from the water balance model was used as an input for the water balance calculation and to simulate groundwater flow. The split sample calibration of the model used water level data from 1982 to 1990 and data from 1991 to 1995 was then used to verify
the model. The model was applied to predict groundwater levels up to 2010 in response to the possible need for intervention in irrigation and/or agricultural practices. The study found that pumping for a cropping intensity of 130% would result in watertables falling by 4.17m, whilst an increase in pumping for a cropping intensity of 150% would result in declining groundwater levels up to 6.57 m. Lining of watercourses and adjustment in cropping pattern could be adopted as alternatives for better management of surface and groundwater resources, as this would result in additional surface water supplies available for irrigation.

2.2.5 Simulating seepage from the Upper Gogera Branch Canal

A MODFLOW model was developed by Arshad et al. (2009) to estimate seepage from the Upper Gogera Branch Canal in the Rechna Doab. Model simulations were undertaken to assess the time dependent seepage to groundwater. The contribution of seepage to groundwater is based on the water balance components including recharge flow, applied irrigation, rainfall, lateral flow and evapotranspiration from the existing cropping system. The monthly average seepage rate from the canal was estimated as 12.10 m³/sec/million m², for a monthly average flow rate of 106 m³/sec. Seepage contribution to groundwater ranged from a low of 1425 m³/day/100 m of canal length during February 2003 to a high of 1942 m³/day/100 m of canal length during July 2003. An empirical relationship between seepage (S) and the canal flow rate (Q) was developed (S = 0.006 Q1.44) to quantify the seepage to groundwater from the canal for any flow rate.

2.2.6 Lower Bari Doab Canal Command model

A MODFLOW model was developed for the Lower Bari Doab canal command by Basharat (2012), Basharat and Tariq (2013) to evaluate long term irrigation cost inequities due to increasing groundwater depletion towards the tail end. They used a uniform grid of 500 m to model the LBDC command covering an area of 7874 km². A total depth of 200 m was modelled with five layers. The model was calibrated over a period of eight years from Kharif 2001 to 2009 with two stress periods per year.
The mass balance for the entire domain from 2001 to 2009 showed total recharge (including groundwater returns) for 8.5 years is 23.45 MAF and tubewell abstraction is 27.02 MAF. Values per year for these two parameters are 2.759 MAF (3403 Gl/yr) and 3.178 MAF (3920 Gl/yr), respectively, showing that groundwater abstraction is higher than the recharge to the aquifer. The groundwater budget component due to evaporation is relatively small due to watertable being deep in most of the command areas (Basharat and Tariq 2013).

The irrigation network (main and secondary canals) seepage decreases from head to tail of the LBDC command. This is due to the decreasing density of the channels (main canal, branches and distributaries) and their discharges towards the tail of the irrigation system. With the prevailing canal supplies and increasing climate severity in the downstream direction, groundwater recharge from canal supplies and rainfall reduces from 430 mm at head end to 285 mm at tail end. Thus, decreasing rainfall and increasing crop water requirement towards the tail end is resulting in greater groundwater depletion downstream from canals particularly at the tail end. The temporal trends of average depth to water for each HSU (Hydrologically Similar Units) is shown in Figure 2.2.

The deeper watertables at the tail ends incur additional costs for farmers as indicated by Basharat and Tariq (2015). Cost per cubic metre of pumped groundwater increases about 3.5 times as the depth to watertable drops from 6 to 21 m from head to tail in LBDC command. Due to excessive groundwater depletion, a tail end farmer currently incurs 2.19 times higher irrigation costs as compared to the head end counterpart. An additional depletion of 8–11 m (about 0.35 0.45 m per year) is expected in the lower half of the command by 2031. They concluded that with the existing canal water distribution, the comparative cost of groundwater pumping and the combined cost of canal and groundwater use are expected to further increase from 2.37 to 2.53 and 2.19 to 2.36 times, respectively, from 2011 to 2031, resulting in greater inequity between head end farmers and tail end farmers.

Figure 2.2 Temporal trends of average depth to water for HSU’s in Lower Bari Doab (after Basharat and Tariq 2013)
2.2.7 Lower Bari Doab Canal Improvement Project (LBDCIP)

A model of the Lower Bari Doab (LBDC) was developed by Lahmeyer International and NDC consultants with funding from ADB as part of the Lower Bari Doab canal improvement project (Lahmeyer International 2013). The LBDC model was developed using MODFLOW, to understand the groundwater conditions in the LBDC command and to model the spatial and temporal behaviour of recharge and discharge dynamics of the LBDC aquifer and salinity transport across the seasons. From 1995 to 2012 the area with fresh groundwater resources reduced from 71% in 1995 to 32% in 2012. The area with marginal groundwater quality increased from 22% in 1995 to 49% in 2012. The area under hazardous water quality has been increased from 7% in 1995 to 19% in 2012. The trend over the last 17 years is that groundwater quality in LBDC command is generally deteriorating. In some area near the Ravi River and along the main canal, the EC of groundwater declined, whereas in some areas away from the Ravi River and towards the centre of the doab the EC of the groundwater increased. This finding is consistent with our current understanding of salinity dynamics in the other doabs.

The LBDC model was used to determine the impact of different scenarios of canal water availability and groundwater abstraction to show the impact of surface and groundwater resources in LBDC. The main finding from the scenario runs showed that reducing tubewell pumping and increasing canal water supplies seems to be the only effective way of arresting the current pace of groundwater drawdowns in large areas of LBDC.

2.3 Lessons learned from previous models for regional model of Indus Basin Irrigation System

In general, there is an urgent need for integrated regional surface water/groundwater model (and possibly for an integration of groundwater and river system models) covering the entire Indus Basin and solute transport models in areas of salinization, given the:

- rapid increase in tubewells in Punjab and in the freshwater zones in Sindh,
- lack of regulatory and policy frameworks for managing groundwater,
- dynamic linkage between surface water and groundwater availability.

Boundary conditions of previous doab-level models (Rechna Doab, Upper Chaj, Lower Bari) are fit-for-purpose models at the scale of a single doab. In many of these models, doab-bounding rivers formed no-flow boundaries in the sense of a groundwater divides assuming that horizontal flow across these boundaries is negligible and vertical fluxes are dominant (Figure 2.3).

This assumption is limited to typical “doabs” between two rivers, but does not hold true for several command areas in the Indus basin that not bounded by two major rivers (e.g., D.I. Khan, D.G. Khan, Bawahal areas, left and right bank areas in the Lower Indus). Furthermore, increasing groundwater overdraft from irrigation and urban demand induce cones of depression encroaching into neighbouring doabs/areas beyond doab-bounding rivers, especially if those rivers became disconnected from groundwater (Figure 2.3).
For a regional groundwater model of the IBIS of Pakistan, different external boundary conditions are needed to

- simulate boundary flows into the entire irrigated Indus basin of Pakistan, such as mountain-front recharge from the Himalayas;
- define variable boundary heads at general head boundaries;

In addition, different internal boundary conditions within the basin are needed to simulate intra-basin flows across the boundaries of doab/areas that are

- not bounded by two major rivers boundary and
- bounded by rivers to simulate increasing groundwater overdraft on either side of doab-bounded rivers over historic periods or in future scenarios.

The literature review shows that there are a number of models in the eastern doabs of Punjab, but there are glaring deficiencies in model coverage in southern and western Punjab, and virtually no models covering upper, middle and lower Sindh.

Given the rapid increase in tubewells in Punjab and in the freshwater zones in Sindh, and the lack of regulatory and policy frameworks for managing groundwater, there is an urgent need for groundwater and solute transport models covering the entire Indus Basin. The CSIRO SDIP project aims to build both surface water modelling and groundwater modelling tools which will form the basis for improved management of surface and groundwater in the Indus Basin. A regional groundwater flow model of the Indus Basin will provide the first assessment of groundwater conditions in the entire basin. However, more importantly, it will provide the impetus for further detailed studies at a sub-regional scale and at distributary level similar to the extensive work undertaken in Rechna Doab and the eastern doabs of Punjab.
3 Physical setting and data report

The Indus basin is a transboundary river basin with an area of 1.12 million km² distributed between Pakistan (47%), India (39%), China (8%) and Afghanistan (6%). The Indus basin stretches from the mountainous regions of the Himalayas in the north to the semi-arid to arid alluvial plains of Sindh province and flows out into the Arabian Sea to the south. The basin covers around 520,000 km², comprising 65% of Pakistan, including the provinces of Punjab and Khyber Pakhtunkhwa, most of the province of Sindh, and a portion of the eastern part of Balochistan (Aquastat 2016).

Climate in the Indus Basin varies from subtropical arid and semi-arid to temperate subhumid on the plains of Sindh and Punjab provinces to alpine in the mountainous highlands of the north. Annual rainfall ranges from a low of 100 mm in the lowlands up to 2000 mm on mountain slopes, where it feeds streams heading south can causing floods through the arid lowlands towards the sea (Bender and Raza 1995). Ojeh (2006) indicated that snowfall at high altitudes above 2500 m accounts for most of the river runoff. For agricultural purposes, river water is stored or retained by reservoirs and headworks and led to its fixed destination by the world’s largest contiguous irrigation system (Bender and Raza 1995) of canal mains, links between the mains, branches, and distributaries.

The domain of the Indus Basin groundwater model reported herein covers the alluvial parts of the Indus basin in Punjab and Sindh, which form a deep unconsolidated unconfined aquifer. Surface and groundwater are a highly connected system due to the sandy and silty nature of the aquifer. It includes the Indus River and its main tributaries and the entire canal conveyance system of the Indus Basin, but does not extend into the mountainous parts of the basin. Since the 1980s, pumping of groundwater for supplementary irrigation has changed the aquifer from being partially confined into a typical unconfined aquifer in many areas of Punjab where groundwater is being intensely utilised for irrigation. As a result of the reduced groundwater levels, seasonal discharge of groundwater to the river has disappeared and the leakage from rivers and canals to groundwater has become the predominant form of surface water and groundwater interaction. The local groundwater dynamic is marked by seasonal variations primarily driven by the monsoon period during Kharif and irrigation recharge during Rabi.

Prior to constructing the numerical model, data on climate, water levels, geohydrology, and river and canal network have been gathered from multiple sources, which has resulted in a compendium of hydrologic data as part of this study:

- Spatially and temporally distributed climate data were retrieved from gridded daily data (116 meteorological stations from 1960 to 2013) covering the entire Indus basin and Pakistan (section 3.1).
- Water level data were organised in a common georeferenced database and can now be used for water level trend analysis, contour maps, initial heads for the groundwater model, and the calibration of simulated heads (section 3.2).
- A geohydrologic framework was created based on digitized and georeferenced borelog lithology. This framework allows for the delineation of the base of the alluvial aquifer and the association of major lithologic component with typical ranges of hydraulic parameters. A separate database was developed for observed hydraulic parameters (section 3.3).
A simplified river system was developed using ‘flow directions’ in ArcGIS that covers the major rivers (Beas, Chenab, Indus, Jhelum, Ravi, Sutlej), but did require the inclusion of some upstream major tributaries, of which gauges had been used also for the SOURCE river system model (CSIRO 2016c). A canal conveyance network from the Indus River System Authority (IRSA) was generalized to just Main Canals, Link Canals, Feeders and Branch Canals (>500 cfs). Drains were not considered in this study, except the Left Bank and Right Bank Outfall drains (LBOD and RBOD) that prevent waterlogging in southern Sindh. (section 3.4)

3.1 Climate Data

For this study, precipitation and evapotranspiration data were needed to formulate sources and sinks into and out of the groundwater, such as groundwater pumping, diffuse recharge, and evapotranspiration from groundwater specified or simulated by Well, Recharge, and Evapotranspiration Packages of MODFLOW (WEL, RCH, EVT).

Spatially and temporally distributed precipitation is contributing as a supply source to satisfy crop water use. Spatially and temporally distributed potential or reference evapotranspiration ETc-pot is used for multiplication with a crop coefficient to obtain potential, or well-watered, crop evapotranspiration, ETc-pot, which defines the crop water demand. Crop coefficients used for ETc-pot were associated with temporally variable yet spatially lumped district-wide crop statistics (see section Potential or Well-watered Crop Evapotranspiration). Crop water demand not satisfied by precipitation formulates a crop irrigation requirement in the calculation of the groundwater pumping requirement in excess of surface water irrigation that is specified using the Well Package (see section 4.7). Precipitation in-excess of crop water demand contributes to recharge (see section 4.9). Spatially and temporally distributed potential or reference evapotranspiration is also used to specify a maximum evapotranspiration for the calculation of head-dependent uptake from groundwater (see section 4.8).

A preferred method to derive physically based reference evapotranspiration is the Penman-Monteith method (Allen et al. 1998), which, however, requires measurements of air temperature, relative humidity, solar radiation, and wind speed. Unfortunately, the number of weather stations with long term or multi-parameter data records in the Indus Basin is limited and the climate data in much of the region is limited to the maximum and minimum temperatures, and rainfall. In this study, we therefore used the Hargreaves equation (eq. (1)) to calculate ET₀, since it can be calculated from only the maximum and minimum temperature and solar radiation as a function of latitude and month (Allen et al. 1998; Hargreaves 1994). Ullah et al. (2001) noted that the Hargreaves gives a slightly larger estimate than the usually preferred Penman-Monteith method in the Punjab, whereas it gives a slightly smaller estimate in Sindh. For the approximation of estimates described here, we ignored these factors. In addition, for time steps of a period of five days or longer, Hargreaves showed that his equation is suitable for estimating reference crop evapotranspiration (Hargreaves 1989). In that context, the methods appears sound given the fact, that in this study the Hargreaves method is used to provide reference crop evapotranspiration for monthly MOFLOW time steps.

\[
ET₀ = C_H R_s (T_{max} - T_{min})^{E_H} - \left( \frac{T_{max} + T_{min}}{2} + C_T \right)
\]

(1)

\[ ET₀ \] is the reference evapotranspiration (mm/d); \[ R_s \] is solar radiation (mm/d); \[ T_{max} \] is daily maximum temperature (°C); \[ T_{min} \] is daily minimum temperature (°C); \[ C_H \] is an empirical coefficient (\[ C_H = 0.0023 \]); \[ E_H \] is an empirical exponent (\[ E_H = 0.5 \]); and \[ C_T \] is an empirical temperature coefficient (\[ C_T = 17.8 \]) after Hargreaves (1994).
Spatially and temporally distributed climate data were retrieved from gridded daily data (116 meteorological stations from 1960 to 2013) covering the entire Indus basin and Pakistan an overall area of 1.4 million km². Gridded datasets of minimum and maximum temperature required as input into the Hargreaves evapotranspiration (Hargreaves 1994) and of rainfall were developed using the ANUSPLIN package (Hutchinson and Xu 2013) which has been specifically designed for elevation dependent interpolation of climate data. It implements a facility for transparent analysis and interpolation of noisy multi-variate data using thin plate smoothing splines. It has underpinned continent-wide interpolation of climate variables for Australia and other continents since the early 1990s. It has been demonstrated to perform well in relation to other techniques (Hutchinson et al. 2009), particularly in sparse data regions with complex topography (Price et al. 2000). A principal reason for its accuracy in such regions is its robust region-wide parametrisation of spatially varying dependence on appropriately scaled elevation (Hutchinson 1995). The ANUSPLIN package Version 4.5 was applied to the interpolation of daily and monthly temperature surfaces. SRTM DEM at 250 m resolution was resampled to 2.5 km resolution by calculating simple local averages across each 0.025 degree (latitude and longitude) which is sufficient to capture the elevation dependence. Where minimum temperatures exceeded maximum temperature an average of these was adopted for both. This only occurred in very high elevations where lapse rate extrapolations caused this issue.

For each centroid of a 5km MODFLOW grid cell, the nearest gridded data set of 2.5 km evapotranspiration or 1 km resolution rainfall datasets was adopted to represent the associated cell. The daily data for reference evapotranspiration and precipitation were re-gridded for locations where data were available within the MODFLOW domain at the 5km MODFLOW resolution, aggregated to monthlies (and Figure 3.2), and stored as a shapefile database. If precipitation and evapotranspiration grids showed “no data” in areas of the active MODFLOW model domain, interpolation of data was required to fill gaps in these areas. This was necessary for missing evapotranspiration data in a small area where the coastline meets the international border with India and for missing precipitation data in a larger area in a section of the Thar Desert region (see area in grey between within active model boundary in Figure 3.2). This region was filled using an Inverse-Distance-Weighting interpolation with the data values surrounding the margin of the missing region as inputs. These data clean up processes were accomplished using python scripts and ArcGIS10.3.

Examples of the results of ET₀ calculation using Hargreaves method and re-gridding to a 5km MODFLOW resolution are provided in Figure 3.1 for January (Rabi) and June (Kharif) of 2003. The general pattern is a north-south reversal of ET between Rabi and Kharif. During Rabi, ET ranges from a mimimum in north-eastern Punjab to a maximum in southern Sindh and the Tharparkar desert exceeding 100 mm/mo. During Kharif, lowest ET₀ is reaches along the coast and highest values are found in north-western Punjab and in the Sibi and Kachhi districts of Balochistan with nearly 300 mm/mo. Note that the overall magnitude of ET₀ in Rabi is approximately one third of that in Kharif. Examples of the results of re-gridding precipitation to a 5km MODFLOW resolution are shown in Figure 3.2 for January (Rabi) and August (Kharif) of 2003. During Rabi, rainfall is sparse throughout the basin and only about a tenth of the monsoon rainfall during Kharif. Maxima of rainfall are reaches in both seasons near the mountain front in northern Punjab with around 30 mm/mo in January and 300 mm/mo in August.
Figure 3.1 Reference crop ET₀ using the Hargreaves method for January and June for 2003 (no data in grey)

Figure 3.2 Precipitation for January and June for 2003 (no data in grey)

(Coordinate System for figures above: LCC1)
3.2 Water Levels

Water level data for this study are utilized for water level trend analyses (e.g., in areas of groundwater overdraft or near the international border), creating water level contour maps or initial heads for the MODFLOW model, as well to calibrate simulated heads to observations. Depth to water measurements have been provided initially by WAPDA and, at a later stage, also from PID. While the former data were properly cleaned up and archived in one common database, the latter data were stored, yet did not undergo a quality assessment/control and clean-up process. These data can be quite helpful in areas or time of low data density during the calibration phase.

Water levels have been provided by WAPDA for a period from 1975 to 2012 for the Upper Indus doabs in Punjab of Bahawalpur, Bari, Lower and Upper Chaj, Dera Ghazi Khan, Rahim Yar Khan, Rechna, and Upper and Lower Thal. Water levels were also provided for Khyber Pakhtunkhwa for the areas of Peshawar, Mardan, Potohar, and Dera Ismail Khan. Although, among the latter, only D.I. Khan reaches into the active model areas, Peshawar, Mardan, and Potohar were also included into the database. For the Lower Indus WAPDA provided water level data for a period from 1977 to 2012 for Sindh for the right and left Indus-bank areas of Guddu (extending into Balochistan), Sukkur, and Kotri and, in addition, for Upper Nara canal command extending from Guddu Left Bank. Note that data availability on bore locations in Guddu Right Bank in Balochistan was much better than in Guddu Right Bank in Sindh.

3.2.1 Water Level Data Preparation

For this project, we created one common database of all depth-to-water measurement of the IBIS of Pakistan with unified date formats and water-level elevation calculations. Firstly, all records belonging to one doab/area were combined into one single sheet using a scripted repetitive process. Secondly, all sheets of all doabs were joined into one database for all doabs, where each doab’s records are combined in a respective tab.

Firstly, a thorough examination of the provided data has been performed for potential errors that included checking for inconsistencies such as inaccurate or falsely georeferenced location coordinates, inaccurate dates, and well-ID mismatching.

Historic water levels and recently GPSed coordinates of monitoring wells were provided by WAPDA as separate datasets. To match the two datasets, names of wells where historic water level records exist were matched with wells where well locations are known. For that, a database with coordinates of well IDs had to be created with in one coordinate system. Most of the coordinates were listed in longitude and latitude in WGS1984. Where data that were in LCC1, they were converted into longitude and latitude. For the Modflow model, all water levels were converted later back into LCC1. The coordinates were mainly surveyed in the years 2011 and 2012. Where multiple datasets of coordinates existed for the same well IDs, their quality and validity had to be assessed and a choice had to be made. The purpose of this ‘coordinates database’ was to look up coordinates for all the historic depth to water measurements from 1975 to 2009 received from WAPDA, which all did not have coordinates. For this look-up process, the unique IDs of wells with historic measurements had to be replicated in a list of IDs associated with coordinates. Note that the record of wells IDs where coordinate locations are known from 2011 and 2012 also contained DTW measurements. These water levels were added to the historic records from 1975 to 2009.
In order to match the IDs in the list of wells with historic measurements, several variations of IDs had to be created to increase the chance of matching with IDs in the coordinate’s database. This was done by macros and entailed for a first cleaned-up version of IDs removing blanks first, but not hyphens, and then in a second version the removal all blanks and hyphens. The second version then was also used as a basis for making manual correction such as, but not limited to, manually changing roman into Arabic numbers, deleting redundant prefixes such as “No.”, etc. In addition, manual changes were made when detecting commonalities and differences by visually comparing batches of historic IDs with coordinates-IDs. Hundreds of outliers of longitude or latitude were corrected manually. Often, a typo in the second or third digit would shift the well far to the east/west or north/south. These errors become apparent when inspecting the surrounding wells in the datasets of these outliers. If outliers could not be corrected, they were not included into the analysis.

In conversations with Dr. M. Ahmad, CSIRO, the Rechna Doab data from 1980 to 2000 (“Rechna_80-2000”), previously cleaned up during his PhD dissertation, are considered of better quality then other Rechna Doab data. Similarly, Dr. M. Basharat had produced an improved, final compilation of coordinates in 2016 for all of Punjab (“Basharat_final”). Hence, coordinates of these two dataset have been given priority over others. However, when multiple sources produced several different locations for the same ID, rules needed to be established:

- If a historic well ID matches those an ID in “Rechna_80-2000”, then those coordinates are chosen first priority.
- For all other data, else evaluate first the variance of all other longitudes and latitudes:
  - When 2, 3 or 4 different locations from various sources vary beyond a set variance, a determination of the best/valid location cannot be determined and the ID and its related measurements will be discarded.
  - However if the variance is below a certain threshold, then generally data from "Basharat_final" were prioritized over "2011_2012", but not for Rahim Yar Khan, where the data in "Basharat_final" have some issues.
- Coordinates for Thal and D.G. Khan from the period 2001 to 2003 were originally not used because of a projection issue. However, especially for Thal, the data coverage is quite scarce and the following approach was used to make use of these data:
  - Regressions of Easting and Northing between 2001-2003 and 2011-2012 were calculated to correct coordinates.
  - If no initially correct coordinates data are available, only then were corrected 2001-2003 coordinates used for Thal and D.G. Khan.

For all final coordinates, elevations from 90 m digital elevation models (90m DEM) were extracted in ArcGIS. Water-level elevations were calculated from ‘depth-to-water’ measurements below surface elevations extracted from the 90m DEM. This was preferred over using recorded or computed elevations of measuring points (“Reduced Levels of Natural Surface Level”), as they were only available for some wells and often inaccurate in comparison with the DEM or from each other if there are two sources for the same well ID. For Sindh, GPSed elevations of measuring points were not available at all.
3.2.2 Recorded Water Levels and Depth to Water in the IBIS

The frequency of depth to water measurements increased steadily starting from around 1980. By 1990, around 2500 to 3000 measurements were taken per season (Figure 3.5). During Kharif 2008, more than 5000 measurements were taken, which is the most in recording history. Therefore, this season was chosen to display a most representative groundwater flow field in the Indus Basin (Figure 3.6).

![Figure 3.3 Depth to Groundwater (m) in the Indus Basin, KPK, and Peshawar](image1)

![Figure 3.4 Water level elevations (m ASL) in the Indus Basin, KPK, and Peshawar](image2)

(coordinate system: LCC1; graticule: WGS1984 with longitude and latitude)
3.3 Geohydrology

Prior to this study, no geohydrologic framework existed for the Indus Basin of Pakistan. As part of this project, a geohydrologic framework was created or all of the IBIS of Pakistan as well as eastern Thar and Cholistan deserts based on digitized and georeferenced borelog lithology (Figure 3.7). This framework allows for the delineation of the base of the alluvial aquifer and the association of major lithologic component with typical ranges of hydraulic parameters (see section 4.4.2).

In addition, a database on observed hydraulic properties of the alluvial aquifer of the Indus Basin of Pakistan was compiled and georeferenced. These properties will be used to constrain the model results during the model calibration phase.

3.3.1 Geohydrologic Framework of Alluvial Indus Basin Aquifer

A database of 1497 bores with borelogs was compiled from sources provided by WAPDA from various previous field studies (WAPDA 1965, 1980, 1981; Hussain and Khan 1974, 1975, 1978; Sheikh et al. 1968; Mueller et al. 1991). These logs were scanned, georeferenced (e.g., for Rechna Doab,
Figure 3.8) and compiled in a lithology database. The digitised logs along with locations and reference elevations were included in the database. The aim was to include information from as many bores as possible in order to have adequate spatial coverage of the Indus Basin as shown in Figure 3.7. Although the spatial coverage is a reasonably good coverage of the Indus Basin, there is an extensive area along the eastern margin of the basin which has a dearth of bores. Almost all the bores are in the canal command areas in Punjab and Sindh, with very few bores outside the canal command areas other than a handful of bores in the Cholistan desert and in Tharparkar district from a German technical cooperation study (Mueller et al. 1991). The borelogs for these 1479 bores have been documented and plotted in a separate report using Strater, a borehole and well logging software (Punthakey et al. 2017).

![Map of Indus Basin showing borehole locations and lithology](image)

**Figure 3.7** Locations of digitized bores with bore log data used for estimating aquifer properties (Coordinate system: LCC1; graticule: LCC1 with Easting and Northing and WGS1984 with longitude and latitude)
Many of the bores are drilled to different depths and do not necessarily penetrate the full thickness of the alluvium. Thus, future efforts should be directed to improve the mapping of the basement structure. Not only is this important from a flow perspective but it also has a significant influence on salinity transport as salinity concentrations in the Indus are known to increase with depth. This is particularly important for Punjab as large volumes of groundwater are extracted from the top 60 m and to a lesser extent from 60 to 90 m.

The final borelog lithology database contains the following fields:

- Reference area
- Hole or well ID
- CSIRO bore ID - ID assigned for this project (ABB_CCDD_ORIGINAL-ID: A = Province, B = District, C = CSIRO_Area, D = Canal Command Area)
- Longitude
- Latitude
- LCC1_E - Easting in LCC1 coordinate system (chosen for the MODFLOW model)
- LCC1_N - Northing in LCC1 coordinate system (chosen for the MODFLOW model)
- Depth of borelog (m)
- Thickness of layer (m)
- Elevation of bottom of bottom layer (m ASL)
- Reference elevation from 90m-DEM (m ASL)
- General description as found in borelog reports
- Major lithologic component
• Minor lithologic component
• Grainsize
• Colour
• Consistency
• Sorting
• Report year
• Description of area or site
• Explanation of well ID
• Agency
• Source

This database was also made available to the Pakistani project partners as a HYDSTRA database. HYDSTRA is a hydrological data management software tool of Kisters Pty Ltd.

### 3.3.2 Hydraulic Properties of Alluvial Indus Basin Aquifer

Hydraulic properties, such as horizontal and vertical conductivity as well as specific yield, had been derived from pumping test and described for Punjab by WAPDA (1965b) and for Sindh by Bennet et al. (1967). We digitized the tabulated data and were able to use georeferenced locations of test wells, which also provided borelogs for the lithology database. The well IDs were matched with doabs/areas and well IDs were looked-up in coordinates of georeferenced lithology bores. One issue with the attribution of hydraulic properties from these data is that the on the one hand depth of tube well and screen length known, one the other hand, the top and bottom of screens are not known. Hence the hydraulic properties cannot be matched with particular lithologic formations. The intended use of these data for this project is to set bounds for varying parameters in sensitivity analysis and calibration.

A summary of hydraulic properties for Punjab and Sindh using only georeferenced bores is given in Table 3.1 and its spatial distribution is shown in Figure 3.9. Naturally, the horizontal hydraulic conductivity, $K_h$, is highest in areas of coarser, clastic sediments near the mountainfront in northern Punjab with a maximum of around 250 m/d and lowest near deltaic sediments near the coast in Sindh with a minimum of around 10 m/d. A similar pattern can be seen for the vertical hydraulic conductivity, $K_v$, although locally, in Sindh, one can observe an increase of $K_v$ along the flood plains of the quaternary flood of the Lower Indus River (Figure 3.9). The anisotropy ratio between $K_h$ and $K_v$ is on average 63:1 in Punjab and 44:1 in Sindh. The specific yield ranges between 0.01 and 0.43 with no clear distinction between the two provinces. However, local areas of higher specify yield are discernible (e.g., “Bar” Uplands of lower Rechna Doab, Chaj Doab and river floodplains.

| Table 3.1 Aquifer hydraulic properties in Punjab and Sindh provinces (WAPDA 1965b & Bennet et al. 1967) |
|------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| No.                                                   | $S_y$                                               | $K_h$ (m/d)                                          |
|                                                      |                                                     | $K_v$ (m/d)                                          |
| Min                                                   | 0.01                                                | 15.80                                               |
|                                                      |                                                     | 0.26                                                 |
| Max                                                   | 0.42                                                | 255.45                                              |
|                                                      |                                                     | 3.16                                                 |
| Geometric Mean                                       | 0.11                                                | 73.00                                               |
|                                                      |                                                     | 1.09                                                 |
|                                                      |                                                     | 0.08                                                 |
|                                                      |                                                     | 34.96                                               |
|                                                      |                                                     | 0.22                                                 |

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3.4 Rivers, Canals, and Drains

The alluvial parts of the Indus Basin form a deep unconsolidated unconfined aquifer. Surface and groundwater are a highly connected system due to the sandy and silty nature of the aquifer. Prior to large scale groundwater exploration starting from the 1980s, isolated portions of the aquifer were partially confined by clay and silt lenses, and recharge occurred from the river to the groundwater in some seasons and in other seasons groundwater discharged to the river. Since the 1980s, pumping of groundwater for supplementary irrigation has changed the aquifer into a typical unconfined aquifer in many areas of Punjab where groundwater is being intensely utilised for irrigation. As a result of the reduced groundwater levels, the leakage from rivers and canals to groundwater has become the predominant form of surface water and groundwater interaction. The local groundwater dynamic is marked by seasonal variations primarily driven by the monsoon period during Kharif, and irrigation recharge.

3.4.1 Rivers

For this study, we have developed a simplified river system guided by the criterion that only major rivers should be used that coincide with gauges used by SOURCE river system model (CSIRO 2016c). This covers the major rivers, but did require the inclusion of some upstream major tributaries. Rivers were generated from a drainage network (streams) and watersheds (catchments) using pour points (gauge locations) in ArcGIS. For this, we used a 90 m DEM, calculated flow and flow accumulation, generated drainage network and a flow direction. In some areas some flow paths were erroneous, picking up directions were no surface water feature exists (e.g., in between sand dunes or paleo channels). This was corrected manually. The remaining network was reduced to the major rivers and some tributaries that coincided with SOURCE gauges: Beas (with Chakki tributary), Chenab (with Jammu_Tawi and Munawar_Tawi tributaries), Indus (with Kurram and Gomal tributaries), Jhelum, Ravi (with Ujh tributary), and Sutlej.
3.4.2 Canals

The canal conveyance network was obtained from the Indus River System Authority (IRSA) and clipped to the active model boundary. We only retained categories Branch Canal, Feeder, Main Canal, and Link Canal under attribute “TYPE”. “Minor” and “distributary” under attribute “W_TYPE” were deleted and small diameter “Branches” that came off of deleted distributary canals were deleted as well (often only 4-7 m in diameter). Canals that were still proposed or only recently completed after the MODFLOW model period were also eliminated (e.g., Rainy Canal or sections of Greater Thal Canal). Finally, as per suggestion of Dr. Basharat (WAPDA), we only included branches with more than 500 cfs.

Figure 3.10 Stream and Canal Network in the IBIS of Pakistan (not including minor and distributary canals) (Canals modified from IRSA) (Coordinate system: LCC1; graticule: WGS1984 with longitude and latitude)
3.4.3 Drains

In this study drains are generally not simulated as most of the IBIS is dominated by basin level irrigation with no or minimal excess irrigation surface runoff. However, drains can be important sinks for subsurface returnflows, especially in areas of minimal hydraulic gradient, such as in southern Sindh. Two drains have significant relevance for the prevention of water logging in Sindh. These are the Left Bank and Right Bank Outfall drains (LBOD and RBOD). Among the two, only the LBOD (Figure 3.11 and Figure 3.12) is relevant for the model period that ends in 2012. The RBOD was completed and operational after that period. The network of the LBOD main drain and the associated tributary branch drains was obtained from SID as kmz-file (Figure 3.12).

Figure 3.11 Map of LBOD Stage 1 Project (Kori et al. 2013).

Figure 3.12 Main and Branch Drains Left Bank of Indus River in southern Sindh (coordinate system: LCC1; graticule: WGS1984 with longitude and latitude)
4 Numerical Model Development

A regional groundwater model for the Indus Basin of Pakistan was developed using MODFLOW in conjunction with the ongoing development of an integrated river system model for the Indus Basin (CSIRO 2016c). The interaction between both models will assist Pakistan in developing an integrated water resource model of the Indus basin. The Indus Basin groundwater model is a basin wide model of the alluvial parts of the basin in Punjab and Sindh (Figure 4.1). The model will be used to better understand groundwater dynamics, surface groundwater interaction, the impact of development on fresh and saline groundwater areas, and to better represent the distribution of crop water use between surface and groundwater resources. This is particularly timely in the Pakistan context as extractions from groundwater for irrigation particularly in Punjab are equal to or in excess of surface water use. To give the reader a perspective it is important to quantify groundwater extraction, which at current estimates exceeds 55 billion m³ annually.

The spatial extent of the groundwater model covers the Indus basin of Pakistan, but is restricted to the alluvial aquifer of the basin and does not extend into the highland areas as shown in Figure 4.2. The groundwater model was designed to cater for surface water and groundwater interaction and to incorporate the major stresses on the system so as to provide a planning tool for managing groundwater in the Indus Basin. The model will provide a quantifiable mechanism to assess the overall groundwater budgets on a regional and sub regional scale and in future projects to link finer resolution models (e.g. doab or command areas) with the coarser scale regional groundwater model. Moreover, future work also proposes to extend the present work to develop a basin wide salinity transport model for the Indus Basin.

This work has been undertaken in close collaboration with stakeholders in Pakistan in particular active collaboration with IWASRI, PID and SID in data collation and analysis and in developing the framework for the groundwater model. Moreover, an important additional outcome of this collaboration is the planned capacity building in groundwater modelling in Pakistan.

In this chapter we cover the design and structure of the numerical model. The structure and extent of the model grid, the conceptual model for the Indus Basin and the approach used for estimating aquifer parameters as well as key components of the model development process are also covered.

4.1 Model extent

The groundwater model extends horizontally across the entire irrigated Indus basin of Pakistan and beyond encompassing the entire quaternary alluvial basin (Figure 4.1) as well as surrounding areas that may influence boundary flows, such as metropolitan water users, the Indus delta, and mountain-front recharge from the Himalayas. It is limited vertically to the alluvial aquifer of the Indus basin as the primary focus is surface-groundwater interaction and, as such, does not extend into the tertiary highland areas shown in Figure 4.1, Figure 4.2, and Figure 4.3.
Figure 4.1 Active Model Boundary of Quaternary Alluvial Aquifer (outline in black) (modified from Geol. Survey of Pakistan & U.S. Geol. Survey 1964)

(Coordinate system: LCC1; graticule: WGS1984 with longitude and latitude)
Figure 4.2 Image of Indus basin showing model boundary (outline in red), major cities > population of 200,000, and district codes (see left for districts) (source of image: World Imagery, ArcGIS)

(Coordinate systems: LCC1; graticules: LCC1 outside and WGS1984 with longitude and latitude inside)

The model window extends 930 km E W and 1150 km N S from Easting 2600,000 to 3520,000, to Northing 130,000 to 1010,000 in the projected Lambert Conformal Conic 1 (LCC1) coordinate system of Pakistan (Figure 5.2). LCC1 is generally the projection of choice for Punjab while LCC2 is normally chosen for Sindh. However, LCC1 was chosen for the Indus basin wide model in recognition that irrigation areas in Punjab are 62% of the total irrigated area and, hence, by far larger than Sindh or the other areas. This is also in accordance with the project’s Rainfall Runoff Model (CSIRO 2016b), which is also in LCC1. The areas of Punjab and Sindh have respective discrepancies of 0.14% and 0.93% from equal area projections, such as Albers Equal Area. The Indus Basin regional groundwater model covers an area of approximately 121,625 km2 (12.1625 Mha) shown in Figure 4.2.
4.2 Conceptualization of Boundary Conditions

Previous doab-scale models assumed vertical-flux domination and no flows across boundaries formed by doab-bounding rivers (Figure 2.3) with groundwater divides assuming groundwater streamlines that are parallel to, diverging from, or converging to the divide. In contrast, the function of an Indus-Basin-wide model is to simulate horizontal groundwater flow across doab-bounding rivers induced by excessive groundwater extraction for irrigation and urban water in neighboring doabs/areas (e.g., irrigated areas across the border to India (if needed), metropolitan water users such as the city of Lahore, the Indus delta, and mountain-front recharge from the Himalayas) and to allow future scenario perturbations of the model to interact with model boundaries. This transition from initial vertical-flux domination to ever increasing horizontal boundary flows is addressed by the regional model, or, in the case of potential future doab-level child models, by dynamic parent-child boundary conditions.

By extending the external model boundaries to hard-rock formations (no-flow west and north of basin), to the coast (general head), and to the east near the Indian border (general or constant head), internal river boundaries will be used no longer as external boundaries of doabs, but – along with the canal network – as internal sources or sinks of stream seepage into the aquifer or groundwater discharge into streams (Figure 3.10) using the River (RIV) or Streamflow Routing (SFR) Packages of MODFLOW (Harbaugh 2005). The calculated stream-aquifer interaction will also allow for a future linkage to the SOURCE river system model (CSIRO 2016c). This opens the door for future scenarios that help formulate constraints on streamflow, such as Global Climate Models and related changes in river streamflow. Other internal boundary conditions, such as diffuse-rainfall and irrigation recharge into groundwater, evapotranspiration from groundwater are also considered using the Recharge (RCH) and Evapotranspiration (EVT) packages of MODFLOW (Harbaugh 2005), respectively. Mountain-front recharge (Kirthar Range or along the northern boundary) and supplemental groundwater pumping are defined using injection and extraction wells of the Well Package (WEL) of MODFLOW (Harbaugh 2005).

Groundwater underflow occurs as inflows and outflows from the landward eastern and offshore southern boundaries. These are lateral and vertical hydrologic boundaries of the groundwater flow system that are simulated as a head-dependent flow using general-head boundaries. These regions are simulated with the General Head Boundary Package (GHB) of MODFLOW (Harbaugh 2005). General-head boundaries are specified in layer 1 of the landward eastern boundary and in outcrop of the alluvial layers offshore with time-varying boundary heads and cell specific conductance. The time-varying boundary heads are specified for landward subregions of the general-head boundaries on the basis of water levels from selected wells adjacent to the model area.

External boundary conditions that define the outline of or flow across the active model domain are discussed in sections 4.2.2 to 4.2.4. Internal boundary conditions specified or simulated by MODFLOW’s stress packages are described separately in sections 4.7 to 4.10.
4.2.1 Conceptual Model across Upper and Lower Indus Basin

A generalised conceptual model of the upper Indus Basin is shown in Figure 4.5. The conceptual model shows the major inflows are recharge from rainfall and irrigation, seepage from rivers and canal leakage. There are also boundary flows particularly along the northern alluvial boundary and inflows from the basin margin where there are significant highland areas at the edge of the alluvium. Additionally, the eastern boundary along India will need to be defined with general head boundaries to account for groundwater inflow/outflows across this boundary. The major outflows are river outflows, evapotranspiration and groundwater pumping for irrigation and for city water supplies. The leakage between layers is shown by the double arrow heads. The layering shown in Figure 4.5 shows the aquifers modelled and basement structure which represents a no flow boundary.
A generalised conceptual model of the lower Indus is represented in Figure 4.6. The eastern boundary of the alluvium is contiguous and stretches in India. This is not a no flow boundary as it is not constrained by bedrock or basin margin. In this case general head boundaries will be specified to account for inflows/outflows along the boundary.

**Figure 4.6 Conceptual hydrogeological cross section of the lower Indus Basin**

### 4.2.2 Western and Northern Boundary – No Flow Boundary

Several command areas in Punjab extend west of the Indus River and are not bounded by rivers (in the sense of “river no-flow boundaries” as described above), but by a no-flow boundary of mostly tertiary outcrops. The western boundary includes all of the quaternary fluvial, floodplain, deltaic, and piedmont deposits, but not any non-alluvial pre-quaternary (i.e., tertiary and older) outcrops (Figure 4.1). The inclusion of tertiary sediments is not favourable, since the conductivity of such formations is low (i.e., shale dominated), except in the Kirthar Range, where such tertiary formations are composed of sandstone or limestone. In the latter case, mountain-front recharge and, if necessary surface inflows into the stream network, will define the local boundary flows straddling the western boundary. A few non-quaternary no-flow areas are isolated within the active model boundary (Figure 4.1 and Figure 4.8) (Tertiary outcrops northeast of Gujrat, southwest of Sheikh Sultan, south of Sukkur, east of Dera Ghazi Khan, south of Hyderabad, south of Makli; Precambrian outcrops of Kirana Hills and of the Chiniot divide called Sangla Hill and Shah Kot).

### 4.2.3 Southern Boundary – off-shore General Head Boundary

The city of Karachi is located on the south-western edge of the Indus River delta and will be excluded from the model domain. The southern boundary includes the delta all the way to the east across the international border to India, where it reaches the Mesozoic-to-Proterozoic outcrops in Gujarat, India, which forms a short stretch of no-flow boundary. Going further east along the southern boundary, the “Rann of Kutch” area (a large barren area of salt marshes and mud flats) will be excluded from the model, but its northern edge will serve as a head boundary to the Thar Desert. This southern edge of the Thar Desert also follows a lineament, called Luni-Sukri lineament (Bakliwal and Ramasamy 1987), and a fault called Nagar Parkar Fault (Biswas 2005).

Offshore areas will be simulated as a General Head Boundary using an approach similar to Hanson et al. (2014a and 2014b). The changes in boundary heads for the offshore boundaries represent the median monthly changes in sea level as an equivalent fresh-water head for each offshore boundary cell for the entire simulation period. The hydraulic conductance of the offshore boundary cells are
based hydraulic conductivity of the aquifer sediments (described in the section 4.5). Hydraulic conductances will be adjusted during model calibration. The equivalent freshwater head can be evaluated if the bathymetry (elevation of the seabed), sea level (spatially lumped, but time varying if inter-annual changes or long-term sea-level rise is significant), and seawater salinity are known (Guo and Langevein 2002, page 7 and 53). Note that we will ignore variable density flow inland in the coarse resolution model.

4.2.4 Eastern Boundary – General Head and No-Flow boundaries

Any model boundary to the east of the Indus River Valley is somewhat arbitrary because quaternary aquifers within the Indus Basin potentially extend further east underlying the Aeolian deposits of the Thar Desert. The minimum area to be included into the active model domain is delineated by the easternmost extent of quaternary alluvial deposits or irrigation command areas (e.g., Bahawalpur area), whichever extends further east. These areas are safely included when drawing the eastern model boundary along the international border with India. Naturally, this area will not pose any problems for the parameterization as there is minimal recharge and negligible agricultural irrigation demand or supply. In this area, the boundary following the international border does not describe any natural boundary and is formulated as General Head boundary conditions based on known or assumed time variable boundary heads.

Southeast of the Sutlej River, irrigated agriculture reaches to a line from Ahmedpur East to Fort Abbas demarked by a paleo-stream channel, which continues on the other side of the international border. This corridor follows the original Ur Jumna (or ancient Hakra-Nara) river, which around 2000 BC, according to Wilhelmy (1969), was still flowing from the Himalayan foothills in southwest-direction towards Pakistan passing through the Cholistan Desert (Bender and Raza 1995). From Fort Abbas eastward, the model boundary leaves the international border and follows this paleo channel as no-flow boundary in the sense of a groundwater divide assuming groundwater streamlines are parallel to, diverging from, or converging to it.

On the Indian side of the border a broad arbitrary fringe east of the Sutlej River is included that runs approximately south-north from the Hakra paleo channel to the confluence of Sutlej and Beas River. Similar to the international border further south, here the boundary also does not describe any natural boundary and is formulated as General Head boundary conditions based on known or assumed time variable boundary heads.

From the Beas-Sutlej confluence going north, the model boundary follows the Beas River. It is treated as a no-flow boundary in the sense of a groundwater divide assuming groundwater streamlines are parallel to it, diverging from it, or converging to it.

4.3 Model Structure and Discretization

MODFLOW is a three dimensional (3D) finite difference groundwater model (Harbaugh 2005). It is constructed using a series of packages which consist of fixed properties of a model such as the grid structure, layers and aquifer parameters, and stress packages such as Well, River, Recharge and Evapotranspiration, and boundary and solver packages as shown in the schematic in Figure 4.7. The stress packages allow temporal data to be used in constructing the package. Across from each package a box outlines the data that would be required to construct the package. The Indus Basin groundwater model was constructed using the packages shown in Figure 4.7.
Figure 4.7 Schematic of the MODFLOW model structure and packages used for constructing the Indus Basin groundwater model

The initial setup of the model requires specification of the size of the model, the type of simulation (transient or steady state), the hydrologic options, the solution scheme to be used, and number of rows, columns, layers and stress periods. The simulation period in MODFLOW-2005 (Harbaugh 2005) is divided into nested loops comprising a series of stress periods and time steps. Within a stress period (time interval) all external stresses are constant. A stress period is further subdivided into one or more time steps.

The spatial and temporal discretization is defined using the Discretization Package (DIS). The model domain consists of a finite difference grid with 228 rows and 184 columns and spatial resolution of 5000 x 5000 m (Figure 4.4). A total of 264 monthly stress periods was specified. The model was run for 22 years from October 1990 (beginning of Rabi 1990) to September 2012 (end of Kharif 2012).

The model has three numerical layers, where thickness for the first two layers is 36m and 54m, respectively, and bottom of the third layer extends to the top of clay or in some cases to bedrock where bores have been drilled to a sufficient depth. The rationale behind the layering is explained in section 4.4. The upper layer was specified in the LPF package as unconfined and the remaining layers as unconfined/confined layers.

Active and inactive cells for each model layer (Figure 4.8), and the initial head distribution in each layer (Figure 4.25) are specified using the Basic Package (BAS).
4.4 Aquifer Geometry – Layer Discretization

The purpose of a numerical groundwater model is to provide a means whereby the various elements of the groundwater flow system can be described in a quantitative manner so that the impact of changes to, or stresses on, parts of the system can be predicted. The groundwater flow system has two directional components, namely horizontal and vertical. To accommodate the horizontal component of flow, the groundwater system is considered to be formed of a series of layers, each of
which is given a mathematical representation of the aquifer characteristics for that layer. A grid is overlain on the layers, to provide a means of assigning differing values for these characteristics to different parts of each layer, and to facilitate the simulation of the vertical component of flow.

Each layer then consists of a series of grid nodes in which the water storage and transmission characteristics are given numerical values as described in the section on aquifer parameters (section 5.5). The groundwater system is then simulated by mathematical equations which link the layers and the grid cells, using the values assigned to each grid cell.

Two main surfaces are required to be constructed. The ground surface and the basement of the basin. The top layer is defined by the surface topography derived from a 90 meter Digital Elevation Model (Figure 4.9). The model framework consists of three active layers of which the upper layer is unconfined and approximately 36 m in thickness to ensure that the rivers and canals are included as part of layer 1. The second layer is 54 m in thickness. The rationale for using these layer thicknesses is that groundwater pumping takes place in the top two layers within 90 m of the surface. Most of the pumping is from the first 60 m and few bores penetrate to greater depths. In the Indus Basin water quality declines with depth. Thus the third and deepest layer with relatively higher salinity needs to be differentiated from the pumping layers in layers 1 and 2. The basement of the basin represents the bottom of layer 3 and has been defined as the top the bottom layer encountered in the borehole if low permeability.

### 4.4.1 Basement of Alluvial Aquifer

For this model, the basement or floor of the basin is defined by the top of the deepest clay layer in the borehole or other low permeable bedrock if the drilled bore was deep enough to have encountered the bedrock surface. The bottom of layer 3 represents the topography of this basement which is shown in Figure 4.11. It is assumed to be a no flow boundary i.e. no flow occurs across this surface (Figure 4.10).

![Figure 4.9 Surface topography using SRTM data for entire area (left) and for model boundary (right) (Coordinate system: LCC1)](image)
The bottom surface of layer 3 assumed to represent the bedrock has been created using over 1300 borelogs and represents our current knowledge of the basement structure. However, many of the bores are drilled to different depths and do not necessarily penetrate the full thickness of the alluvium. Therefore, interpretations of the basement surface needs to account for either a less permeable horizon such as a clay sequence if one is present at deepest depth, or where in some cases the bore is deep enough to have reached a basement hard rock formation typified by a major lithology component (e.g., bedrock, boulders, claystone, conglomerate, granite, diorite, hard rock, limestone, sandstone, siltstone, shale, slate, quartzite, rock cuttings). The file containing the estimated depth to basement is filtered by eliminating bores that have been drilled to shallow depths. Using these criteria about 1300 out of 1500 bores were used for defining the bottom surface of layer 3 which is shown in Figure 4.11.

Figure 4.10 Interpretation of Basement from Borelogs based on three examples

Deep bores meet Clay or other formations typical for base of alluvial aquifer

Shallow bore meets sand sequence: not included!
The basement of the alluvial deposits in the Rechna Doab near Chiniot represents the remnants of a buried ridge of indurated metamorphic and igneous rocks. The isolated bedrock hills near the villages of Kirana, in southern Chaj Doab, and Chiniot, Sangla, and Shah Kot, in central Rechna Doab are known as the Kirana Hills. These consolidated rocks are exposed near Chiniot, Sangla and Shahkot along the mid-western boundary of the Doab and according to Khan (1978) are of Pre Cambrian age. Greenman et al. (1967) indicated that the north westerly alignment of the Kirana Hills and associated outcrops form part of the Shahpur Delhi (or Sargodha) bedrock ridge that is largely buried by alluvium. These crystalline rocks trend in a south-easterly direction extending through the central part of the Rechna Doab from near Sargodha and extending beneath Kirana, Chiniot, Sangla, Shahkot and Mangtanwala as shown by the basement structure in Figure 4.12. The alluvial fill was deposited in subsiding troughs by the ancestral and present tributaries of the Indus River system (Khan 1978) which effectively divides the unconfined aquifer into two sub basins comprising the
upper and lower reaches of the doab. Thus it is important that the basement surface shown in Figure 4.11 is able to show the basement highs near Chiniot and the effective partitioning of the upper and lower reaches of Rechna Doab.

![Figure 4.12 Basement structure for Rechna Doab (m AMSL) (after Punthakey et al. 2015)](image)

The Shahpur Delhi ridge trends to the northwest and scattered outcrops are located along the strike between Shah Kot and Charnali. The bedrock surface dips sharply to the northeast of the ridge in the upper reaches of the Rechna Doab as indicated by a test hole near Sheikhupura, which gave a depth of about 460 m without reaching bedrock. In the lower reaches of the Rechna Doab trending in a south westerly direction the surface of the ridge slopes more gradually, and test holes from 275 to 460 meters deep near the lower end of the Rechna Doab bottomed in alluvium (Greenman et al. 1967; Aslam 1997).

The average thickness of the alluvium over the crest of the ridge is on the order of 120 to 150 m. Close to the outcrops the bedrock is present at shallower depths, however, between the outcrops the thickness of the alluvium can increase sharply indicating the presence of deep gorges or channels between the outcrops. Improved mapping of the basement structure would improve our understanding of groundwater flow conditions.

It is probable that the structure of the basement highs may locally impede the movement of groundwater near bedrock outcrops or where the crest of the ridge is shallow and overlain by relatively impermeable alluvium. Additionally, the presence of bedrock outcrops and clay bodies in proximity to the rivers are factors that locally control or restrict the circulation of fresh groundwater. However, on a regional scale the buried ridge is not considered a barrier to the movement of ground water.

### 4.4.2 Cross sections through the model domain

The implementation of the layering concept (see section 4.2.1) in the numerical IBIS groundwater model is shown using cross sections generated in Groundwater Vistas (Figure 4.13 to Figure 4.18). The sections cross through the model domain from west to east for northern Punjab, southern Punjab and Sindh respectively. The location of the cross section is shown in Figure 4.8. The vertical exaggeration is 200:1. The layer configuration has been modified where the layers pinch out such as...
near the edge of the basin, or where basement highs are known such as at Chiniot. We have also eliminated bores drilled to very shallow depths so that the aquifer thickness is not reduced by bores that have not penetrated the full depth of the aquifer.

Figure 4.13 shows the cross section through northern Punjab through the districts of Bhakkar, Chiniot and Shiekhupura. The basement high near Chiniot needs to be more pronounced as discussed in detail in section 5.4. This is an area where the basement structure would need to be revisited to ensure that the Shahpur Delhi bedrock ridge is properly represented, particularly for the more detailed child models.

The cross section through southern Punjab which is shown in Figure 4.14 shows a physical gradient from east to west towards the main Indus River. The section crosses through the districts of Muzaffargarh, Multan, Vehari and Bhawalnagar. It is important to note that the alluvium may be much deeper in parts particularly near the major rivers as the current representation has been constructed using available bore holes. Other than a few very deep bores most of the bores do not penetrate the full extent of the alluvium.

The section in Figure 4.15 crosses through the districts of Kachhi, Sibi, Dera Bugti, Rajanpur, Rahim Yar Khan, and Bhawalpur. It is of interest to note that the deepest part of the alluvium is in Bhawalpur district, which may be due to the presence of deeper bores in this area. This area is
further away from the main Indus and it is possible that bores had to be drilled deeper in this area to reach fresh groundwater. The bores closer to the Indus river would need to be drilled to much shallower depths to encounter fresh groundwater as it is continuously recharged from the Indus.

Figure 4.15 Cross section through model domain from west to east (southern Punjab row 100)

The section in Figure 4.16 crosses through the districts Qambar Shahdadkot, Larkana, Sukkur and Gothki. There is a considerable narrowing of the alluvium in this area. The actual depth of the alluvium is not known but its thickness is considerably less than in the upper reaches of the Indus. Although the model boundary extends up to the border with India, there is considerable alluvium that stretches beyond the border. We do not have access to bore information beyond border into India to verify the extent and depth of the alluvium.

Figure 4.16 Cross sections through model domain from west to east (Sindh row 130).

The cross section though lower Sindh is shown in Figure 4.17. This section crosses through the districts of Hyderabad, Tando Allah Yar, Mirpurkhas, Umerkot and Tharparkar near the eastern model boundary. The alluvium in the eastern district of Tharparkar is considerably deeper, which has been verified by bores drilled in this district under a German technical cooperation program, Groundwater Investigations in Desert Areas of Pakistan (Bundesantalt für Geowissenschaften und Rohstoffe, 1991). Additionally the surface topography in the eastern area is about 100 m higher compared to the surface elevation in Mirpurkhas and Hyderabad.
The cross section though lower Sindh along row 207 which coincides with the mouth of the Indus and the district of Thatta is shown in Figure 4.18.

4.5 Aquifer Parameters – Layer Properties

MODFLOW computes the conductance components of the finite difference equation which determines flow between adjacent cells. It also computes the terms that determine the rate of movement of water to and from storage. The aquifer geometry, leakage between layers, and the properties of the aquifer system need to be specified. The aquifer parameters that need to be specified are hydraulic conductivity ($K_h$) and specific yield ($S_y$) for layer 1, and $K_h$ and specific storage ($S_s$) for layers 2 and 3. This section describes how these properties were estimated.

Once the structure and discretization model layers was finalised, the next step was to estimate a composite value of aquifer properties for each model layer. 1497 bore logs (see 3.3.1) were used to associate various major and minor lithologic components with typical values of hydraulic parameters, that is, hydraulic conductivity, specific yield, specific storage and porosity. The approach provides the initial estimates of aquifer properties for the model domain which will subsequently be refined during calibration. Observations of aquifer properties were provided by WAPDA for 139 test wells for Punjab and 80 test wells for Sindh and compiled and georeferenced in a database (section 3.3.2). These observations will be used as bounds for refining the initial estimates in sensitivity analysis and calibration.

The estimated hydraulic conductivities ($k_h$) for layers 1 to 3 are shown in Figure 4.19 to Figure 4.21. The $k_h$ values for the first 42 m (layer 1) have a range from 1.4 to 117 m/d shown in Figure 4.19. Taking a median value of 57 m/d the average transmissivity of the layer is 2394 m²/d where the layer thickness is 42 m. The distribution of higher $k_h$ values is greater in Bari Doab and parts of Rechna Doab as shown by the dark orange regions in Figure 4.19. There are also areas of low $k_h$ along the
eastern margin of the basin in Bahawalnagar and Bahawalpur districts, however, this could be due to a dearth of boreholes in these areas. Moreover, the $k_h$ are also lower in Badin district in the eastern areas of Tharparkar.

The $k_h$ values for the next 54 m (layer 2) have a range from 0.03 to 131 m/d shown in Figure 4.20. Taking a median value of 62 m/d the average transmissivity of the layer is 3348 m²/d. The distribution of higher $k_h$ values is greater in Bari Doab and parts of Rechna Doab as shown by the dark orange regions in Figure 4.20. There is also a zone of high $k_h$ stretching from east of Kasur near the border with India in a northwest arc towards Lahore. As discussed earlier in section 1.2.2 and shown in Figure 1.4 and Figure 1.5 the high transmissive zone extends into India where there is considerable extraction of groundwater for irrigation and other uses has the potential to impact on groundwater resources in Pakistan. There are also areas of low $k_h$ along the eastern margin of the basin in Bahawalnagar and Bahawalpur districts; however, this could be due to a lack of boreholes in these areas. Lower $k_h$ are also found in the north east and northwest mostly in the Chaj doab. Lower $k_h$ values are also present in the districts of Badin, Thatta, and in the eastern areas of Tharparkar.

The $k_h$ values for layer 3 (96 m to base) have a range from 0.00021 to 150 m/d shown in Figure 4.21. The median value for the deepest layer is 64 m/d and the average transmissivity of the layer is variable due to the variable thickness of layer 3. In some areas the transmissivity can be very high in excess of 20,000 m²/d. The distribution of higher $k_h$ values is much greater in Bari Doab as shown by the dark orange regions in Figure 4.21 and much lower in Rechna Doab. There are zones of high $k_h$ at Okara, Sahiwal, Pakpattan, Vehari, Multan and a small zone northeast of Toba Tek Singh between Burala and Lower Gugera branch canals. There are also areas of low $k_h$ along the eastern margin of the basin in Bhawalnagar and Bahawalpur districts, and low $k_h$ in the districts of Tank and South Wazistan. Lower $k_h$ values are also present in the districts of Badin, Thatta, and in the eastern areas of Tharparkar.

The spatial distribution of specific yield ($S_y$) for layer 1 shown in Figure 4.22 is reasonably high with a median value of 0.132. The $S_y$ for the doabs are reasonably high and extend along the left bank of the Indus. Much of the lower $S_y$ zones are in Sindh away from the Indus River in districts of Badin and Umerkot and north eastern parts of Tharparkar. Eastern parts of Bahawalnagar and Bahawalpur districts also have lower $S_y$ zones again this could be due to a lack of drilled boreholes in these areas.

The spatial distributions for specific storage ($S_s$) for layers 2 and 3 are shown in Figure 4.23 and Figure 4.24. The mean $S_s$ for layer 2 is $7.3 \times 10^{-5}$ (1/m) which gives an average storage coefficient of 0.0039. The range of $S_s$ for layer two is from $6.0 \times 10^{-7}$ to $7.5 \times 10^{-4}$. The mean $S_s$ for layer 3 is $8.6 \times 10^{-5}$ (1/m) and the range is from $3.7 \times 10^{-5}$ to $8.0 \times 10^{-5}$ (1/m).
Figure 4.19 Hydraulic conductivity ($k_h$) for layer 1

Figure 4.20 Hydraulic conductivity ($k_h$) for layer 2

Figure 4.21 Hydraulic conductivity ($k_h$) for layer 3

Figure 4.22 Specific yield ($S_y$) for layer 1
Figure 4.23 Specific storage \( (S_s) \) for layer 2

Figure 4.24 Specific storage \( (S_s) \) for layer 3

(coordinate system for Figure 4.19 to Figure 4.24: LCC1)

### 4.6 Initial heads

The selection of the model period from the beginning of Rabi 1990 to the end of Kharif 2012 was determined by the sufficient coverage of water levels of Punjab and Sindh observations. The histograms of measurements in Figure 3.5 indicates that after a linear increase of measurements from 1980 to 1990, the number of data stays relatively steady. For this reason, the beginning of the model period was chosen to be October 1990. The initial heads for October 1990 are shown in Figure 4.25. These heads provide a starting point for model simulation. It was not possible to differentiate water levels in each model layer as the depth of the piezometers or top and bottom of screens have not been recorded. Heads range from 0.87 m AMSL near the southern boundary to 315.2 m AMSL near the north western boundary of the model in northeast Punjab. Groundwater flows in a south-westerly and southern direction in Punjab and Sindh, respectively. Flow patterns are influenced by the river system, aquifer material, bedrock ridges, and highly transmissive zones. The initial heads will be adopted for all three layers.
Groundwater pumping requirements are calculated for and extracted from each active model cell using the Well Package (WEL). In this model, groundwater pumping requirements and groundwater pumping in this model are synonymous. That is, groundwater pumping requirements are specified as pumping rates for ‘virtual wells’ in the Well Package. Note that in this model, groundwater pumping is not constrained by maximum well capacities or groundwater allotments. However, in this model we cap pumping with an assumed maximum limit in saline groundwater areas (see 4.7.3).

The groundwater requirement, Q_{gw}, for each MODFLOW cell equals the total irrigation delivery requirement, TDR, not satisfied by the delivery of surface-water supply, Q_{sw}, to the MODFLOW cell (see eqs. (2) to (7)). The resulting cell-by-cell pumping requirement is shown in Figure 4.26. The left graph shows an example of low demand and high supply from precipitation and surface water with the result of minimal Q_{gw}. The only area, where a Q_{gw} exists, is in the riverine areas located in between the canal command areas where no surface water is available. The right graph demonstrates the effect of the 1998-2002 drought during its beginning in August 1998. The lack of
rain and surface water leads to record Qgw. One can clearly see the Qgw in northwest Punjab outside the canal command. Yet, in this area, higher rainfall also reduces the need for groundwater pumping. Note that at this point, the Qgw in the corridor between the international border to India and the eastern model boundary is set to zero.

\[ Q_{gw_{ij}} = TDR_{ij} - Q_{sw_{ij}} \]  \[ \text{[L}^3\text{T}^{-1}] \]  \[ (2) \]

\[ TDR_{ij} = \frac{CIR_{ij}}{E^f_{ij}} \]  \[ \text{[L}^3\text{T}^{-1}] \]  \[ (3) \]

\[ CIR_{ij} = \left( E^d_{ij} - P_{ij} - ET_{gw}^{ij} \right) \times \left( \sum_{ic=1}^{NiCM} A_{ic_s} \right) \times C_{ij} \]  \[ \text{[L}^3\text{T}^{-1}] \]  \[ (4) \]

\[ E^f_{ij} = \left( \frac{1}{\sum_{ic=1}^{NiCM} A_{ic}} \left( \sum_{ic=1}^{NiCM} E^f_{ic} A_{ic} \right) \right)_{ij} \]  \[ \text{[L}^3\text{T}^{-1}] \]  \[ (6) \]

\[ Q_{sw_{ij}} = \left( SW_{CCA} \times E^i_{sw} \times E^j_{sw} \right)_{ij} \times \left( \sum_{swic=1}^{NswiCM} A_{swic_s} \right) \]  \[ \text{[L}^3\text{T}^{-1}] \]  \[ (7) \]

Qgw = Groundwater irrigation requirement at each MODFLOW cell [L^3T^-1]
Qsw = Surface water delivery flow rate to the MODFLOW cell [L^3T^-1]
TDR = Total delivery requirement accounts for crop irrigation requirement and on-farm inefficient losses [L^3T^-1]
CIR = Crop irrigation requirement equal to crop water demand not satisfied by precipitation or uptake from groundwater (latter is neglected in this model) [L^3T^-1]
i = 1, 2, ... total number of rows; j = 1, 2, ... total number of columns
t = 1, 2, ... total number of stress periods (months)
ic = 1, 2, ..., total number of surface-water or groundwater irrigated crops within a Modflow cell (NiCM), i.e., regardless of whether inside or outside a CCA.
swic = 1, 2, ..., total number of surface-water irrigated crops within a Modflow cell (NswiCM), i.e., inside a CCA.
C = ratio between historic cropped areas from crop statistics and remotely sensed (irrigated) cropped area
\[ A^d_{c-stat} = \text{monthly cropped area per district derived from historic crop statistics in equation (11)} \]
\[ A^d_{c-rs} = \text{cropped area per district from remote sensing for either season s = Rabi or Kharif} \]
\[ A^d_{ic-rs} = \text{irrigated cropped area per district from remote sensing for either season s = Rabi or Kharif} \]
\[ A_{ic-s} = \text{irrigated cropped area within a MODFLOW cell (from remote sensing) for s = Rabi or Kharif} \]
\[ A_{swic_s} = \text{irrigated cropped area within a MODFLOW cell (from remote sensing) for s = Rabi or Kharif} \]
s = season; s = Kharif, if mod(t,12) = 4, 5, 6, 7, 8, 9; = Rabi if mod(t,12) = 10, 11, 12, 1, 2, 3

ETd = depth of area-weighted potential crop evapotranspiration per district derived from crop statistics in equation (10) for any MODFLOW cell within that district [LT^-1]
ETgw = Uptake from groundwater (neglected in this model)
P = Precipitation depth \([LT^{-1}]\)

\(E^f\) = irrigation (field) efficiency accounts for on-farm losses (deep percolation or runoff (latter neglected)) [ ]

\(E^{sw1}\) = surface water delivery efficiency to account for conveyance losses of major canals (main, branch, link) for all of Indus basin; not available per CCA) [ ]

\(E^{sw2}\) = surface water delivery efficiency to account for conveyance losses of minor canals and water courses for all of Indus basin; not available per CCA) [ ]

\(SW_{CCA}\) = Depth of surface water delivery/diversion to each CCA equal to efficiently delivered surface water to the MODFLOW cell and inefficiently lost canal seepage along the way. \([LT^{-1}]\)

Figure 4.26 Groundwater pumping requirement for each MODFLOW cell (left: December 2006; right: August 1998; units in m3/day per MODFLOW model cell)
(Coordinate system: LCC1)

### 4.7.1 Total Delivery Requirement

The total delivery requirement (TDR) is determined as crop irrigation requirement (CIR) increased sufficiently to compensate for inefficient use from irrigation with respect to plant consumption. The TDR is equal to CIR divided by an average of crop-specific efficiencies for each season weighted by the cropped areas.

**Crop Irrigation Requirement**

Crop water demand not satisfied by precipitation formulates a crop irrigation requirement in the calculation of the groundwater pumping requirement that is specified using the Well Package. The crop water demand is represented by district-wide, temporally variable potential crop evapotranspiration depths and discussed in this section. Precipitation is specified as spatially and temporally distributed monthly precipitation depths as described in section 3.1, Climate Data.
volumetric rate of crop irrigation requirement is calculated by multiplying the CIR depth by the cropped area within each MODFLOW.

**Potential or Well-watered Crop Evapotranspiration**

Spatially and temporally distributed potential or reference evapotranspiration is used for multiplication with a crop coefficient to obtain potential, or well-watered, crop evapotranspiration, $ET_{c,\text{pot}}$, which defines the crop water demand. Crop coefficients used for $ET_{c,\text{pot}}$ were associated with temporally variable yet spatially lumped district-wide crop statistics.

We calculated well-watered evapotranspiration in the districts of Pakistan for the main crops and crop groups, where a crop group comprises several crops of similar water use characteristics (such as summer grains, or pulses). By well-watered evapotranspiration, we mean the evapotranspiration from a crop – soil system that is not limited by shortage of water, and is similarly not limited by pests or diseases, lack of plant nutrients or any other limiting factor. We calculated the well-watered evapotranspiration, $ET_{c,\text{ww}}$, of a crop or crop group as the product of reference evapotranspiration, $ET_{\text{ref}}$, and a crop coefficient, $K_c$ (Allen et al. 1998):

$$ET_{c,\text{ww}} = ET_{\text{ref}} K_c$$  \hspace{1cm} (8)

The equation gives the well-watered evapotranspiration as the depth of water (often in mm) at a point (i.e., it is a one-dimensional calculation), and for a single crop or crop group. To calculate the well-watered evapotranspiration for an area (such as an administrative district in Pakistan), the point well-watered evapotranspiration for each crop or crop group is multiplied by the area occupied by that crop or crop group, $A_c$, and the results summed to give the volume, $ET_{Dv,\text{ww}}$, or depth, $ET_{Dd,\text{ww}}$, of evapotranspiration for the entire district:

$$ET_{Dv,\text{ww}} = \sum_{i=1}^{nC} (ET_{c_{i,\text{ww}}} \times A_{c_{i}})$$  \hspace{1cm} (9)

$$ET_{Dd,\text{ww}} = \sum_{i=1}^{nC} (ET_{c_{i,\text{ww}}} \times A_{c_{i}}) / \sum_{i=1}^{nC} (A_{c_{i}})$$  \hspace{1cm} (10)

$$A_c = \sum_{i=1}^{nC} (A_{c_{i}})$$  \hspace{1cm} (11)

where $i$ is the $i$-th crop or crop group and $nC$ is the number of crops and crop groups within a district.

We calculated $ET_{c,\text{ww}}$ and $ET_{Dd,\text{ww}}$ (in mm) and $ET_{Dv,\text{ww}}$ (in million cubic metres, mcm) in equations (8) to (10) for the districts of Pakistan. The crop coefficients, $K_c$, were based on Ullah et al. (2001), with the following additional factors:

- we assumed that fodder performed at or near the (grass) reference rate most of the time, and therefore set the crop coefficient at 1 throughout the Rabi (for Rabi fodder) or Kharif season (for Kharif fodder);
- we assumed that evergreen orchards (citrus, etc.) have a 70% canopy cover, and set the crop coefficient to 0.7 throughout the year;
- crop coefficients for deciduous orchards (apricots, etc.) are based on Allen et al. (1998).
As described in section 3.1, ‘Climate Data,’ the reference evapotranspiration, $ET_{ref}$, is based on the Hargreaves method and on elevation dependent interpolation using the ANUSPLIN package (Hutchinson and Xu 2013).

The areas of crops were based on Pakistan crop survey records, which for recent years are available at district level for many crops. For earlier years, the district level information is available for a number of major crops. Kirby and Ahmad (2016) collated crop area information from several sources into a consistent format. They estimated district minor crop areas for earlier years by assuming that the ratios of minor crop areas to major crop areas remained the same as it has been in recent years. The minor crops were grouped into the crop group categories that we used in the study that is the subject of this report. Kirby and Ahmad (2016) also mapped the district crop area data onto the canal commands of Pakistan and hence also estimated the district areas of crops and crop groups that are outside the canal commands, which (because the crop areas outside canal commands must use groundwater only) is helpful in estimating the relative amounts of surface and groundwater use for irrigation in different districts.

For the calculation of the crop irrigation requirement of the MODFLOW model, we used district-wide depths of $ET_d$ as area-independent potential crop evapotranspiration depths, hereafter referred to as $ET_{c-pot}$ to distinguish between actual crop evapotranspiration, $ET_{c-act}$.

A shapefile of district-wide $ET_{c-pot}$ was intersected with the MODFLOW grid to obtain cell-by-cell $ET_{c-pot}$ any district-wide $ET_{c-pot}$ data that reached beyond a digitized coastline were clipped (Figure 4.27). Note that in some parts of the active model domain, the $ET_{c-pot}$ is zero, e.g., within the narrow corridor across the international boundary. No $ET_{c-pot}$ data were obtained for the corridor across the international boundary. Hence, for these areas, no CIR or TDR was calculated.

![Figure 4.27 Gridded potential crop evapotranspiration from district crop statistics](image)

![Figure 4.28 Gridded precipitation (see section 3.1) from district crop statistics](image)

(Units in mm/month; coordinate system in LCC1)
Precipitation

Spatially and temporally distributed precipitation is contributing as a supply source to satisfy crop water use and used to derive the crop irrigation requirement in equation (4). As described in section 3.1 (Climate Data), the precipitation array was created based on an elevation dependent interpolation using the ANUSPLIN package (Hutchinson and Xu 2013).

Spatially and temporally distributed precipitation data were retrieved from gridded daily data (116 meteorological stations from 1960 to 2013) covering the entire Indus basin and Pakistan an overall area of 1.4 million km². For each centroid of a 5km MODFLOW grid cell, the nearest gridded data set of 1 km resolution rainfall datasets was adopted to represent the associated cell. The daily data were re-gridded for locations where data were available within the MODFLOW domain and then aggregated to monthlies. Any cell-by-cell precipitation data that reached beyond a digitized coastline or the active model boundary were clipped (Figure 4.28).

Effective Precipitation

In empirical methods, generally, “effective” precipitation is subtracted from actual crop ET to obtain crop consumptive use or crop water requirement. In Pakistan, depending on the empirical method, effective rainfall amounts to approx. 13 to 43% in the humid zone of Northeast Punjab and Northwest KPK and 54 to 100% in arid zone of Southwest Sindh and Southern Balochistan (Adnan and Khan 2011). These are regional estimates derived with empirical methods, which do not account for local conditions. Also they relate to effective rainfall in the sense of actual transpiration from precipitation and cannot be used in models, where actual ET or its E and T components are not available or simulated.

According to Brouwer and others (1985) and Brouwer and Heibloem (1986), “effective rainfall is the total rainfall minus runoff minus evaporation and minus deep percolation.” In other words, effective rainfall can be defined as actual transpiration from precipitation (T_p-act). However, in this model, neither actual crop ET nor its transpiration or evaporation portions are available or simulated. In lieu of having ET_c-act, we use ET_c-pot. Subtracting an assumed crop-growth-effective precipitation (as product of P with a specified P_e percentage) from ET_c-pot would be inconsistent to obtain a crop irrigation requirement, because ET_c-pot still contains E_c-pot, which is related to the fraction of the water vapour pressure saturation deficit from exposed and wetted areas and this. Unless a model fractionates T_c-pot and E_c-pot, we cannot subtract the evaporation or transpiration portions separately. Hence, if the evaporative portion of ET_c-pot is still included (as E_c-pot), it also needs to be still included in the precipitation term (as E_p-pot) for consistency.2

In summary, in this model, if non-beneficial evaporation from exposed and wetted areas is still embedded in the potential “crop consumptive use” and we are not distinguishing between evaporation and transpiration, then all non-beneficial evaporation needs also to be still included in the precipitation term that is subtracted from the potential “consumptive use.” Therefore, from a conceptional standpoint, it seems justified for the purpose of this model to use all of the available precipitation to satisfy this type of potential “consumptive use.”

2 For example: If a cell’s ET_c-pot is 90% evaporation and only 10% transpiration and not distinguished from each other, then it would be false to only subtract a crop-growth-effective portion of rainfall that is assumed to be T_p-act. For instance, if ET_c-pot and P are both equal to 100 units, but a lumped P_e percentage for a particular region is known to be 60%, then, P_e of 60 units would compare badly with 10 units of transpiration from precipitation and subtracting 60 units from ET_c-pot would yield a false crop irrigation requirement of 40 units. Furthermore, in this example, 10 units of transpiration still represent ‘potential’ crop transpiration not yet reduced by stresses like wilting or anoxic conditions, meaning the actual transpiration from rainfall may be even less than 10 units and compare even worse with the specified 60 units of P_e.
In the numerical model, rainfall in the humid zone exceeds evapotranspiration in most areas and most of the year. That is, if ET << P, then all the comparatively low water vapour pressure saturation deficit will all be satisfied by just a small portion of the precipitation and the majority of the precipitation will be lost non-beneficially. Instead of using empirical methods or tables, which take into account consumptive use and rainfall to estimate effective rainfall over large regions, the numerical model will, on a cell-by-cell basis, compare precipitation and ET_{crop} and produce in-excess of consumptive use losses from precipitation, which then will all be attributed to recharge (neglecting surface-water runoff). The arid zones are known to have a nearly 100% effective rainfall. If ET >> P, then the sparse rainfall will be completely consumed by the comparatively high water vapour pressure saturation deficit. That is, in this case, it is justified to simply reduce the consumptive use by the entire rainfall to evaluate the irrigation requirement.

**Cropped areas**

Generally, land-use distribution through mapping or remote sensing would be favourable to define cropped areas for particular time windows. In this case, neither one of the two was available over the period of the model. However, the University of Faisalabad (UF) has created land-use maps for Rabi and Kharif 2013-14 for this SDIP Indus project with an estimation of cropped area using vegetation time series at modest resolution, i.e. six hectares using MODIS NDVI (Cheema 2016, unpublished) (Figure 4.29).

While the land-use maps from the UF show a spatial crop distribution, they do have a few minor issues. Firstly, a category ‘other crops’ was spread out over clearly non-cropped areas, for instance, like native vegetation, sand dunes, salt marshes, urban areas (e.g., city of Lahore). Secondly, non-irrigated rain-fed areas and irrigated areas were not distinguished. A similar resolution land-use cover from the ESA GlobCover 2009 Project was used to eliminate non-cropped areas to obtain cropped areas and to delete rain-fed areas to further reduce cropped areas to irrigated, cropped areas (Figure 4.30). The GlobCover land cover map is derived using observations from the 300m MERIS sensor on board the ENVISAT satellite mission for the year 2009 (ESA 2017).

Cropped areas were intersected with districts to obtain cropped areas per district from remote sensing, A^{d}_{crs}, for a ratio between cropped areas per district from crop statistics, A^{d}_{c-stat}, and A^{d}_{crs} (see below). Irrigated, cropped areas were overlayed with the MODFLOW grid to obtain cell-by-cell areas of irrigated, cropped areas, A^{d}_{ic}, used for multiplication with the CIR. In addition, irrigated, cropped areas were intersected with the MODFLOW grid and canal command areas to obtain cell-by-cell areas of surface-water irrigated, cropped areas, A^{d}_{swic}, used for multiplication with the surface-water delivery depths.

The benefit of remote sensing maps is the spatial distribution of crop types, which is missing in the historic, district-wide crop statistics. However, multiplying area-independent depths of crop irrigation requirements derived from time varying crop statistics with non-time varying cropped areas from recent remote sensing in order to obtain a CIR rate is problematic. To reconcile this issue, the resulting CIR rate was scaled by the ratio between cropped areas from crop statistics, A^{d}_{c-stat} and cropped areas from remote sensing, A^{d}_{crs}, as shown in equation (4). However, if the portion of cropped area covered by irrigated crops is much larger than the area of non-irrigated crops (e.g., >80% versus <20%), we chose to scale up the CIR rate by a ratio between A^{d}_{c-stat} and irrigated cropped areas from remote sensing, A^{d}_{ic-rs}.
Efficiencies

We distinguish between two types of efficiencies. On-farm efficiencies account for losses from irrigation in-excess of crop consumptive use. Off-farm efficiencies describe conveyance losses of surface-water deliveries between the diversion and farm gate.
On-farm, or also called field application, efficiency is needed to account for inefficient losses from irrigation with respect to plant consumption. The total delivery requirement includes both the crop irrigation requirement (CIR) and these inefficient losses. For that, the crop irrigation requirement (CIR) is increased sufficiently to compensate for inefficient use from irrigation. The TDR then is equal to CIR divided by an average of crop-specific efficiencies for each season weighted by the cropped areas. In lack of available on-farm efficiencies typical for particular regions, we made lumped assumptions for crop-specific on-farm or field application efficiencies (Table 4.1). The overall average of 76% compares well with parameters from the literature (FAO 2016: 75%, Basharat 2013, 80%). Therefore, we take our assumptions to be reasonable. Area-weighted averages were created for Kharif due to the wide range of efficiencies between rice and cotton (50 and 85%) using equation (7) with the spatial distribution of irrigated crops for Kharif 2014 from remote sensing (cotton, fodder, sugarcane, rice, other crops). All irrigated crops present during Rabi 2013-14 (wheat, fodder, sugarcane, and other crops) were assumed to have the same efficiency of 80%.

Table 4.1 On-farm and off-farm efficiencies in the Indus Basin Irrigation System

<table>
<thead>
<tr>
<th>Type of Efficiency</th>
<th>Component or crop, which efficiency applies to</th>
<th>CSIRO 2017 (3)</th>
<th>FAO 2011</th>
<th>Basharat 2013</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{w1}$</td>
<td>canals (main, branch, link): from canal head to minor canal (1)</td>
<td>75.00</td>
<td>81.28</td>
<td>78.14</td>
<td></td>
</tr>
<tr>
<td>$E_{w2}$</td>
<td>minor canals and watercourses: from minor canal head to farm gate (2)</td>
<td>70.00</td>
<td>75.00</td>
<td>72.50</td>
<td></td>
</tr>
<tr>
<td>$E^1$</td>
<td>irrigation (field application)</td>
<td>0.76 (avg)</td>
<td>75.00</td>
<td>80.00</td>
<td>77.02</td>
</tr>
<tr>
<td>Fallow</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>0.50</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basmati Rice</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>0.85</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar Cane</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer grains</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seeds</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulses</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fodder summer</td>
<td>0.80</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fodder winter</td>
<td>0.80</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orchard evergreen</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orchard deciduous</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other: used field application efficiency of 80% from Basharat 2013</td>
<td>0.80</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$E_{w1} \times E_{w2}$: Portion of diversions delivered into minor canals & water courses
$E_{w1} \times E_{w2}$: Portion of diversions delivered to farm gate
$E_{w1} \times E_{w2}$: Portion of diversions delivered into minor canals & water courses
$E_{w1} \times E_{w2}$: Portion of diversions delivered into minor canals & water courses

Off-farm efficiency is needed to reduce known barrage diversions by conveyance losses along major and minor canals and watercourses to the surface-water delivered to the farm gate (i.e., to the MODFLOW cell). We used a combined efficiency equal to the product of the portion of diversions from the canal heads along major canals delivered into minor canals and the portion from the head of the minor canals to the farm gate and then averaged the over data from two sources (FAO 2016, Basharat 2013) (Table 4.1: $E_{w1} \times E_{w2} = 0.57$). In the MODFLOW model, losses associated with the first portion will have to approximately equal to the canal seepage that is explicitly simulated with the RIV or SFR package. This may involve a reciprocal approach between modifying canal bed
conductivity or the efficiency assumption in the model calibration process. Losses related to the second portion are losses along minor canals and water course not explicitly simulated in this MODFLOW model. Therefore, these losses have to accounted for as part of Recharge Package (RCH), which will specify other recharge components, such as diffuse recharge from irrigation or precipitation in-excess of crop consumptive use (see section ‘Recharge’). Losses along the minor canals and water courses are equal to the portion of diversions delivered to the heads of minor canals minus the portion that reaches the farm gate. (Table 4.1: $E_{sw1} - E_{sw1} \times E_{sw2} = 0.21$).

![Figure 4.31 Total Delivery Requirement for each MODFLOW cell](image1)

![Figure 4.32 Surface Water Delivery to each MODFLOW cell](image2)

(Units in m$^3$/day; coordinate system in LCC1)

### 4.7.2 Surface-Water Delivery

In a surface-water dominated irrigation setting like the IBIS, the total irrigation delivery requirement, TDR (Figure 4.31), is satisfied by the delivery of surface-water supply, $Q_{sw}$, by first priority before applying supplemental groundwater supply (see eqs. (2) to (7)). Surface-water deliveries to the MODFLOW cells (i.e., to the farm gate) are derived from diversions for each canal command areas reduced by all conveyance losses within one canal command area. This includes losses along main canals as well as minor canals and water courses. That is, diversions were multiplied with a “combined surface-water efficiency” along canals (for portions of diversion delivered into minor canals & water courses) and efficiency along minor canals & water courses (for portions delivered to farm gate) (data from FAO 2016, Basharat 2013) (Table 4.1: $E_{sw1} \times E_{sw2} = 0.57$).
A data set of diversions for each canal command called “Default Input Set – Diversions”\(^3\) has been supplied by WAPDA as daily time series and covers the period from April 1991 to March 2009 for all water diversions from barrages on the Indus River. The period from April 1991 to March 2009 covers most of the model period of the MODFLOW model from October 1990 to September 2012. That is, only a short period before and after had to be appended. For the period after March 2009, we were able to use actual deliveries from the “Canal Indents and Deliveries” data set\(^4\) that has been supplied by Punjab Irrigation Department (PID) and covers the period 2007-2013 for all of the irrigation canals in the Punjab province. These data were used to append/splice data for the remaining period from April 2009 to September 2012. Where actual deliveries are not available, five-year averages of the diversion were used for the period from April 2009 to September 2012 as well as October 1990 to April 1991.

The daily diversion volumes (in ML/d) were then aggregated to monthly averages in meter/day, divided by irrigated areas within each canal command area for Rabi or Kharif and finally multiplied by the combined surface-water efficiency (as described above) (Figure 4.32).

Note that surface-water deliveries to the MODFLOW cells are not constrained by any surface-water allotments or rights within a canal command area. In addition, simulated canal seepage of major canals simulated by the Streamflow Routing Package may be temporally or locally higher than the lumped conveyance losses using assumed inefficiencies of major canals (Table 4.1: \((1-E_{sw1}) = 0.22\)). A variation of canal bed parameters (e.g., canal bed hydraulic conductivity) during the calibration process will be required to match the two terms. Losses along minor canals and water courses are not explicitly simulated and are added to the diffuse recharge (see section 4.9.3).

### 4.7.3 Groundwater Salinity Impact on Groundwater Pumping

For the purpose of this groundwater flow model, groundwater salinity is not considered in its three-dimensional spatial and temporal distribution as it would be for a solute transport model. The only aspect of groundwater salinity for this model is to get an approximation of saline groundwater areas, where we assume that farmers will not use the maximum possible discharge of tube wells. That is, after eliciting various experts in the region (e.g., Dr. Basharat, WAPDA), we came to the conclusion to cap the previously calculated groundwater pumping requirement, \(Q_{gw}\), in areas of salinity (Figure 4.33) of TDS>1000 ppm with a particular maximum limit, which is still to be determined. For this procedure, only groundwater quality maps were considered, where the sampled tube wells represent depths of shallow groundwater usable for production.

- For Punjab: Our map in Figure 4.33 is based on a TDS map provided by WAPDA for areas with TDS>1000 ppm based on tube wells sampled between 2001 and 2004 (Basharat 2016);
- For Sindh: For Figure 4.33, we georeferenced a historic map of “Saline Ground Water Area” (Khero 2016) most likely created in the 1960s assuming that this relates to TDS >1000 ppm.

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\(^3\) This data set is supplementary to the “Canal indents and Deliveries” data supplied by PID because it only contains the actual water diverted, rather than the water that was diverted and the water that was requested (indent). As such, this data set is used to verify the model diversion for the longer time series SOURCE model.

\(^4\) This data set is used in the Source model for calibration purposes by setting the water demand time series at the canal command head to either the indent time series (the water that is ordered at the canal command) or more commonly to the delivered time series. The water demand time series is used by the SOURCE model to request the release of water from upstream storages. Thus, these time series play the important role of triggering the transfer of water out of storage, along link canals and to the canal command areas that require the water. Ultimately, the Source model will independently calculate these water demands from the provincial shares allocated under the Water Apportionment Accord and the Canal Indents and Deliveries data will then be used to verify the model results.
Due to the similarity in extent of the >1000ppm class in a figure in MacDonald (2015 and 2016).

- Outside the coverage of the above mentioned map we approximated areas with TDS>1000 ppm derived from a figure in MacDonald (2015 and 2016).

Depth-dependent groundwater quality data are generally available along with borelog lithology data from the 1960s obtained from WAPDA for this study (section 3.3.1). However, digitizing these data was beyond the scope and budget and is more relevant for solute transport modelling at a future stage. Note that recent maps of shallow groundwater salinity for the Lower Indus do exist (e.g., Qureshi et al. 2004, or Basharat et al. 2014, figure 6.27). However, a figure in the former citation is of very small scale and in units of EC and the latter is mostly based upon hand pumps, i.e., too shallow to represent tube wells. Much of the information for the Lower Indus stems from surveys in the 1960s (e.g., used historic map provided by Khero 2016). After the 1960s, the shallow groundwater quality might have improved, but is not known due to the absence of any recent survey.

![Areas of hazardous Salinity](image)

**Figure 4.33 Marginal and hazardous groundwater salinity above 1000 ppm TDS**

(Coordinate system: LCC1)
4.8 Evapotranspiration from Groundwater

Evapotranspiration (ET) is one of the main components of the water cycle and its accurate estimation at large spatial scale is needed for water planning and management. Generally, water productivity analysis, irrigation scheduling and planning can be addressed appropriately if timely and accurate information on consumptive use by different crops is available. In this model, we use potential crop ET as a demand component for the calculation of a monthly groundwater irrigation requirement, \( Q_{gw} \) (see section 4.7), which provides input for the Well Package (WEL). That is, we approximate irrigation demand for long-term and large scale purposes, but do not attempt to simulate any short-term irrigation scheduling and planning. In addition, in this model, \( Q_{gw} \) is pre-processed externally to MODFLOW and, hence, does not account for the simulated ET uptake from groundwater. To account for this mass balance component, we use the Evapotranspiration Package of MODFLOW (EVT), which calculates head-dependent uptake from groundwater. The EVT Package requires specification of a maximum ET flux at a so-called “ET-surface elevation” and a depth below the surface at which the ET flux becomes extinct, also called extinction depth. For these three parameters we used (a) spatially and temporally distributed potential or reference evapotranspiration, (b) ground surface elevation, and (c) extinction depths for different soil types from the literature, respectively.

Spatially and temporally distributed Hargreaves reference evapotranspiration data were calculated from gridded daily datasets of minimum and maximum temperature (116 meteorological stations from 1960 to 2013) covering the entire Indus basin and Pakistan an overall area of 1.4 million km² (using the ANUSPLIN package of Hutchinson and Xu 2013; see section 3.1). For each centroid of a 5km MODFLOW grid cell, the nearest gridded data set of 2.5 km evapotranspiration datasets was adopted to represent the associated cell. The daily data were re-gridded for locations where data were available within the MODFLOW domain and then aggregated to monthlies.

The so-called “ET-surface,” which the maximum ET flux is related to, was chosen to be equal to the 90 m DEM ground surface elevation and interpolated to each MODFLOW cell centre.

Table 4.2 Extinction Depths for Different Soil Land Covers (after Shah et al. 2007)

<table>
<thead>
<tr>
<th>Soil</th>
<th>Land cover type (cm)</th>
<th>Bare soil</th>
<th>Grass</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td>50</td>
<td>145</td>
<td>250</td>
</tr>
<tr>
<td>Loamy sand</td>
<td></td>
<td>70</td>
<td>170</td>
<td>270</td>
</tr>
<tr>
<td>Sandy loam</td>
<td></td>
<td>130</td>
<td>230</td>
<td>330</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td></td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Sandy clay</td>
<td></td>
<td>210</td>
<td>310</td>
<td>410</td>
</tr>
<tr>
<td>Loam</td>
<td></td>
<td>265</td>
<td>370</td>
<td>470</td>
</tr>
<tr>
<td>Silty clay</td>
<td></td>
<td>335</td>
<td>430</td>
<td>530</td>
</tr>
<tr>
<td>Clay loam</td>
<td></td>
<td>405</td>
<td>505</td>
<td>610</td>
</tr>
<tr>
<td>Silt loam</td>
<td></td>
<td>420</td>
<td>515</td>
<td>615</td>
</tr>
<tr>
<td>Silt</td>
<td></td>
<td>430</td>
<td>530</td>
<td>630</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td></td>
<td>450</td>
<td>550</td>
<td>655</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td>620</td>
<td>715</td>
<td>820</td>
</tr>
</tbody>
</table>

Notes: Depths are rounded up to nearest 5 cm

Maximum rooting depth for grass and forest was assumed to be 100 and 200 cm, respectively.
The ET extinction depth was estimated by using 1496 borelogs from the Indus Basin and interpreting the soil type of near surface layer of a bore log. The extinction depths assigned to each log was adopted from Shah et al. (2007) which is shown in Table 4.2. The interpreted extinction depths for each log were then gridded and a value for each model cell obtained. The image map for the extinction depths shown in Figure 4.34, range from a low of 0.5 m to 7.14 m, and a mean of 2.78 m and a median value of 2.82 m. Less than 5% of extinction depths are range from 0.5 to 1 m, and 5% of values are greater than 4.8 m.

![Evapotranspiration Extinction depths (m)](image)

Figure 4.34 Evapotranspiration Extinction depths (m)
(Coordinate system: LCC1)

### 4.9 Recharge

For this study, recharge into the aquifer is specified as a combination of diffuse recharge from irrigation and precipitation in-excess of crop water demand and conveyance losses along minor canals and watercourses. For every active model cell, a recharge flux term was specified as input into the Recharge Package (RCH) and attributed to the uppermost active layer.

One difference between $Q_{gw}$ in section 4.7 and recharge is that the former is specified as flow rates attributed to virtual wells using the Well Package while the latter is specified as a depth, which
MODFLOW then again multiplies by the area of the cell internally. For that reason, the sum of all flow terms in equation (12) have to be divided by the area of the MODFLOW cell to obtain a uniform depth of diffuse recharge flux for each cell.

\[ R_{ij} = \left( R_{ij}^l + R_{ij}^r + S_{sw,i,j} \right) / A_{MF-cell} \]  \hspace{1cm} \text{[LT}^{-1}]  \hspace{1cm} (12)

\[ R_{ij}^l = \left( I_{ij} - CIR_{ij} \right) \left( 1 - IE_{sw}^l \right) \text{, with: } I_{ij} = TDR_{ij}; IE_{sw}^l = 0 \]  \hspace{1cm} \text{[L}^3T^{-1}]  \hspace{1cm} (13)

\[ R_{ij}^p = \left( P_{ij} - ET_{d}^{i,j} \right) \times \left( \sum_{c=1}^{NCM} A_{c_s} \right) \times C_{ij} \times \left( 1 - IE_{sw}^p \right) \]  \hspace{1cm} \text{[L}^3T^{-1}]  \hspace{1cm} (14)

with: \( C_{ij} = \left( \frac{A_{c-stat}}{A_{c-rs}} \right)_{ij} \); \( IE_{sw}^p = 0 \)

\[ S_{sw,i,j} = \left( SW_{CCA} \times E_{sw}^2 \left( 1 - E_{sw}^2 \right) \right)_{ij} \times \left( \sum_{swic=1}^{NswICM} A_{swic_s} \right)_{ij} \]  \hspace{1cm} \text{[L}^3T^{-1}]  \hspace{1cm} (15)

\( R = \) Recharge flux at each MODFLOW cell \([\text{LT}^{-1}]\)

\( R^l = \) Recharge rate from irrigation at each MODFLOW cell \([\text{L}^3\text{T}^{-1}]\)

\( R^p = \) Recharge rate from precipitation at each MODFLOW cell \([\text{L}^3\text{T}^{-1}]\)

\( S_{sw} = \) Rate of seepage losses of minor canals & water courses to the MODLFOW cell \([\text{L}^3\text{T}^{-1}]\)

\( I = \) Applied Irrigation \([\text{L}^3\text{T}^{-1}]\)

\( TDR = \) Total delivery requirement accounts for crop irrigation requirement and on-farm inefficient losses \([\text{L}^3\text{T}^{-1}]\)

\( CIR = \) Crop irrigation requirement equal to crop water demand not satisfied by precipitation or uptake from groundwater (latter is neglected in this model) \([\text{L}^3\text{T}^{-1}]\)

\( i = 1, 2, \ldots \) total number of rows; \( j = 1, 2, \ldots \) total number of columns

\( t = 1, 2, \ldots \) total number of stress periods (months)

\( c = 1, 2, \ldots \), total number of crops within a Modflow cell (NCM)

\( swic = 1, 2, \ldots \), total number of surface-water irrigated crops within a Modflow cell (NswICM), i.e., inside a CCA.

\( C = \) ratio between historic cropped areas from crop statistics and remotely sensed cropped area

\( A_{c-stat} = \) cropped area per district variable from month to month derived from historic crop statistics in equation (11)

\( A_{c-rs} = \) cropped area per district from remote sensing for either season \( s = \) Rabi or Kharif

\( A_{cs} = \) cropped area within a MODFLOW cell (from remote sensing) for \( s = \) Rabi or Kharif

\( A_{swic,s} = \) irrigated cropped area within a MODFLOW cell (from remote sensing) for \( s = \) Rabi or Kharif

\( s = \) season; \( s = \) Kharif, if mod(t,12) = 4, 5, 6, 7, 8, 9; \( = \) Rabi if mod(t,12) = 10, 11, 12, 1, 2, 3

\( ET = \) depth of area-weighted potential crop evapotranspiration per district derived from crop statistics in equation (10) for any MODFLOW cell within that district \([\text{LT}^{-1}]\)

\( P = \) Precipitation depth \([\text{LT}^{-1}]\)

\( E_{sw}^1 = \) surface water delivery efficiency to account for conveyance losses of major canals (main, branch, link) for all of Indus basin; not available per CCA)

\( E_{sw}^2 = \) surface water delivery efficiency to account for conveyance losses of minor canals and water courses for all of Indus basin; not available per CCA)

\( SW_{CCA} = \) Depth of surface water delivery/diversion to each CCA equal to efficiently delivered surface water to the MODFLOW cell and inefficiently lost canal seepage along the way \([\text{LT}^{-1}]\)
4.9.1 Recharge from Irrigation

The calculation of recharge from applied irrigation, I, in-excess of crop irrigation requirement, CIR, is simple as the relevant terms were already calculated as part of Qgw (see eqs. (2) to (7)). The applied irrigation, I, is taken to be equal to the total delivery requirement, TDR, assuming no deficit. The crop irrigation requirement, CIR, can also be re-used. It should be noted that, due to the domination by basin-level irrigation in the IBIS, we neglect the portion of inefficient losses from irrigation to surface runoff, IE\textsubscript{sw}.

4.9.2 Recharge from Precipitation

The calculation of recharge from precipitation, P, in-excess, of crop ET, is slightly more complicated since recharge from precipitation in-excess of crop ET is related to an area of all irrigated and non-irrigated crops (eq. (14)) as opposed to the crop irrigation requirement (eq. (4)), which is only related to an area of irrigated crops. Therefore, this term has to be multiplied first by the cropped area of each MODFLOW cell and then scaled by the ratio between district-wide cropped areas from crop statistics and district-wide cropped areas from remote sensing. Note that the portion of inefficient losses from precipitation to surface runoff are neglected in this model. The active model domain is demarcated to the North and West by the suture between mountainous, tertiary and alluvial-basin, quaternary formations. Most of the active alluvial domain is relatively flat and, for simplicity, excess precipitation is routed to deep percolation as opposed to surface runoff (IE\textsubscript{sw} = 0). Clearly, this does not capture short-term flash floods that are quite common in Pakistan though. However, short-term events cannot be simulated in a MODFLOW model with monthly time steps anyway.

4.9.3 Seepage from minor canals and water courses

Losses along minor canals and water courses are not explicitly simulated in this MODFLOW model. Therefore, these losses have to be accounted for as part of the Recharge Package. Losses along the minor canals and water courses are equal to the portion of diversions delivered to the heads of minor canals minus the portion that reaches the farm gate. (Table 5.1: E\textsuperscript{sw1} - E\textsuperscript{sw1} \times E\textsuperscript{sw2} = E\textsuperscript{sw1} (1- E\textsuperscript{sw2}) = 0.21).

4.10 Stream aquifer interaction

The River or Streamflow Routing Packages in MODFLOW model the interaction of rivers and canals and the groundwater system by adding recharge from the streams to the groundwater system and also allowing for discharge of groundwater back to the streams. The flow rate to or from the aquifer is controlled by the difference in head between the river and the aquifer within a model cell and the conductance of the river bed. The direction of flow is controlled by the head in the aquifer or the river whichever being the greater at a particular point in time.

A stream or canal is divided into reaches such that each reach is completely contained in a single cell, and stream aquifer seepage is simulated between each reach and the model cell that contains that reach. A stream is separated from the groundwater system by a layer of low permeability streambed material, and the stream aquifer inter connection is represented as a conductance through which 1 dimensional flow is assumed to occur. However, in many instances a discrete low permeability layer may not be present, in which case appropriate values of conductance must be
prescribed to represent these situations. The model of stream-aquifer interaction described here assumes the interaction is independent of the location of the stream reach within the cell, and that the stream level is also uniform over the reach and constant over the stress period. The use of a single conductance term to describe an essentially 3-dimensional flow process is a simplification, which requires adjustment during the calibration process. The parameters required to simulate stream-aquifer interaction for each designated stream cell in the model domain are stage, bed conductance and the streambed bottom elevation. In order to prepare this data file, a substantial amount of data collection and processing is required. The network of rivers and tributaries used for the MODFLOW model domain is shown in Figure 3.10. The rivers modelled for the Indus Basin model are the Indus, Jhelum, Chenab Ravi, Beas and Sutlej rivers which are listed in Table 4.3. Four major tributaries, Gomal, which flows into the Indus river, Jammu Tawi and Manawar Tawi, which flow into the Chenab upstream of Marala headworks, and Ravi Ujh, which flows into the Ravi (note Kurram is outside model boundary), will need to be processed later once stage or discharge information from these tributaries is obtained from WAPDA and/or PID. Alternatively if stage data is not available then the Source model can be used to provide stage data. Processing of the river package for the rivers was undertaken in a series of steps summarised below.

Note that initial River Package data input sets described below will be converted at a later stage to the Streamflow Routing Package, because SFR can be set to be mathematically identical to RIV, when setting particular flag to zero ([ICALC=0]). If ICALC is zero, SFR simulates seepage based on specified stage exactly the same way as RIV does. However, using SFR does open the door for future model modifications to simulate variable stage, flow, and seepage. The other advantage of converting RIV to SFR is that SFR allows the specification of conductance sub-terms individually, i.e., reach length and width, bed elevation, and vertical hydraulic bed conductivity, which allows for more flexibility during the calibration phase when keeping more or less certain parameters variable or fixed.

4.10.1 Rivers of the Indus Basin of Pakistan

The river discharge, gauge elevations, river bottom elevations and bed widths were obtained from data supplied by PIDA and from previous reports for the headworks on the Indus, Jhelum, Chenab, Ravi, and Sutlej Rivers. Although there are headworks on the river Beas, these are located in India and data for these gauges are not available. River flows are regulated by the headworks on the Indus (Jinah, Chashma, Tauns, Guddu, Sukkur, Kotri), the Jhelum (Mangla Reservoir and Rasul), the Chenab (Marala, Khanki, Qadirabad, Trimmu and Punjnad), the Ravi (Baloki and Sidhnai), and two headworks on the Sutlej (Sulemanki and Islam). The headworks were constructed to divert and control river flows and to regulate water supplies into the main canals in order to provide adequate water supplies for irrigated agriculture in the canal command areas.

The headworks on the Indus river system provide crucial discharge and stage data which is used for constructing the river package. At most of these gauging locations both upstream and downstream discharge and stage is measured daily. Much of this data is recent from 2000 onwards for Chenab and Ravi rivers, and from October 2001 for the Indus, Jhelum and Sutlej rivers. In order to construct the river package the data at the gauging station was utilised to develop monthly stage and discharge values for each gauge where data was available. Where missing data was encountered these data gaps were filled using long term monthly averages. Since the model run from October 1990 to September 2012, the data prior to October 2001 was estimated as follows:
Additional processing was undertaken at selected points along the river, namely at the start and end of the river cell in the model domain. As no data is available at these points the data was simulated by comparing elevation differences between the starting cell and the closest headworks. So, for instance, the starting river cell at the head of the river was simulated using data from the nearest headworks downstream, and for the ending river cell the closest headworks upstream from the tail end of the river was selected. A list of gauging stations for rivers in the Indus Basin is given in Table 4.3. Other information estimated was the width of the river and the depth of the river at each gauging station. The width was estimated from google maps, and the depth was estimated by comparing the stage at high and low discharge. These estimates can be improved after consultation with WAPDA, PID and SID as data at the headworks both upstream and downstream should exist as these are structures involved major engineering design studies and engineering construction. Backwater calculations for each of these structures should also be available which would provide good information at least in the vicinity of the headworks. One other crucial data obtained from GIS mapping was the reach length of the river in each of the model grid cells.

Once the stage at the start and end cells were simulated, both upstream and downstream discharge and gauge data on a monthly time step was used along with reach lengths for the rivers to estimate river stage along each model cell between the headworks. The interpolation is weighted according to the reach length in each river cell giving greater weighting at the start of the interpolation. This process is then repeated for each month to construct the river package for each monthly stress period. A total of 264 stress periods were simulated to construct the river package for MODFLOW.

To determine the flow between stream and aquifer the hydraulic conductance, $C$, of the stream aquifer interconnection of each cell needs to be specified:

$$C = \frac{K_r L w}{m} \tag{16}$$

Where: $K_r$ = vertical hydraulic conductivity of the bed sediment; $L$ = length of the stream reach; $w$ = width of the stream reach; $m$ = thickness of the bed.

Of the four variables in the conductance term, only the length of the river in the cell is known accurately, the width along the reach is estimated from head and tail sections. There is no easy or economical way of determining the vertical hydraulic conductivity of the stream bed ($k_r$) and the thickness of the stream bed accurately. In developing the Lower Murray groundwater model, Punthakey et al. (2001) determined river bed conductance by assuming a linear decay of $k_r$ along the river, starting with an estimated value at the upstream head of the river. The approach adopted here was to estimate the vertical hydraulic conductivity of the stream bed at head and tail sections and then using linear interpolation between gauging stations to generate a set of $K_r$ to calculate the conductance term. This approach allows one to adjust $K_r$ at gauging stations during model calibration and also affords greater control in adjusting the level of river aquifer interaction along selected river reaches. The procedure described here is used to construct a river file that allows the complex river network to be modelled, which can be included directly into MODFLOW. It is important to note that the process of constructing the river package offers a starting point to calibrate the model. During calibration river parameters can be adjusted and the river file reconstructed. Ideally, once the river
system is fully simulated in the SOURCE model, the stage obtained at each river cell can be updated to improve both accuracy but also integration of the SOURCE and MODFLOW models.

The model will not just be calibrated against observed groundwater heads, but also streamflow differences (i.e., seepage integrated between gauges, e.g., data received by PID) if the RIV package is used. After conversion to the SFR package, calculated stream stage, streamflow (e.g., discharge data from PID), and also streamflow differences (i.e., seepage integrated between gauges (e.g., data received by PID) can be calibrated against observations.

Table 4.3 List of Gauging stations used to create the river system for the Indus basin model

<table>
<thead>
<tr>
<th>No.</th>
<th>River</th>
<th>Location</th>
<th>row</th>
<th>col</th>
<th>Gauge Zero Width</th>
<th>Station file</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indus</td>
<td>Old Mari Indus</td>
<td>8</td>
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<td>211 360</td>
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<td>95</td>
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<td>94</td>
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<td>Beas</td>
<td>Beas at Railway Bridge (Main Line)</td>
<td>37</td>
<td>168</td>
<td>217.8</td>
<td>300</td>
<td>Rv_Be2Rb99.stg</td>
</tr>
<tr>
<td>47</td>
<td>Beas</td>
<td>Beas at Railway Bridge (Main Line)</td>
<td>37</td>
<td>167</td>
<td>215</td>
<td>300</td>
<td>Rv_Be3Rb99.stg</td>
</tr>
<tr>
<td>48</td>
<td>Sutlej</td>
<td>Harike (Pong Level at Harike)</td>
<td>45</td>
<td>161</td>
<td>205.2</td>
<td>650</td>
<td>Rv_Su4Hu99.stg</td>
</tr>
<tr>
<td>49</td>
<td>Sutlej</td>
<td>Harike (Pong Level at Harike)</td>
<td>46</td>
<td>161</td>
<td>201.2</td>
<td>650</td>
<td>Rv_Su5Hd99.stg</td>
</tr>
<tr>
<td>50</td>
<td>Sutlej</td>
<td>Border Ganda Singh Wala</td>
<td>49</td>
<td>154</td>
<td>191.4</td>
<td>600</td>
<td>Rv_Su6BG99.stg</td>
</tr>
<tr>
<td>51</td>
<td>Sutlej</td>
<td>Border Ganda Singh Wala</td>
<td>49</td>
<td>153</td>
<td>190</td>
<td>600</td>
<td>Rv_Su7BG99.stg</td>
</tr>
<tr>
<td>52</td>
<td>Sutlej</td>
<td>Sulemanki Barrage US</td>
<td>64</td>
<td>142</td>
<td>171</td>
<td>650</td>
<td>Rv_Su8Su11.stg</td>
</tr>
<tr>
<td>53</td>
<td>Sutlej</td>
<td>Sulemanki Barrage DS</td>
<td>64</td>
<td>141</td>
<td>170</td>
<td>120</td>
<td>Rv_Su9Sd12.stg</td>
</tr>
<tr>
<td>54</td>
<td>Sutlej</td>
<td>Islam Barrage US</td>
<td>77</td>
<td>117</td>
<td>135.7</td>
<td>500</td>
<td>Rv_Su10Uu21.stg</td>
</tr>
<tr>
<td>55</td>
<td>Sutlej</td>
<td>Islam Barrage DS</td>
<td>77</td>
<td>116</td>
<td>131</td>
<td>500</td>
<td>Rv_Su11Id22.stg</td>
</tr>
<tr>
<td>56</td>
<td>Sutlej</td>
<td>Sutlej Chenab Junction</td>
<td>88</td>
<td>88</td>
<td>101.6</td>
<td>350</td>
<td>Rv_Su12Ch99.stg</td>
</tr>
</tbody>
</table>
Considering the importance of water resources monitoring and management to the future food security and economic wellbeing of Pakistan, the table above highlights data gaps which need to be considered for expanding the existing monitoring program. The rivers are the arteries of the country providing water which is the lifeblood of the country. As part of this project an important policy outcome would be an evaluation of critical gauging stations on major rivers and tributaries. Additional gauging stations will help in collecting critical data which will reduce assumptions and reliance on simulated data which will lead to improved modelling efforts and improved information for policy analysts and water planners.

4.10.2 Canals of the Indus Basin

The canal network consisting of main and branch canals, distributaries, minors, sub minors and water courses is too extensive to model at a regional scale where grid scales are relatively coarse. To rationalise the modelling, a simplified network of main, link, and branch canals (see section 3.4.2) was used to simulate the canal-aquifer interaction, i.e., canal seepage. Input data for that were added on to the Streamflow Routing Package, simulating the rivers. Canal bed elevation were calculated using elevations retrieved from the 90m DEM along this course and averaged over the length of each canal reach within a MODFLOW cell. Errors resulting from human activity and/or vegetation along the canal levies were eliminated by smoothing the upstream-to-downstream canal slope with a moving average and filtering out negative slopes resulting from occasional higher elevations in downstream reaches.

The conductance term is calculated analogous to the conductance term of the rivers (equation (16)) and described there. Parameters bed width, bed thickness, and bed vertical hydraulic bed conductivity are more uncertain in this order. Therefore, bed conductance terms are variable during model calibration.

4.10.3 Outfall Drains in Sindh

The Left Bank Outfall Drain network, which acts as a sink for groundwater returnflows in southern Sindh, is simulated using MODFLOW’s Drain Package. Among the network, only the main stem “Drain Main” (Figure 3.12) is simulated. In this model, surface runoff from irrigated agriculture is considered minor and, hence, not explicitly simulated. If drain inflows from excess irrigation surface runoff, drain flows, or drain stages were known, an integration of the drain network into the Streamflow Routing Package would be preferable. However, as this information is not available, the simplest option is to calculate seepage of groundwater into drains driven by a gradient between the drainbed elevation and the aquifer head as well drainbed conductance.

Input parameters for the DRN package are the horizontal and vertical location as row, column, drainbed elevation as well the conductance of the drainbed. The course of the main LBOD drain was given by a Google-Earth KMZ-file provided by SID. Elevations retrieved from the 90m DEM along this course were averaged over the length of each drain reach within a MODFLOW cell. Note at the commencement of this study no 30m DEM was available. However, recently the Global terrestrial region of the ALOS Global Digital Surface Model “ALOS World 3D - 30m” (AW3D30) was made available (JAXA 2017). Changes in elevation along the drains by human activity or vegetation introduce a significant error in the estimate of drain elevations if the DEM resolution is too coarse.
The conductance term is calculated analogous to the conductance term of the rivers or canals (equation (16)) and described there. Parameters bed width, bed thickness, and bed vertical hydraulic bed conductivity are more uncertain in this order. Therefore, bed conductance terms are variable during model calibration. Note that in this model, branch drains are not simulated. That is, seepage from groundwater into the simulated “main drains” will also need to take into account the portion of the groundwater discharge related to branch drains in order to achieve a fit between simulated and observed groundwater heads. In that sense the final drainbed conductance is strictly spoken no longer a physically based parameter. Groundwater heads in the area of southern Sindh in the final model are expected to be highly sensitive. Small changes in input parameter may result very quickly in unrealistic heads above ground surface if drain returnflow are not conceptualized correctly.
5 Future Tasks and Outlook

At the current status of the IBIS groundwater model, the parameterization of several stress packages and external boundary conditions in Groundwater Vistas has not yet been fully completed. This includes recharge, canal and drain seepage, as well as general head boundaries. After finalizing the model construction, the next step is to run, debug, and calibrate the model, test its sensitivity, and analyse the model results. This insures that the model is robust enough for future scenarios. The second step is the quantification of surface water groundwater interaction internal to the MODFLOW groundwater model and between coupled MODFLOW groundwater and SOURCE rivers system models (CSIRO 2016c). This step entails a number of model scenarios to improve understanding of the water balance and sustainability of groundwater extractions. The final step is the selection and creation of child models in areas of local or provincial relevance and their coupling to the coarser resolution parent model. The purpose would be defined by local and provincial stakeholder, e.g., to assess storage potentials of individual doabs or canal command areas, better represent the distribution of crop water use, or for focused salinity analyses.

5.1.1 Delivering a robust IBIS groundwater model for Pakistan

This activity includes running, debugging, calibrating and analysing the model. The primary objective is to achieve successful model runs where simulated groundwater levels and stream-aquifer interaction are within reasonable convergence criteria and mass balance errors. To achieve this objective, multiple iterations between model runs, amending data or computation errors, or changing methods may be required.

The primary objective of calibrating the model is to insure that simulated water levels and stream seepage match historic observations with a reasonably good fit. A secondary objective is to investigate the sensitivity of simulations of head, storage changes, and stream/canal seepage to input parameters. The aim is to produce not just a calibrated, but robust model that can be used for various future scenarios or any other future use of the model. Predictions that are of interest for future uses are seepage along the conveyance network (for a linkage between SOURCE and MODFLOW) and inter-zonal flows or inter-zonal flows between subregional zones (for child models coinciding with zones).

Regional and subregional groundwater budgets of flows into and out the groundwater need to be created. The latter can be achieved using MODFLOW’s ZONEBUDGET. The budget analysis can demonstrate zones of groundwater storage depletion and the factors causing it. Subregional zones may coincide with doabs and or canal commands or also districts and are at the discretion of Pakistani partners or stakeholder. Water budget time series visualise trends of budget components (e.g., stream seepage or boundary flows) and serve as a management tool for stakeholders and partners in Pakistan to discern the severity of these trends in different areas.
5.1.2 Quantifying surface-water / groundwater interactions

The primary objective of the IBIS groundwater model is to better understand the interaction of shallow, quaternary, alluvial aquifers with surface water in irrigated areas. Of particular interest is the identification areas where groundwater usage could affect river streamflow (stream seepage capture). This analysis depends on the method of estimating groundwater usage and applying it to the model. For instance, if the usage were spatially distributed over an entire Doab, one would only expect shallow cones of depression without a major effect on river streamflow. However, scenarios of increased groundwater exploitation in particular areas may not only create deep and widened cones of depression, but may cause the pumping regime to switch from the depletion of the aquifer to depleting river streamflow. Once completed, the model is able to identify areas where groundwater pumping is at risk of depleting river streamflow.

Another focus of surface-groundwater interaction is the coupling of the SOURCE river system (CSIRO 2016c) to the MODFLOW groundwater model. Losses identified by the Indus-basin wide river system model will need to be verified by comparison with stream seepage calculated by MODFLOW prior to the actual linkage. The concept of the actual linkage is that SOURCE provides the simulation of stream stages and irrigation recharge and MODFLOW simulates stream seepage based on the SOURCE-simulated stage and recharge (Rassam et al. 2013). Facilitating the linkage requires writing an interpretative code as interface between the two models. This linkage helps support the building of a national integrated water resource plan for the IBIS through analyses of joint SOURCE/MODFLOW model scenarios.

Re-calibration of the MODFLOW model will become necessary as the parameterization of the model changes along the linkage process, for instance, because flows or stages used in SOURCE would also influence the seepage and head calculations in MODFLOW.
5.1.3 Engagement of Pakistani stakeholders in topics of local or provincial relevance

Finer-resolution child models can be created in areas of local or provincial relevance and coupled to the coarser resolution parent model. The child models can then be used to assess storage potentials of individual doabs or canal command areas and better represent the distribution of crop water use. They can also contain their own focused salinity analyses. Child models can be simulated either simultaneously with the surrounding Indus basin parent model or independently (i.e., disconnected from the parent). Initially, we suggest building a ‘pilot’ child model that re-uses the boundaries of zones, where MODFLOW’s ZONEBUDGET was used during the sensitivity and water budget analysis (e.g., Rechna Doab). Subsequently, other child models would follow and make use of lessons learnt from previous work.

Another objective of creating child groundwater models is to better understand the impact of groundwater development on fresh and saline groundwater areas. Solute transport models within fine resolution child models can highlight, where groundwater salinity in irrigated areas matters. Such child transport models in hotspots of salinity are more feasible than creating an Indus-basin wide ‘variable density’ transport model would have to include the estuarine areas of the delta with salinity concentrations close to seawater. The solute transport child models should be implemented based on smaller irrigation-command-scale child flow models that are embedded in an Indus-basin wide parent model. The creation of solute transport child models and their calibration is subject to the availability of water quality data sets.

Child models, whether flow or transport, need to be calibrated. Re-calibration of the parent model may be necessary, because the parameterization of the parent model may change along the child modelling process or if the propagation of changes in flows across the parent-child boundary causes significant changes in the parent model results. Re-calibration of the parent model is also needed when new data become available and the model is updated. This task is essential to keeping the model current. The creation of solute transport child models and their calibration is subject to the availability of water quality data sets.

Local and provincial stakeholders, e.g., the PID and SIS, should select and create the child models tailored to their purpose. For instance, decisions would need to be made on whether doab-level child models are chosen to highlight sections of stream capture along certain rivers or rather where spatially distributed crop consumptive use is better known.
6 Assumptions and Limitations

The development of the model described underlies certain budgetary and time constraints, which demanded a low complexity implementation in MODFLOW. This involved making some assumptions and making use of limited data. Assumptions were that the dependency of crop irrigation requirement, irrigation supply, and returnflow on the aquifer head or flooding can be ignored. Groundwater demand and supply are assumed to be synonymous. Surface-water deliveries are specified and not simulated as routed deliveries. Stream seepage is simulated, but based on specified, not simulated, stream stages. Evapotranspiration from groundwater is simulated, but not included as component of crop consumptive use. ETgw is assumed to reach a maximum, when the water level is at the ground surface. The base of the aquifer was constructed using borelog lithology data of available bore holes, which were not distributed uniformly across the entire domain and did not always fully penetrate the alluvium. Data for a corridor between the international border with India and the eastern model boundary are not available with the exception of climate data and, hence, no groundwater pumping requirements are calculated for this portion of model. Digital elevation model data are based on a 90m DEM as no 30m DEM was available at the commencement of the study.

6.1 Fit-for-purpose Methodology

Despite assumptions made and certain data limitations, we believe that the present model will be fit-for-purpose to deliver on its primary focus, which is the interaction between surface water and shallow groundwater, a better understanding of groundwater dynamics and of groundwater budgets on a regional and sub-regional scale, and to provide boundary conditions for finer resolution flow and solute-transport child models (e.g., doab or command areas). The limitations described below are not expected to cause major differences in these deliverables or overall and sub-regional budgets. However, as we cannot foresee model results at this point, they are listed for transparency and to aid partners in Pakistan in aspects that may need improvement in the future.

6.2 Methodology limitations

This model pre-estimates irrigation pumpage and recharge external to MODFLOW and does not take into account the beneficial or detrimental influence of shallow groundwater as a contribution to or impediment for crop consumptive use or as a trigger for rejected infiltration. This may have direct consequences for flows that depend on the calculated crop irrigation requirements. For instance, if uptake from groundwater anoxic conditions under the influence of shallow groundwater is dominant, the surface- or groundwater deliveries will be smaller, because the crop water demand is already satisfied by ETgw (eq. (4)). If anoxic conditions under the influence of shallow groundwater or during flooding events prevail, the surface- or groundwater deliveries will also be smaller, because irrigation is not needed under growth-impeding conditions where crop ET is reduced (eq. (4)).

We do not expect the beneficial and detrimental influence of shallow groundwater to significantly alter the results simulated by the EVT package, but – as outlined above – it could introduce errors in the calculation of groundwater irrigation pumpage specified in the WEL package:
• While, in this model, evapotranspiration from groundwater (ETgw) is ignored as contributor to the crop water demand, it is indeed accounted for through the use of the EVT package. In the EVT package, ETgw is assumed to linearly increase from an extinction depth to a maximum at the surface, where it reaches the spatial and temporally distributed Hargreaves reference ET. Ignoring the contribution from ETgw as a contributor to the crop water demand is justified unless phreatophytic uptake is quite high and, in turn, the needed groundwater irrigation pumpage specified in the WEL package is much reduced. In such a case, ignoring the contribution from ETgw would lead to a much higher groundwater irrigation pumpage term, which, together with the already high ETgw-term in the EVT package, would lead to an overestimation of drawdown.

• The assumption of a maximum of ETgw to be equal to the Hargreaves reference ET when the water level reaches the surface may be problematic. This is the case especially when transpiration is actually near zero for certain crops with little tolerance for anaerobiosis under water logging or flooding conditions (i.e., not an issue for rice tolerant to near-saturation or ponding conditions). However, since, in this model, we do not separate transpiration and evaporation, ETgw simulated by the EVT package would still account for most of the reference ET if the water level reaches the surface even though transpiration under anoxic conditions is reduced. Ignoring the reduction of the crop water demand by the detrimental effect of shallow groundwater, water logging, or flooding to the crop water demand is justified unless it leads a shut-down of crop consumptive use and, in turn, the needed groundwater irrigation pumpage specified in the WEL package is no longer needed. In such a case, ignoring the reduction of crop water demand would lead to much higher groundwater irrigation pumpage term, which, together with the already high ETgw-term in the EVT package, would also lead to an overestimation of drawdown.

Recharge or runoff from inefficient irrigation losses are also altered if the calculated applied irrigation varies with varying groundwater heads. That is, recharge from excess irrigation will be smaller if crop irrigation requirements are reduced through the beneficial uptake from shallow groundwater. Recharge from rainfall also can depend on the groundwater level in the sense that shallow groundwater or water logging or flooding prevents any recharge, since the infiltration will be rejected. Recharge in this model also does not account for delayed recharge through the unsaturated parts of dewatered aquifers. Note that in this model, we neglect the portion of inefficient losses from irrigation or precipitation to surface runoff due to the domination by basin-level irrigation in the IBIS.

A dynamic synchronization of crop irrigation requirement, water supply deliveries, and returnflows is possible in MODFLOW, but requires MODFLOW methods of a higher level of complexity, which for this project, was not feasible within budgetary and time constraints. For this model, we do not expect, but cannot exclude that beneficial uptake or detrimental influence of shallow groundwater matters (e.g., in southern Sindh). In contrast, depleted aquifers (e.g., in Bari Doab) may experience a delay in recharge, yet is probably not relevant in the large-scale long-term regional model. If the dependency of deliveries, returnflows, or recharge on groundwater heads led to significant inaccuracies in the water balance or model convergence issues, then a more complex MODFLOW tool, such as the Farm Process for MODFLOW (Schmid et al. 2006; Schmid and Hanson 2009; Hanson et al. 2014) could address these issues and would replace the well (WEL), recharge (RCH) and evapotranspiration (EVT) packages.
In this model, groundwater demand and supply (i.e., groundwater pumping requirements and groundwater pumping) are assumed to be synonymous. Groundwater pumping is not constrained by maximum well capacities or groundwater allotments. Similarly, the routing of surface-water deliveries to the MODFLOW cells is specified, but not simulated and the deliveries are not constrained by any surface-water allotments or rights within a canal command area. Shortfalls of surface water or groundwater supply caused by droughts or water rights are not addressed. That is, the model assumes that in controlled irrigation settings, such as the IBIS, no significant deficit between demand and supply occurs and the demanded water is indeed supplied. Therefore, any drought response to such a deficit irrigation scenario cannot be simulated, unless the model is upgraded using more complex tools to adjust the crop water demand to constrained supplies, if supply is less than demand. In essence, the low-complexity model described herein is a supply-driven system, but not a demand-driven and supply-constrained system, which is however fit-for-purpose to deliver on its primary focus, which is the interaction between surface water and shallow groundwater, a better understanding of groundwater dynamics and of groundwater budgets on a regional and sub-regional scale, and to provide boundary conditions for finer resolution flow and solute-transport child models (e.g., doab or command areas). A more complex model would integrate the simulation of movement and use of all the water everywhere and all of the time in demand-driven and supply-constrained systems of fully coupled land use/surface-water/groundwater with budgets over water accounting units of stakeholders’ choosing (Hanson et al. 2014). Surface-water deliveries to MODFLOW cells are MODFLOW-externally pre-processed and derived from diversions for each canal command areas reduced by assumed conveyance losses within one canal command area. The assumption of these conveyance losses is based on parameters from the literature (FAO 2011; Basharat 2013). A portion of these conveyance losses are the inefficiencies of major canals. These inefficiencies of major canals play a role in the calculation of surface-water deliveries, but canal seepage from major canals is also simulated by this model. This simulated canal seepage of major canals may be temporally or locally higher than the assumed lumped conveyance losses. The simulation of seepage from rivers and canals is, at this point, simulated by the River Package (RIV), which requires stage data as input and does not allow for a simulation of variable stages and flows. In the future, such stage data can be provided by a linked SOURCE river system model (CSIRO 2016c). The RIV package data input set can be upgraded to the more up-to-date Streamflow Routing Package (SFR) without any changes to the results, because SFR can be set to be mathematically identical to RIV. That is, SFR can also simulate seepage based on specified stage exactly the same way as RIV does. However, SFR can also be set to simulate variable stage, flow, and seepage if needed. In areas where surface-water gradients are very small (e.g., in southern Sindh), the even more advanced Surface-Water Routing (SWR) Process (Hughes et al. 2012) is available to accurately simulate stages, surface-water flows, and surface-water/groundwater interactions using a simplified form of the Saint-Venant equations for hourly to daily time steps. SWR can account for surface-water flow controlled by backwater conditions caused by small water-surface gradients, overbank flooding, and surface-water control structures (such as culverts, weirs, and pumps).

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1 In this context, “movement” means all land-use and hydrologic processes & flows; “use” means “demand for and supply of conjunctively used surface- and groundwater; “all the water everywhere and all of the time” means that no mass is lost within the simulation space/time domain; “demand-driven” means demand driven by climate, crop type, aquifer head, other supply components (residual demands depend on prior supply components); “supply-constrained” means supply components are surface water, groundwater, other supply types (imported, trucked, recycled water) constrained by physical, socioeconomic, and ecological properties, conditions, and requirements; “budgets over water accounting units” means budgets over zones of interest of stakeholder’s choosing, e.g. supply/demand budgets, physical budgets (e.g., groundwater budgets, farm budgets).
However, SWR cannot replace hydrodynamic models that solve the full Saint-Venant equations and are applied to event simulations such as flooding event with dam break evaluations (sub-hourly time steps). Both the SFR and SWR package are linked to the Farm Process through routed surface water deliveries from SFR or SWR features to water accounting units and through runoff from those units back to SFR or SWR features in form of inefficient losses from irrigation/precipitation or rejected infiltration or groundwater discharge to surface water into a stream network (Hanson et al. 2014).

6.3 Data limitations

The base of the aquifer derived was constructed using borelog lithology data of available bore holes. It is an approximation in the sense that many bores did not fully penetrate the alluvium. It also did not include information on the alluvium in areas outside the canal command areas, e.g., near major rivers, where the alluvium may be much deeper as the aquifer base in the model. In addition, some areas exhibited no or sparse borelog lithology data, such as Chaj Doab in northern Punjab, or Kotri Left Bank in southern Sindh. Conversely, depth-dependent groundwater quality data were generally available along with borelog lithology data from the 1960s obtained from WAPDA for this study. However, digitizing these data was beyond the scope and budget and is more relevant for solute transport modelling at a future stage.

Water level observations were also sparse to non-existent in areas outside the canal commands, that is, in riverine areas, in areas between outer boundary of the active model domain and the canal command, and in the fringe between the international border and the eastern boundary. The international border with India cuts through the alluvial Indus basin aquifer and is not suitable as a boundary condition. Assumed general head boundary conditions were moved further east to the Beas River encompassing the western portion of the Indian State of Punjab. However parameterizing this GHB may be difficult without the knowledge of water levels in this areas. In addition, at this point, no groundwater pumping requirements are calculated for this portion of model. Data for this region are unavailable with the exception of climate (rainfall, evapotranspiration), but groundwater pumping could be approximated based on assumptions for agricultural and urban water use.

Ground surface elevation in this model were derived from a 90 meter Digital Elevation models. Elevations from the 90m DEM along the course of rivers, canals, and one drain were averaged over the length of each reach within a MODFLOW cell to obtain bed elevations. Inaccuracies caused by vegetation and structures along the course of rivers and canals could easily be corrected due to dominant slope. However, changes in elevation by human activity or vegetation introduce a significant error in the estimate of drain elevations if the DEM resolution is too coarse. However, this is only an issue along the Left Bank Outfall drain (LBOD) in southern Sindh, where slopes are very small. Note that at the commencement of this study no 30m DEM was available. However, recently the Global terrestrial region of the ALOS Global Digital Surface Model "ALOS World 3D - 30m" (AW3D30) was made available (JAXA 2017), which may be suitable for model upgrades.
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FOR FURTHER INFORMATION

LAND AND WATER
Wolfgang Schmid
t +61 2 6246 5793
e wolfgang.schmid@csiro.au

LAND AND WATER
Mobin-ud-Din Ahmad
t +61 2 6246 5936
e mobin.ahmad@csiro.au