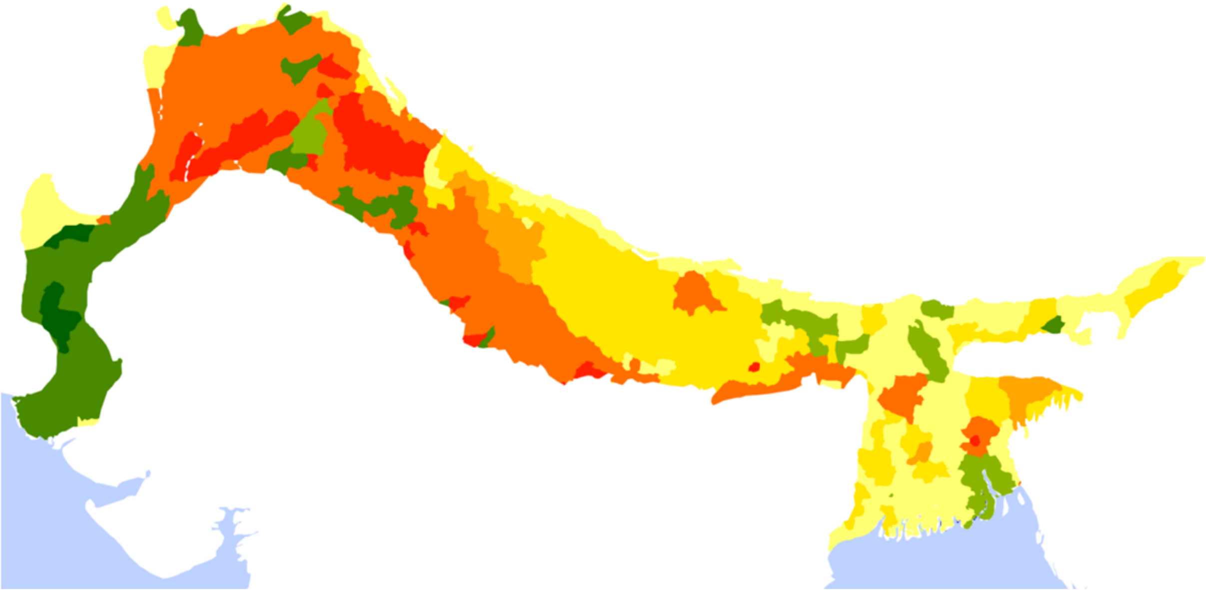
IGB GROUNDWATER RESILIENCE

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UKaid
from the British people

Groundwater resources in the Indo-Gangetic Basin

Resilience to climate change and abstraction



Collaborating organisations:

British Geological Survey
IIT Kharagpur
ISET-Nepal
ISET International
MetaMeta
National Institute of Hydrology (Roorkee)
Overseas Development Institute
University College London
University of Dhaka
Bangladesh Water Development Board

British Geological Survey Open Report

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (WELSH publications only) see contact details below or shop online at **www.geologyshop.com**
The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.
We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.
The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.
The British Geological Survey is a component body of the Natural Environment Research Council.

Version date
31 July 2015

Keywords
Indo-Gangetic Basin; groundwater; resilience; abstraction; climate change.

Front cover

Map of long-term trends of groundwater level change across the Indo-Gangetic Basin, developed by the project.

Bibliographical reference

MacDonald AM, Bonsor HC, Taylor R, Shamsudduha M, Burgess WG, Ahmed KM, Mukherjee A, Zahid A, Lapworth D, Gopal K, Rao MS, Moench M, Bricker SH, Yadav SK, Satyal Y, Smith L, Dixit A, Bell R, van Steenbergen F, Basharat M, Gohar MS, Tucker J, Calow RC and Maurice L. 2015. Groundwater resources in the Indo-Gangetic Basin: resilience to climate change and abstraction. *British Geological Survey Open Report*, OR/15/047, 63pp.

Copyright in materials derived from the British Geological Survey's work is owned by the Natural Environment Research Council (NERC) and/ or the authority that commissioned the work. You may not copy or adapt this publication without first obtaining permission. Contact the BGS Intellectual Property Rights Section, British Geological Survey, Keyworth, e-mail **ipr@bgs.ac.uk**.

© NERC 2015. All rights reserved Keyworth, Nottingham. British Geological Survey 2015.

Acknowledgements

This work was funded by the South Asia Research Hub of the UK Department for International Development (DFID). The research group are indebted to the DFID staff managing this project, Dr Guy Howard, Dr Anirbun Ganguly, and Jean-Marion Aitken, and the additional members of the Steering Group chaired by Prof Stephen Foster (GWP & IAH) for their invaluable overview and advice: Prof Ashvin Gosain (Indian Institute of Technology, Delhi), Prof Declan Conway (London School of Economics and Political Science); Dr Sardar Tariq (Pakistan Water Partnership), Dr Vidisha Samarasekara (Asian Development Bank), and Prof Feroze Ahmed (Institute of Water and Flood Management, BEUT, Bangladesh). Particular thanks also go to Dr Cliff Voss (U.S. Geological Survey) and Andy McKenzie (BGS) for their individual advice and input to the project outputs.

Special thanks also to BGS staff: Dr George Darling and Dr Daren Gooddy for help with analysis and interpretation of residence time indicators; Debbie White for providing invaluable assistance to the organisation of field equipment; Craig Woodward and Keith Henderson for all their help with illustrating the research, and James Gamgee, Martin Brown and David Adam for overseeing much of the project administration.

Executive Summary

Groundwater within the Indo-Gangetic Basin (IGB) alluvial aquifer system forms one of the world's most important and heavily exploited reservoirs of freshwater. In this study we have examined the groundwater system through the lens of its resilience to change – both from the impact of climate change and increases in abstraction. This has led to the development of a series of new maps for the IGB aquifer, building on existing datasets held in Pakistan, India, Nepal and Bangladesh, a review of approximately 500 reports and papers, and three targeted field studies on under-researched topics within the region. The major findings of the study are described below.

The IGB groundwater system

1. The IGB alluvial aquifer system comprises a large volume of heterogeneous unconsolidated sediment in a complex environmental setting. Annual rainfall varies from <25 mm per annum in southern Pakistan to > 2000mm in the Bengal basin, and the system is dissected by the major river systems of the Indus, Ganges and Brahmaputra. The groundwater system has been modified by the introduction of large scale canal irrigation schemes using water from the Indus and Ganges since the 19th and early 20th centuries.

2. High yielding tubewells can be sustained in most parts of the alluvial aquifer system; permeability is often in the range of 10 – 60 m/d and specific yield (the drainable porosity) varies from 5 – 20%, making it highly productive.

3. High salinity and elevated arsenic concentrations exist in parts of the basin limiting the usefulness of the groundwater resource. Saline water predominates in the Lower Indus, and near to the coast in the Bengal Delta, and is also a major concern in the Middle Ganges and Upper Ganges (covering much of the Punjab Region in Pakistan, southern Punjab, Haryana and parts of Uttar Pradesh in India). Arsenic severely impacts the development of shallow groundwater in the fluvial influenced deltaic area of the Bengal Basin.

4. Recharge to the IGB aquifer system is substantial and dynamic, controlled by monsoonal rainfall, leakage from canals, river infiltration and irrigation returns. Recharge from rainfall can occur even with low annual rainfall (350 mm) and appears to dominate where rainfall is higher (> 750 mm). Canal leakage is also highly significant and constitutes the largest proportion of groundwater recharge in the drier parts of the aquifer, partially mitigating the effects of abstraction on groundwater storage.

5. Deep groundwater (>150 m) in the Bengal basin has strategic value for water supply, health and economic development. Excessive abstraction poses a greater threat to the quality of this deep groundwater than climate change. Heavy pumping may induce the downward migration of arsenic in parts of Bangladesh, and of saline water in coastal regions, but field evidence and modelling both suggest that deep groundwater abstraction for public water supply in southern Bangladesh is in general secure against widespread ingress of arsenic and saline water for at least 100 years.

IGB Groundwater typologies

The IGB alluvial aquifer system has been divided into seven major and four minor typologies each with different characteristics which define how resilient groundwater is to change. These typologies are: 1. The piedmont margin; 2. The Upper Indus and Upper-Mid Ganges; 3. The lower Ganges and Mid Brahmaputra 4, the fluvial influenced deltaic area of the Bengal basin; 5. The Middle Indus and Upper Ganges; 6. The Lower Indus; and 7. The Marine influenced deltaic areas.

Summary table of the different typology environments

	permeability	**storage (Sy)**	**thickness (m)**	**Salinity**	**arsenic**	**Recharge** *mechanism*	**abstraction**	**Water-levels**
Piedmont margin	High	V High	<100	No	local	High *rainfall*	Mod	stable
Upper Indus and Upper-Mid Ganges	V High	High	>200	local	local	High *rainfall canals*	V High	Variable mostly falling
Lower Ganges and Mid-Brahmaputra	V High	High	>200	No	local	High *rainfall & rivers*	Variable	Shallow mostly stable
The fluvial influenced deltaic area of the Bengal basin	High	Mod	>350	No	V High *Low at depth*	High *rainfall*	High	Shallow mostly stable
Middle Indus and Upper Ganges	High	High	200	Yes	local	Moderate *canals & irrigation*	High	Mostly falling rapidly
The Lower Indus	Mod	Mod	200	Extensive	local	Moderate *canals & irrigation*	Low	Rising
The marine influenced deltaic areas	Mod - Low	Low	350	Extensive	local	variable	at depth Bangladesh	Shallow and Variable

Groundwater abstraction and groundwater levels

Data on groundwater abstraction and groundwater levels have been collated from national datasets, regional studies and analysis of data from a subset of individual tube wells with the best available data on groundwater level variations.

6. Groundwater abstraction across the IGB alluvial aquifer system is high, 205 km^3 (20 – 25% of global groundwater abstraction) and estimated to be rising at 2 – 5 km^3 per year. Abstraction occurs through an estimated 15 – 20 million tube wells. Abstraction is not evenly spread, but concentrated in the Indian States of Punjab and Haryana, the Punjab Region of Pakistan, and northern Bangladesh. Ninety percent of abstraction is used for irrigation. Hotspots of intense abstraction are also associated with major cities, most noticeably Dhaka, Lahore and New Delhi.

7. Groundwater levels within the IGB alluvial aquifer system are typically shallow: < 5 m below ground surface with important exceptions. In areas of high groundwater abstraction in north west India and the Punjab in Pakistan, groundwater levels can be 20 – 50 m bgl and are falling at rates of 0.5 – 1 m/yr. In similar areas of high irrigation abstraction within Bangladesh, groundwater levels remain shallow (<10 m bgl) due to much higher recharge. Groundwater levels are deep and falling in many urban areas, and particularly in large groundwater dependant cities. Rising groundwater levels can be found in the Lower Indus, parts of the Bengal basin and in places throughout the basin as a consequence of leakage from canals and rivers and from irrigation returns. Throughout much of the rest of the basin, groundwater levels are relatively stable.

8. At the scale of an individual canal command, there is considerable spatial variation in groundwater levels with evidence of groundwater levels in individual wells rising or falling within several kilometres. In general, groundwater levels are likely to be rising or stable at the head of a canal command where leakage is high and abstraction generally less, and falling towards the end of a canal command, where abstraction is greater and there is less canal water available.

9. There has been considerable change to the groundwater levels within the IGB over the last 150 years. The widespread construction of canal systems in the Indus and Ganges in the 19th and early 20th centuries led to rising groundwater levels and water-logging as early as 1875. Current groundwater depletion should, therefore, be viewed in the wider context of past groundwater accumulation and water-logging.

Resilience to future climate and abstraction: trends in groundwater storage and quality

With uncertainty about future precipitation and the likelihood of continued increases in abstraction, impacts on the groundwater resource are best investigated by assessing its resilience to change. Groundwater resilience to change is governed by the volumes of freshwater in storage, the permeability of the aquifer system and likely long term recharge (Foster and MacDonald 2014).

10. Groundwater storage within the top 200 m of the aquifer is in the order of 30,000 ± 10,000 km^3 with approximately 7,000 km^3 having salinity greater than 1000 mg/L. This compares to average annual flow in the rivers within the basin of 1,000 – 1,500 km^3 per year, and estimated current recharge of approximately 200 km^3. This large volume of groundwater storage offers significant buffering to short term changes in abstraction and climate variability. However, even small declines in groundwater levels within the aquifer can impact aquatic ecosystems and river flows, and restrict access for those relying on shallow wells.

11. Estimates of trends in groundwater storage for the IGB alluvial aquifer system, derived from ground based measurements of groundwater levels and estimates of specific yield, indicate a net average annual groundwater loss of 10 km^3 with significant variation across the basin. The largest depletion occurs in the areas of high abstraction and consumptive use in northern India and northern Pakistan, where between 25 and 150 mm of groundwater can be depleted annually, and in the Middle Indus and Upper Ganges typology where depletion is generally 10 – 25 mm. Across the rest of the basin changes in groundwater storage are generally modest (±2 mm), apart from in the Lower Indus where rising groundwater levels and waterlogging are ongoing issues.

12. In the future, given current forecasts of future rainfall and river flow, groundwater recharge is likely to be maintained within the bounds observed through current climate variability. A greater risk to groundwater recharge is posed by changes to canal leakage, which provides a large proportion of groundwater recharge in drier areas. For example programmes to line tertiary irrigation canals in areas where leakage does no flow to saline sinks, could significant impact the groundwater balance.

13. Degradation of water quality in the IGB aquifer system is a major concern, and is likely to pose a greater threat than widespread depletion. There is evidence of increased areas subjected to salinization due to both phreatic salinization from shallow water tables and water-logging and excessive pumping mobilising older saline groundwater within the drier and coastal typologies in the basin. There is evidence that the recycling of irrigation water and contamination from agricultural and industrial chemicals are leading to degradation in groundwater quality, which can only be abated through changes to land use planning, agricultural practices and industrial controls.

14. Two field studies within this project have shown the variation in response of deep groundwater in different parts of the IGB aquifer system. In the Bengal basin, abstraction from deeper groundwater beneath shallow, arsenic-contaminated groundwater has not led to vertical leakage and recharge from shallow groundwater at a regional scale, but there is evidence of localised leakage around some individual abstraction tubewells. In the upper Indus, however, where the aquifers are more isotropic and low permeability layers less extensive, deeper abstraction has led to increased recharge from shallow groundwater and anthropogenic contaminants being drawn deeper into the aquifer.

15. A third field study in the Middle Hills of the Himalayas, demonstrated that groundwater has an important function in regulating river flows in the headwaters of the IGB and also

provides reliable water supplies for domestic use and irrigation. There remains a high reliance on springs in higher valley regions and these depend on seasonal rainfall with a smaller proportion of discharge from older (possibly decade-old) baseflow. Therefore, although much of the spring flow is not resilient to climate change, some water may still be available through drier years.

16. Many of the cities within the IGB (such as Lahore, Dhaka and New Delhi) are dependent on groundwater. The intensity of both private and public abstraction required to meet growing water demand has led to rapidly declining water-levels within the cities, a problem compounded by contamination from industrial pollutants and sewerage. These city supplies are unsustainable, and strategies will need to be developed to manage demand, control pollution and to augment city pumping with surface water or groundwater from outside urban areas.

Implications for policy

The issues and challenges of managing groundwater in IGB alluvial aquifer system are recognised by the regulatory authorities in each country. Given the volume of abstraction, the large number of private tubewells, and the transboundary nature of the resource, groundwater governance is highly complex. This is compounded by the impact of government policies outside the water sector – particularly in agriculture and energy – which have a major influence on the use of groundwater and pollution loads. Within this section we highlight some of the particular aspects of the groundwater system that will impact on emerging policies for managing groundwater. A central issue is ensuring that the resources and regulatory focus are sufficient to match the scale of the challenge.

Groundwater is more vulnerable to abstraction than climate change. Currently groundwater level change and water quality is being driven by abstraction rather than climate change. Given the current forecasts for future climate and river flows, it is likely that abstraction will remain the main driver of change within the basin.

Groundwater storage, permeability and resilience to change. The groundwater system is characterised by extensive storage – many times greater than the annual volume of groundwater abstraction, and potentially 20 times the annual flow of the river systems. This provides an important buffer to change, although declining groundwater levels can have devastating impacts on aquatic ecosystems and significantly reduce access to groundwater.

Adaptive management: the spatial and vertical heterogeneity of the groundwater system. The study has shown that there is considerable variation in the nature of the aquifer, recharge and quality of groundwater across the IGB aquifer systems. The groundwater typologies developed in this study can be used to help formulate appropriate management strategies for different parts of the IGB aquifer system. Each typology presents its own unique set of challenges and opportunities for groundwater development. The typologies could be used to help prioritise and tailor programmes of groundwater monitoring, exploration and investigation, and inform future groundwater development and management strategies. They can also be used to help identify areas where there is potential for increased groundwater abstraction.

Degradation in groundwater quality is a greater concern than depletion. Most research has focussed on documenting depletion in the IGB aquifer system using remote sensing. However, the increases in salinity driven by irrigation and abstraction, and the contamination of groundwater from both agriculture and industry, pose bigger degradation threats than aquifer depletion.

Deeper groundwater in the Bengal basin. The deep groundwater in the Bengal Basin is a vital source of good quality groundwater in a context where shallow water is contaminated by arsenic. There is little evidence of modern recharge or widespread downward movement of shallow groundwater into this deeper aquifer (although individual abstraction wells can draw down shallow water). Given the finite nature of this resource, its continued use for drinking water should be carefully monitored and managed.

Canal leakage dominates groundwater recharge in drier areas. In much of the drier parts of the aquifer, canal leakage is an important source of recharge to the aquifer. While policies to line canals and reduce leakage may therefore have a positive impact on water delivery and crop productivity, they may have a negative impact on the groundwater balance. Attempts to save water should therefore focus on reductions in non-beneficial consumption, with channel lining restricted to those areas where return flows are lost to further use, or threaten the quality of drinking water or key environmental flows.

Urban groundwater. High rates of abstraction have resulted in local depletion in some cities with groundwater levels falling rapidly (>100 m depth in some locations). In addition, widespread contamination from both sewerage and industrial pollutants has degraded shallow groundwaters, although stratification of the aquifers helps protect some of the deeper groundwater. Maintaining good quality groundwater supply in the largest cities will therefore become more difficult over time unless steps are taken to address degradation threats within cities, and develop protected urban well fields beyond them.

The importance of monitoring. Changes in groundwater quality and groundwater storage within the IGB aquifer system will generally be gradual, and monitoring should provide adequate warning of adverse effects, giving time for a managed response. Continued exploration, testing and monitoring of shallow and deeper groundwaters across the aquifer system is needed to enable timely management systems to be developed to identify and mitigate further degradation.

Contents

1 Introduction

The Indo Gangetic Basin (IGB) alluvial aquifer system is one of the world's most important water resources. Formed with sediments eroded from the Himalayas and redistributed by the Indus, Ganges and Brahmaputra rivers, the IGB forms a flat fertile plain across Pakistan, northern India, southern Nepal and Bangladesh – Figure 1. The groundwater abstracted from the aquifer system comprises approximately a quarter of the world's total groundwater abstraction (Wada 2010, Seibert 2011) with more than 90% used for irrigation which underpins the dramatic agricultural success of the region (Shah 2009). The IGB alluvial aquifer system has been regarded as comprising one highly permeable continuous aquifer, and is often represented as one category on hydrogeological maps (Struckmeier and Richts 2008; CGWB 2012). However, in practice the system is complex and heterogeneous with large spatial differences in groundwater recharge, permeability, storage and water chemistry. This complexity controls how each part of the aquifer responds to current and future stresses.

There are an estimated 15 - 20 million[1] tubewells accessing groundwater from the IGB and this number continues to grow as farmers increasingly intensify agricultural production, and more water intensive crops such as sugar cane are grown. The area is also home to the largest surface water irrigation system in the world, with evidence of irrigation practices occurring for several thousand years, and the construction of large canals during the 19th and early 20th century taking water from the Indus and Ganges and distributing it through a network >100,000 km long. This long history has had a profound impact on the groundwater, and current trajectories of increased groundwater use and agricultural activity have led to legitimate questions about future sustainability of this abstraction (Shah 2009). Already there is evidence of declining groundwater levels (Shamsudduha et al. 2012, CGWB 2014), extensive salinization of shallow groundwater (Quereshi et al. 2008, Yu et al. 2013), concerns over the mobilisation of natural occurring arsenic (Nickson et al. 1998, Fendorf et al. Science 2010), and increasing concentrations of nitrate in the groundwater (Agrawal et al. 1999, CGWB 2010). Compounding these threats is the uncertainty introduced by climate change and the potential for significant change to precipitation, river flows and groundwater recharge (Immerzeel 2010, Turner and Annamalai 2012, IPCC 2013, Taylor et al. 2013).

To continue to develop and use groundwater, while minimising the unwanted side effects, it is important to first understand the aquifer systems and how they respond to abstraction, pollution and climate variability (Foster and MacDonald 2014). To help this process we have developed a series of groundwater typologies for the Indo Gangetic Basin, highlighting areas which are likely to respond in a consistent manner, regardless of international boundaries. In doing so, we have developed several basin wide data sets: building on the geology and sedimentology of the basin; using national datasets of groundwater abstraction, water level change and chemistry; drawing on international climate data; and reviewing many

---

[1] Estimated 8-12 million in Bangladesh (Khan et al. 2007, Holly and Voss 2009); approx.1 million in Sindh and Punjab in Pakistan (Yu et al. 2013); estimated 6 – 7 million in aquifer within India in 2007 (GOI 2012; Rawat and Mukherji 2012)

individual studies, publications and datasets. We do not consider here the many different approaches to governing groundwater across the region; rather, by systemising information on the nature of the aquifer, the current pressures on it, and the resilience of groundwater to change, we provide information that should be useful in assessing the efficacy of current and future approaches to groundwater management.

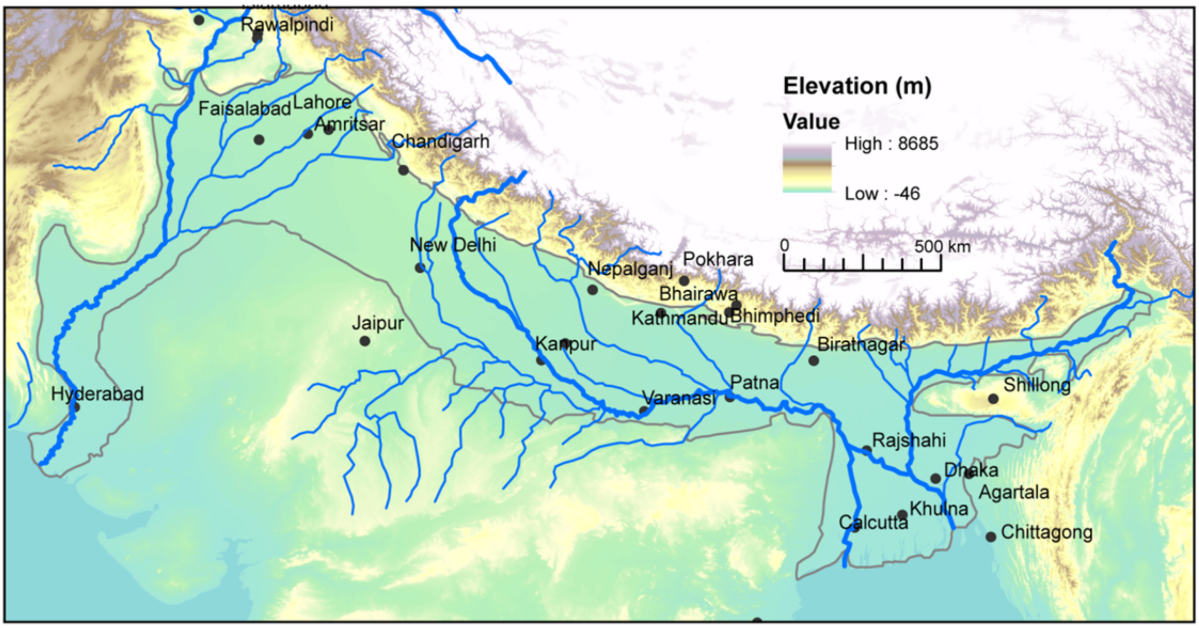


Figure 1 – Location map of the IGB with rivers and digital elevation map

2 Methods

Developing the groundwater typologies

The groundwater typologies reflect differences in aquifer properties, hydrology and climate, which affect the available groundwater storage, recharge and groundwater chemistry in the IGB aquifer system. The typologies were developed from combining together the best available national, regional and local-scale datasets and studies on the geology, sedimentology, aquifer properties, groundwater chemistry, hydrology and climate of the basin. Over 500 studies were reviewed in total – 56 of these focused on geological information; 415 hydrogeological studies and datasets; and 42 relating to climate and hydrological studies. The 80 studies which provided the highest quality systematic regional data form the key benchmark papers for the typologies.

Different processes of alluvial sediment deposition have operated across the basin through time and fundamentally determine the aquifer properties of the IGB. The characteristics of the sedimentology were mapped out for the top 200 m of the basin's alluvium to form a basis for the hydrogeological typologies; this process incorporated a review of geological and sedimentological literature and parameterised with information on likely grain size and modes of deposition. Specific yield (the drainable porosity) was mapped across the basin using available grain size distribution for the top 200 m of alluvium, and validated with several key hydrogeological studies of specific yield undertaken in different parts of the basin. Differences in transmissivity were mapped using a combination of primary data from pumping tests (mainly in Pakistan and India) and a review of existing studies within the area. From this framework broad areas of similar hydrogeological properties could then be identified.

Groundwater chemistry for the IGB alluvial aquifer system was mapped by considering the distribution of elevated concentrations of salinity and arsenic in groundwater, the two most significant water quality issues within the basin. Groundwater salinity was mapped by compiling existing information from hydrogeological maps, with more specific local-scale data studies and literature. In Pakistan, the published hydrogeological maps and drainage atlas were used (WAPDA 2001, IWASRI 2005) in conjunction with specific information from additional studies and surveys. In India a survey of shallow groundwater quality by CGWB was used to estimate the extent of salinity (CGWB 2010) and in Bangladesh a recent survey of specific electrical conductivity (Ravenscroft et al. 2009) combined with a national survey of water chemistry (DPHE/BGHS 2001). Arsenic concentrations across the basin were mapped within India using available data and maps by State Water Resources Agencies, the CGWB and available local datasets (e.g. Mahanta et al. 2012). Within Bangladesh the DPHE/BGS (2001) national hydrochemical survey data and other large-scale studies by Ravenscroft 2007 and Amini et al. 2008 were used.

Climate and hydrology play an important role in determining recharge, availability and use of groundwater resources in the basin. Rainfall for the basin was taken from the CRU datasets for the years 1950 to 2012 (Jones and Harris 2013) and maps of average annual rainfall and number of rainy days were developed. The extent of rivers and canal networks were mapped on GIS using a variety of different sources, and validated on Google® Earth. These three different datasets were used to help develop an understanding of how groundwater recharge may systematically vary across the basin.

The final groundwater typologies for the IGB alluvial aquifer system were developed by combining the basin-wide maps of rainfall, rivers and canals, groundwater salinity and arsenic concentrations with the map of physical hydrogeological properties.

Investigating resilience of the groundwater system to change

To investigate the resilience of the groundwater systems to change two approaches were taken: (1) mapping the volume and distribution of the available freshwater groundwater resource as an estimate of the capacity of the aquifer system to buffer changes in recharge or abstraction; and (2) mapping the current changes in groundwater storage across the IGB alluvial aquifer system and relating these changes to current abstraction and groundwater recharge, as an indicator of the impact of future pressures of climate and abstraction.

The volume of the available freshwater groundwater resource was estimated by integrating the specific yield across the top 200m of the IGB alluvium (with the exception of the Bengal Basin where a depth of 350 m was used) and then attributed to different groundwater quality classes according to the salinity. For the second approach, changes in groundwater storage were calculated from annual changes in post monsoon groundwater level using available maps, databases and individual water level monitoring points collated and QA'd within the project. The annual change in water level could then combined with the maps of specific yield to estimate annual changes in groundwater storage. A basin wide map of groundwater abstraction was developed by combining data available at a district level for India from the CGWB (accessed online 2014), with data for Bangladesh (Holly and Voss 2009, DWASA 2012) and Pakistan (Ahmad 2002, Halcrow 2013, FAO 2013, Cheema et al 2014). Data for the Nepal Terai were estimated from the global assessment from Seibert et al. 2010.

3 The IGB groundwater system

In this chapter we describe the different datasets compiled to develop the groundwater typologies: the geology and sedimentology, the aquifer properties, groundwater recharge and groundwater chemistry.

3.1 Geology

Formation of the basin

The IGB is a foredeep depression which developed 15 million years ago in response to uplift of the Himalaya with lithospheric loading and depression of the Indian continental plate (France-Lanord 1993; Kumar et al. 2014). The basin holds a thick accumulation of sediment derived from the Himalaya and it remains the world's largest area of modern alluvial sedimentation (Sinha et al. 2014).

The structure of the basin is a vast asymmetric trough, holding sediment thicknesses of up to 6 km adjacent to the foothills along the northern margin, but only a few hundreds of metres, or less, of sediment thickness along the inland southern margin (Singh 1996; Srivastava et al. 2015). The Indus basin forms the western part of the IGB and deepens longitudinally away from the Himalaya, whilst the Ganges basin forms the central and eastern part of the basin and deepens tranverse to the Himalaya into the Bay of Bengal (Valdiya 2002). The Haryana-Punjab basin area between the two represents a shallower over-filled region of the basin (Singh et al. 1996). Continued convergence of the Indian plate at a rate of 2-5 cm/yr, has driven uplift of the basin floor in fault bounded blocks, generating basement highs in several areas of the Ganges basin where basin depth is now less than 1 km, and affecting the position of modern river courses (Sahu and Saha 2014).

Sediment characteristics

The IGB contains up to 2 km thickness of recent alluvial sediment (Plio-Pleistocene - Holocene) and older Miocene rocks derived from vigorous erosion of the Himalaya (Singh et al. 1996). The characteristics of these alluvial deposits typically change in a predictable and systematic manner across the basin from coarse gravel and sand dominated megafan deposits (85% sands and gravels) close to the mountain margins of the basin (Shukla et al. 2001; Singh et al. 1996), to the progressively sand-dominated fluvial deposits (70% fine-medium sands) (Singh et al. 1999; Saha et al. 2011), and then silt dominated (70% silts) fluvial and tidally influenced deltaic deposits at the distal ends of the Indus and Ganges basins (Goodbred and Kuehl 2000; Kinniburgh and Smedley 2001; Acharyya 2005) – Figure 2. Along the southern inland margin of the Ganges basin distinct (smectite-rich) sediment is derived from the Indian craton (Heroy et al. 2003; Sinha et al. 2014).

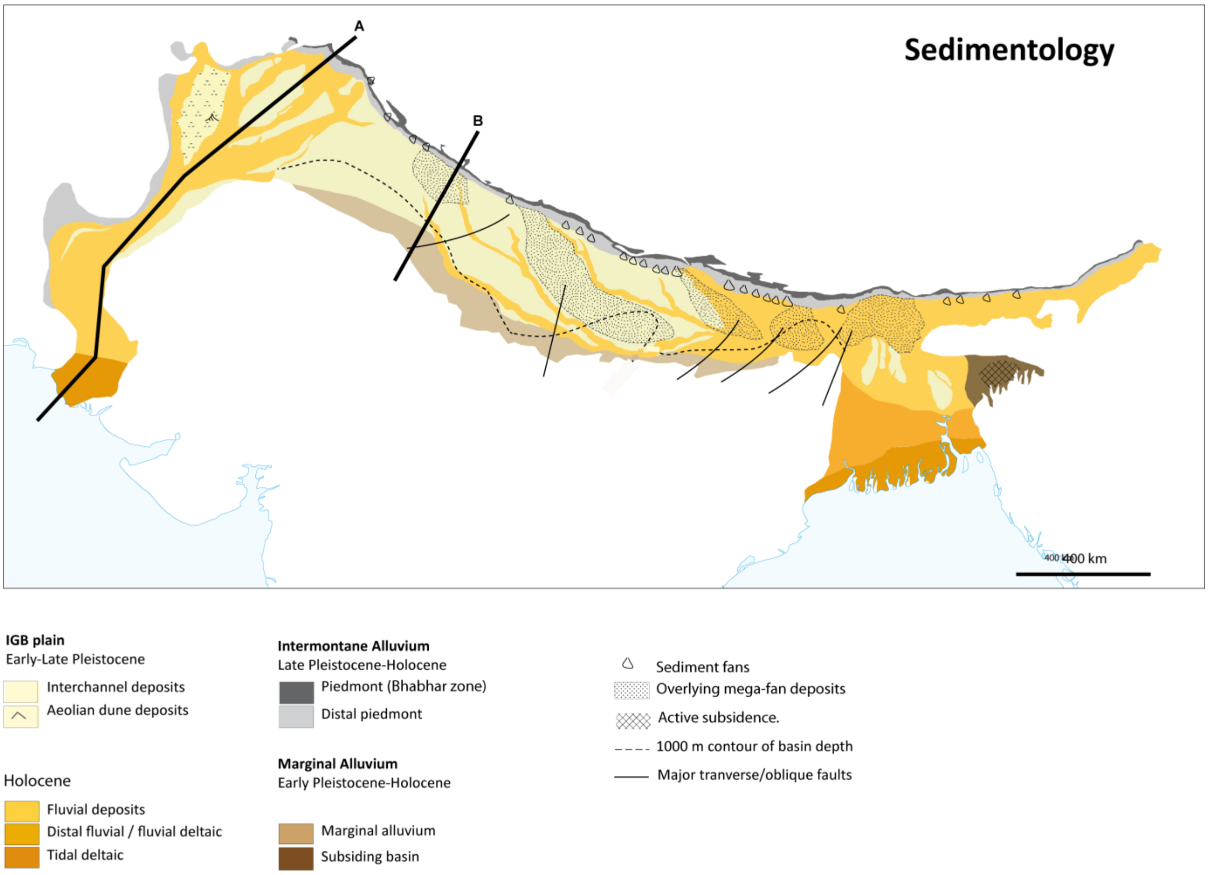


Figure 2 – Typologies of alluvium sedimentology. The location of the cross sections, A and B are shown.

The effective aquifer thickness exploited is generally represented by the upper 200 m of alluvium sediment across most of the basin. Within the Bengal Basin the effective thickness is greater and typically 350 m. The aquifer to these depths is composed of Pleistocene alluvium within the upper Ganges and Indus basins and of younger Holocene alluvium across the major part of the central and lower basin areas (Shroder 1993; Singh et al. 2004) – Figures 2 and 3. This distribution of different aged sediment is the result of different fluvial depositional processes operating in the upper and lower basins: rivers in the upper basins are strongly incising, depositing modern alluvium only within narrow terraces (km wide) in the extensive Pleistocene alluvium cover (Clift and Giosan 2013); whilst in the central-lower parts of the basin, there is a reduced gradient to sea-level, rivers are less incising, and significant amounts of Holocene sediment have been deposited by the numerous lateral aggrading sinuous river channels (Sinha et al 2005). The exact rates of sediment accumulation and geomorphology of these fluvial systems through time are highly sensitive to changes in climate and sediment input, as well as sea-level changes (Valdiya 2002; Goodbred 2003; Sinha et al. 2005). Reduced rates of sediment input and river discharge in drier climatic periods in the last 14,000 years have led to areas of lacustrine (lake) deposition and evaporites with ponding of surface waters in the Indus and within the upper and central parts of the Ganges basin (Validya 2002).

The different distribution of Pleistocene and Holocene sediment across the basin, and their distinct depositional systems and environments, has led to important differences in terms of the IGB aquifer properties and the groundwater resource. Holocene sediments are composed predominantly of channel (medium sand-dominated) deposits within the stratigraphy, and the sediments are generally unoxidised and overall slightly finer than Pleistocene channel deposits since they are in the more distal part of the basin (Singh 1996) – Figure 3. In contrast, the Pleistocene sediment is comprised predominantly of inter-channel deposits (sand and silt dominated), with clustered (laterally and vertically) coarser channel deposits (Singh 1999; Sinha et al. 2005). The Pleistocene sediment in the upper Ganges and Indus basins is proximal to the Himalaya source and contains mainly oxidised coarse sands and silt components (Saha et al. 2011). Both the Pleistocene and Holocene sediments are in essence a continuum of the same complex, heterogeneous alluvium aquifer, deposited by fluvial systems, and composed of stacked channel and inter-channel deposits of a great range of permeability, and which are discontinuous over 10s of kilometres and individual units less than 50 m thick (Sinha et al. 2005; Samadder et al. 2011).

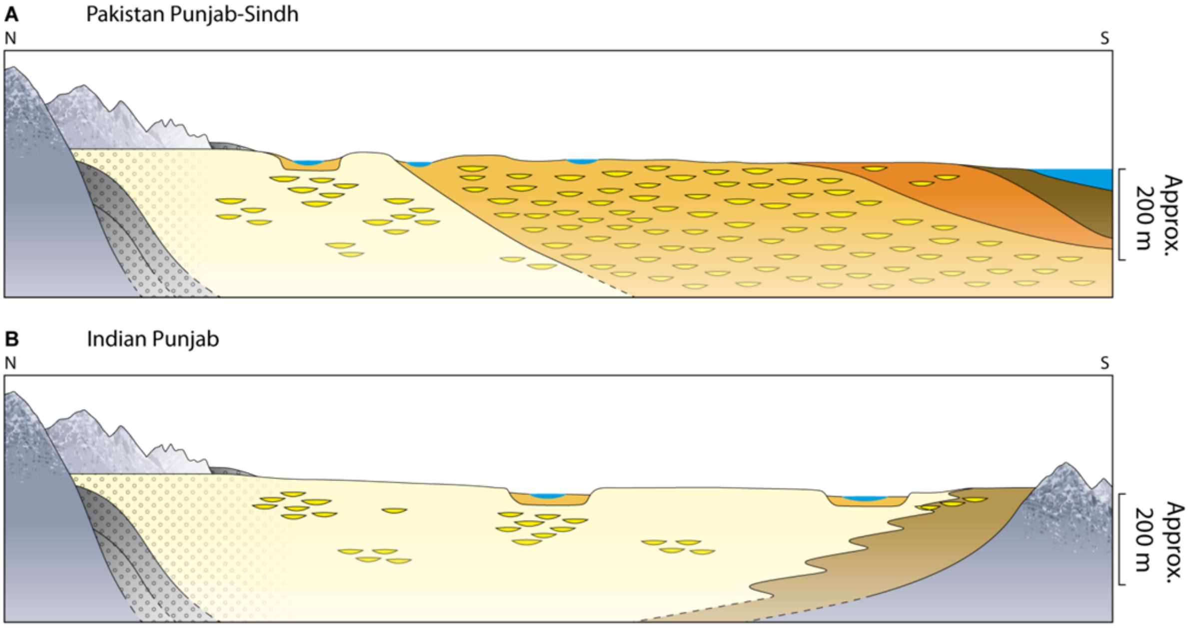


Figure 3 – Schematic cross-sections of the IGB within the Indus (A) and upper Ganges basin (B), illustrating the systematic variations in alluvium sedimentology

3.2 Aquifer properties of the shallow[2] system

Permeability

The sedimentology determines the aquifer properties and, therefore, both permeability and storage tend to vary predictably across the basin – Figure 4. Where sands and gravels predominate, permeability is high - easily sustaining pumping rates of 10 – 100 L/s. In the deltaic parts of the basin, where silts and fine sands are common, permeability reduces but

---

[2] For much of the basin this is the top 200 m; in the Bengal delta the aquifer extends to 350 m depth

remains high by international comparison, and tube wells can often sustain pumping rates of 10 – 20 L/s. Figure 5 shows the variation of permeability measured across the Indus Basin from pumping tests carried out in tube wells generally <100 m deep using data from previous studies by Bennett (1969), Ahmad et al. (1993), Khan et al 2008 and additional data from WAPDA. Permeability ranges from >60 m/d in the Upper Indus to less than 10 m/d in the Sindh reflecting the higher proportion of silts and fine sands within the Sindh.

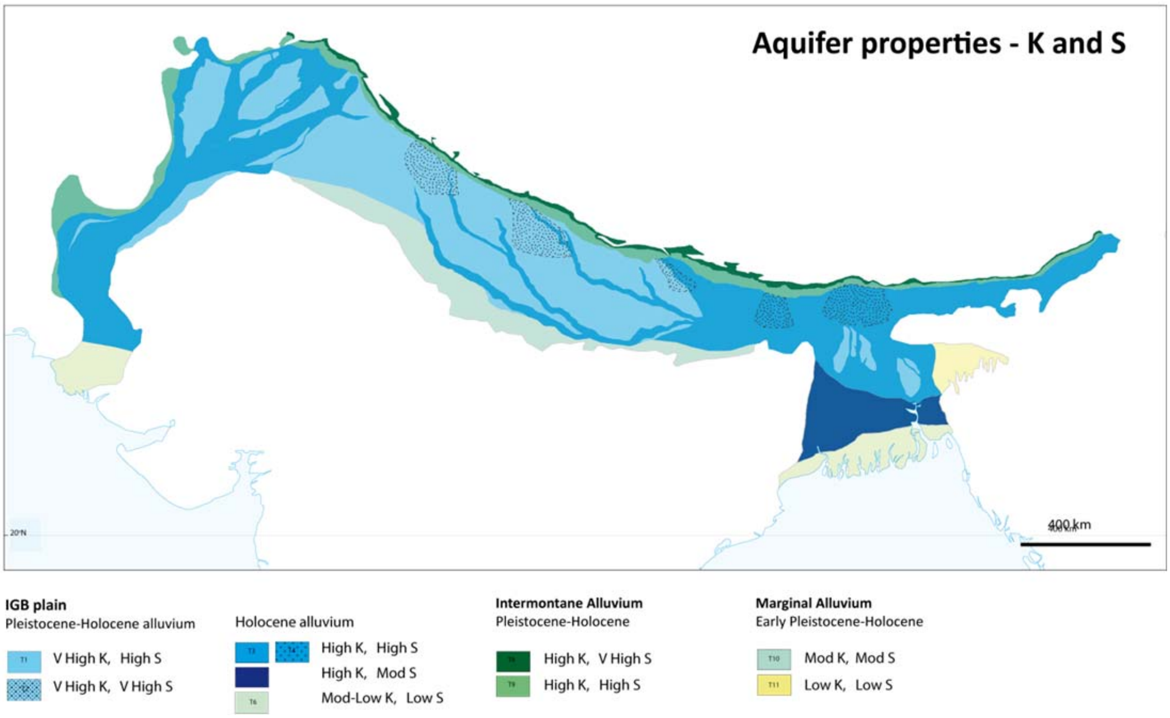


Figure 4 – Aquifer properties of the IGB aquifer system vary systemically on a basin-scale with the sedimentological characteristics of the Plio-Pleistocene – Holocene alluvium

The permeability distribution of the Ganges system is more complex with inputs of sediment along much of the length of the Ganges basin along the front of the Himalayas. Measured transmissivity from pumping tests in successful tube wells across the Upper and Middle Ganges basin in Uttar Pradesh and Bihar vary from several 100 m^2/d to >5000 m^2/d, with median values around 3000 m^2/d and little evidence of consistent trends downstream. Such transmissivity values correspond to permeability values of 5 – 100 m/d (CGWB 2010). A similar range in permeability values is measured from pumping tests from the Brahmaputra system within Assam. Data from detailed pumping tests published for the Bengal Basin (Shamsudduha et al. 2011) show a systematic decline in permeability away from the Himalayas and towards the coast in a similar fashion to the Indus System with permeability reducing from >50 m/d close to the mountains to less than 20 m/d near to the coast.

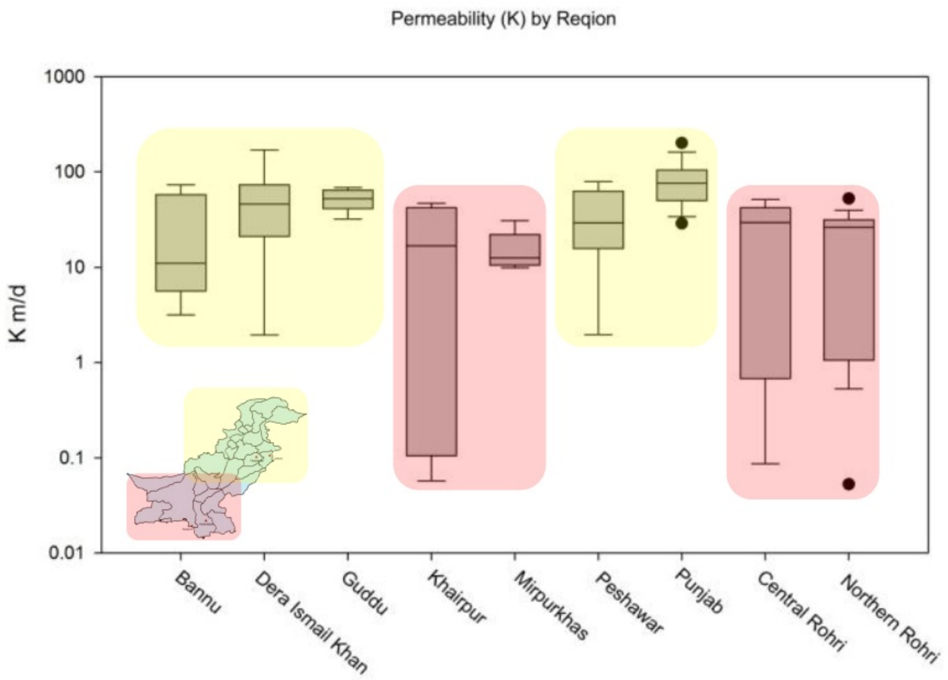


Figure 5 – Estimated permeability from pumping tests in the Indus

Specific Yield

The volume of water stored in an aquifer and readily released is measured by the specific yield. Specific yield is related to the porosity and the grain size: the porosity governs overall groundwater storage, but the grain size and shape govern how easily that groundwater is released from storage, with larger grained sediments generally more easily drained than finer grained sediments. The general variation in specific yield for the top 200 m of the IGB aquifer is shown in Figure 6. The map was developed using sedimentological information on the grain sizes across the basin, parameterised from studies on specific yield for different grain sizes in Bangladesh (DPHE/ BGS 2001) and compared with available published values of specific yield across the basin (Bennet 1969, Mott MacDonald and Partners 1984, Chilton 1986, Ahmad 1993, CGWB 2010, Shamsudduha et al. 2011, Khan et al. 2014). Specific yield is highest in the piedmont and large megafans where grain sizes and porosity are high, although overall aquifer thickness here is often less than elsewhere in the basin. For much of the basin specific yield is in the range 0.1 – 0.15, meaning that 100 – 150 mm of groundwater can be drained for every 1 m decline in the water table. In the delta areas, specific yield reduces to <0.05 due to the increase in silt content

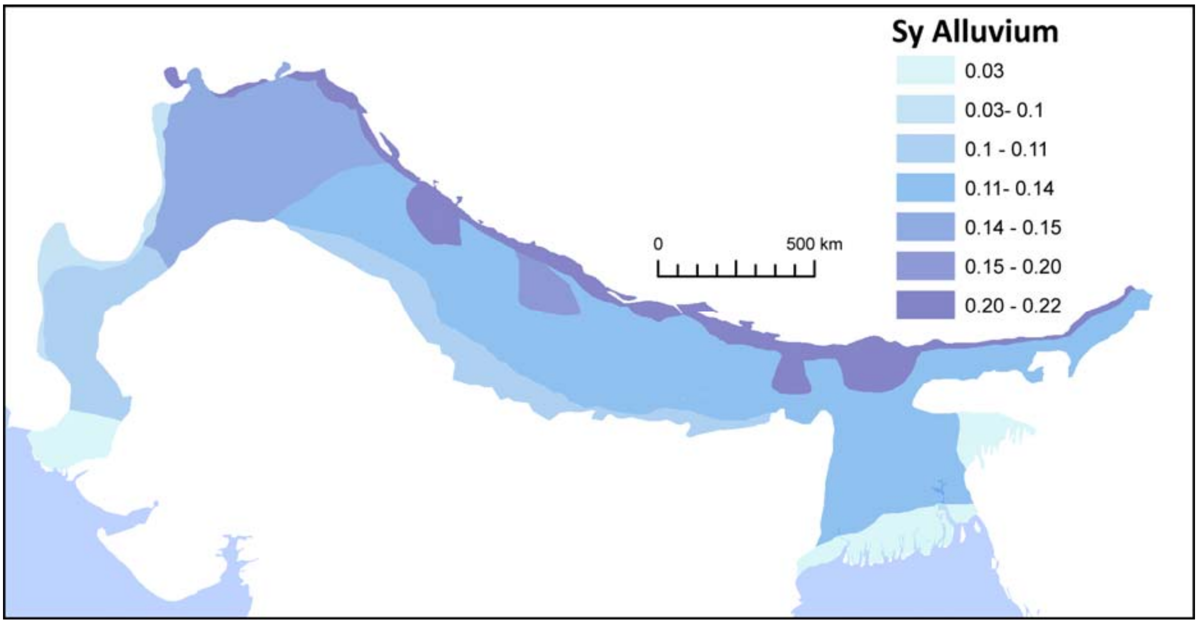


Figure 6 – Variations in Specific yield across the IGB.

Heterogeneity and Anisotropy

As discussed in the previous section on geology, at the local level the aquifer system is highly complex with alternating coarse and fine sands, silts and occasionally clay. Since these sequences have largely been laid down by a sequence of prograding and anastomising rivers, the sediments tend to form discontinuous packages rarely more than a few kilometres across. The high rate of drilling success, particularly in the main basins away from the coastal areas, indicates that sand sediments are usually encountered in a 100 m deep tubewell. In the main Ganges basin and the Upper Indus, lower permeability layers locally-acting as vertical barriers to flow are common and encountered in most tubewells; however, since they are laterally discontinuous, groundwater can still move vertically deeper within the sequence in response to vertical hydraulic gradients induced by pumping. Further down both the Indus and Ganges rivers, closer to the coast, the finer grained sediments predominate and are much more continuous, so vertical hydraulic continuity is more restricted.

A useful way to reflect the potential horizontal rather than vertical groundwater flow across the basin is to estimate the anisotropy in permeability. Studies in the Upper Indus suggest a bulk ratio of horizontal to vertical permeability of approximately 25 (Bennet 1969), rising to 50- 100 in the main Ganges basin (Sinha et al. 2009, Khan et al. 2014), and 200 - 500 in the Lower Indus (Chilton 1986, Ahmad 1995); 10,000 in the southern Bengal Basin and 20,000 in the coastal areas (Michael and Voss 2009). Limited data from modern sediments close to the major rivers show a much lower ratio of <10 (Ahmad 1995).

3.3 Groundwater chemistry: salinity and arsenic

Two of the greatest constraints to using the groundwater in the IGB are the presence of saline water at shallow depths and elevated arsenic concentrations. Other issues, such as pollution by anthropogenic activity (urban and agriculture related) and elevated naturally occurring elements such as fluoride and uranium are a concern, but do not currently impact the IGB to the same extent as salinity and arsenic. Therefore, in this section we concentrate on mapping out areas affected by salinity and arsenic.

Groundwater salinity

The presence of saline groundwater at shallow depths can be a major constraint on the development of groundwater resources. Elevated solute concentrations in water has health impacts if routinely used as drinking water, reduces its value for industry, and agriculture, and can also damage the soil if used for irrigation. The World Health Organisation have no official guidelines for total dissolved solids (TDS) in drinking water, but suggest that waters with less than 1000 mg/l are generally acceptable (WHO, 2003). For agriculture uses, there are no strict definitions for the use of saline water: the FAO classify water as non-saline at less than 500 mg/l, slightly saline from 500 – 1500 mg/l and moderately saline from 1500 – 7000 mg/L (FAO 1992). Crops have different tolerances to salt, and the use of water beyond 1000 mg/L must be carefully managed to sustainably farm without damaging the soil.

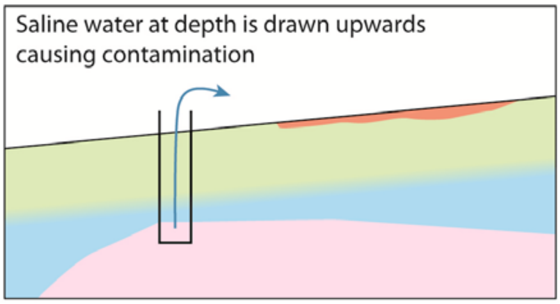
The distribution of saline water in the top 200 m of the IGB aquifer is shown in Figure 7. Approximately 20 - 25% of the aquifer is impacted by the presence of saline water over 1000 mg/L. The origin of the salinity is complex: formed by a combination of natural processes, exacerbated by centuries of irrigation practices – Box 1 (see page 12). The basin has not been subject to widespread marine transgression (Schroder 1993; Valdiya 2002; Goodbred 2003) and the salinity in the Indus basin and Upper Ganges is almost entirely terrestrial in origin. Only in the Bengal basin and the coastal area of Pakistan is there evidence of historical and current marine influence (DPHE/BGS 2001, Schroder 1993).

Across much of the basin, away from the coastal areas, saline groundwater is a consequence of high evaporation relative to rainfall leaving a residue of salt. Current shallow water tables, irrigation or flooding can lead to high evaporation and consequent salinisation of soil and groundwater; pumping can also mobilise water from deeper in the sequence which can be saline due to the presence of evaporite sequences and the longer residence times of groundwater at depth. The distribution of evaporite deposits within the aquifer is largely governed by historical climate, with extended dry periods, or a succession of wet and dry periods, leading to their development. Although there has been much climate variability in the region, the overall relative distribution of rainfall in the basin is likely to have remained relatively stable (Goodbred 2003; Clift and Giosan 2013), with higher rainfall occurring closer to the Himalayas coupled with an east to west trend of increasing rainfall. Therefore, there is a greater likelihood of encountering evaporite sequences at depth in the currently drier areas of the basin.

Box 1 Processes leading to groundwater salinity

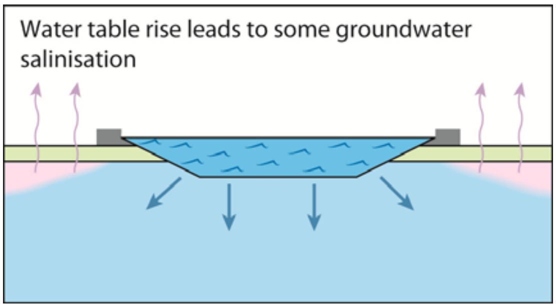
There are many different processes that lead to groundwater becoming saline, some of them natural processes and some that are exacerbated by human activity. Saline groundwater can be marine or terrestrial in origin. Here we describe three of the main mechanisms causing salinization of shallow groundwater across the IGB alluvial aquifer system.

Mobilisation of existing saline water


Saline water at depth is drawn upwards causing contamination

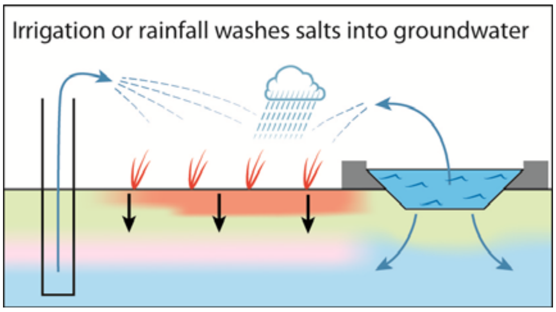
Pumping fresh groundwater that overlies, or is adjacent to saline groundwater, can rapidly degrade groundwater within the aquifer. In coastal areas, abstraction can enhance saline intrusion by reversing the natural hydraulic gradient towards the sea, allowing saline groundwater to intrude further into the coastal aquifer. Inland, throughout much of the drier parts of the Indus and Ganges basins natural saline water occurs at depth. Groundwater abstraction in these areas alters the natural groundwater flow regime, and where low permeable horizons are not extensive the deeper saline groundwater is drawn upwards, contaminating wells.

Rising water tables


Water table rise leads to some groundwater salinisation

In areas where water-tables are shallow, evaporation high and rainfall low, soil and groundwater salinisation can occur. High water-tables are often associated with leakage from canals, particularly at the head of canal commands and areas that are over irrigated. If the additional groundwater from canal leakage or irrigation is not abstracted, groundwater levels within the aquifer rise and are evaporated, causing both soil salinisation and salinisation of shallow groundwater.

Irrigation returns


Irrigation or rainfall washes salts into groundwater

Even where the water-table is deep and falling, groundwater can become saline due to irrigation practices. Irrigation leads to increases of salt within the soil water, particularly if the irrigation water has a moderate mineral content. The excess salts can be leached to the water table, increasing the groundwater salinity, by excess irrigation, heavy rainfall and periodic flooding. This process is exacerbated by recycling of groundwater.

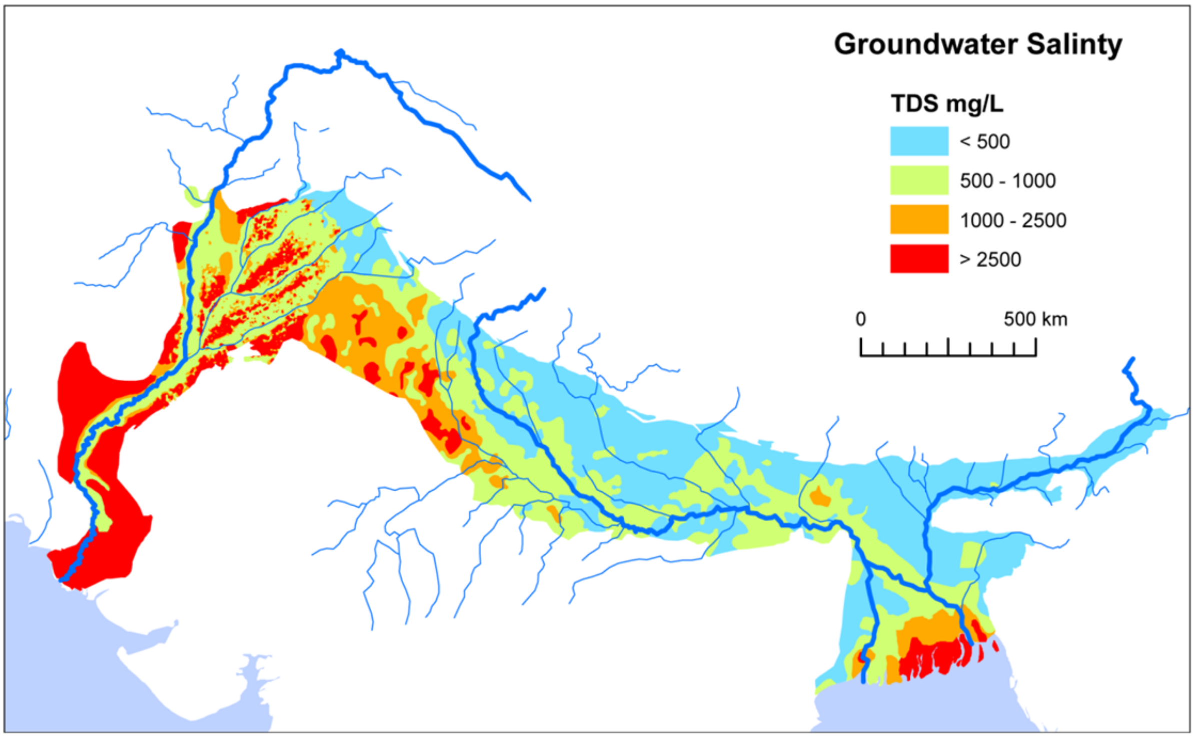


Figure 7 – Distribution of groundwater salinity in the top 200 m of the IGB aquifer. Data from WAPDA 2001, IWASRI 2005*, Quereshi 2008, CGWB 2010,* Ravenscroft et al. 2009 *DPHE/BGS 2001).*

River water can flush out the saline water to provide fresh groundwater close to the rivers. This is most apparent along the length of the River Indus and its tributaries where areas within 50 km of the rivers tends to have low salinity groundwater. Irrigation also has a major impact on the presence of saline groundwater. High rates of irrigation losses from canals can lead to the development of small freshwater lenses in areas with generally saline groundwater. However, where this leads to very shallow water tables (such as in the Lower Indus), waterlogging and increased salinization can occur. Over-irrigation can also leads to degradation of groundwater quality (e.g. Ó Dochartaigh et al. 2010), where accumulating salts in the soil from evaporation are flushed through into the groundwater system.

Arsenic

Since the 1990s, extensive arsenic pollution has become evident in shallow groundwater (<100 m depth) throughout the floodplains of the Bengal Basin. Arsenic in shallow groundwater used for drinking water since the 1980s reaches up to 100 times the WHO guideline limit (10 μg/L), creating a human catastrophe, as many millions of people have subsequently developed symptoms of arsenic poisoning (Smith et al. 2000). Arsenic-rich groundwater occurs in chemically reducing, grey-coloured, Holocene sediments, mostly restricted to groundwater in the uppermost 100 m across the floodplains in the southern Bengal Basin where arsenic is commonly present at >100 μg/L – Figure 8. Half the shallow hand-pumped wells in Bangladesh provide groundwater with 10 – 1,000 μg/L As (Kinniburgh and Smedley 2001). Less extreme arsenic concentration, though still >10 µg/L, occurs in other parts of the IGB, for example Assam, India, southern Nepal, the Sylhet trough in eastern Bangladesh, and within Holocene sediments along the course of the Ganges in northern India, and also within the Indus system – Figure 8. Throughout the IGB, groundwater in Pleistocene and older sediments at >150 m depth, and at shallow depth within the Pleistocene inliers, generally contains less than 10 µg/L As. Groundwater deeper than 150 m has therefore become a popular target in response to the arsenic crisis. High-yielding deep wells have been installed in many rural water supply schemes and provincial towns. Recent investigations have concerned the security of deep groundwater pumping against invasion by arsenic drawn down from shallow levels. Modelling studies have highlighted the need for more measurements of groundwater head in the deep regions of the Bengal Aquifer System (Michael and Voss 2009; Burgess et al. 2010) – one subject addressed by the Deep Groundwater Case Study (see page 26).

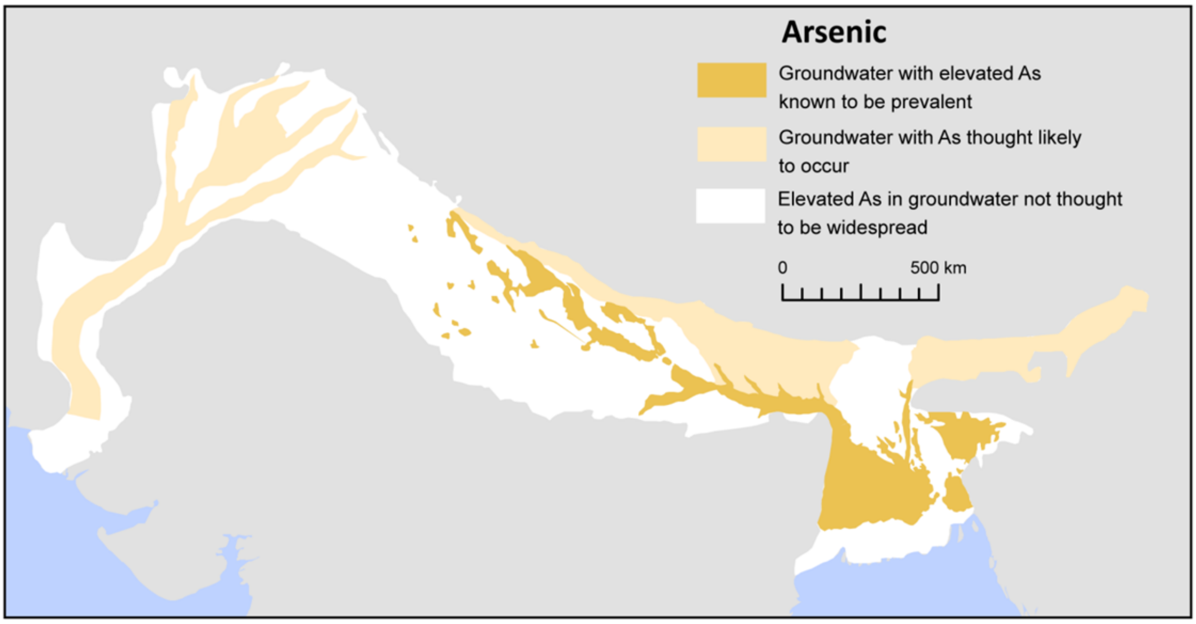


Figure 8 – Known areas with elevated arsenic in the IGB Aquifer system

3.4 Groundwater Recharge

An important factor governing the resilience of the groundwater resource in the IGB to changes in abstraction and climate is how recharge is distributed across the aquifer. Several different mechanisms of groundwater recharge operate concurrently within the basin – Figure 9.

Rainfall recharge

There is considerable evidence of high rates of groundwater recharge from seasonal rainfall within the basin. Studies of groundwater level variations and rainfall in India led to an empirical formula being developed relating rainfall to recharge (Chaturvedi 1973) which has been modified by others (e.g. Kumar and Seethapathi 2002) and tested using environmental tracers (e.g. Goel et al 1977, Datta and Goel 1977). Groundwater recharge is found by these studies to be negligible in areas with average annual rainfall below approximately 350 mm, less than 10% from 350 – 500mm and then increases to between 10 and 20 % of rainfall above 500 mm. These local studies give significantly higher values of recharge than those estimated by global hydrological models (e.g. Doll et al 2008), particularly where rainfall is less than 1000 mm. In areas with extensive clay soils (e.g. central Bangladesh), studies have indicated that groundwater recharge may be less than where the soil is less permeable (Goel et al 1977, Shamsudduha et al. 2011).

Irrigation transport losses

Across the Indus and Ganges canal systems there are more than 80,000 km of distributor canals within the alluvial aquifer system (59,000 km on the Indus and approximately 25,000 km on the Ganges (Quereshi 2008, FAO 2009, FAO 2012)) which distribute water to tertiary canals that deliver water to the fields. Detailed studies of conveyance losses in the tertiary canals in the Indus suggest that losses from the canals are in the range of 0.7 – 1.6 L/s per 100 m, with lined sections of the canals having slightly lower losses than unlined canals (Clyma et al. 1975, Arshad et al 2009, Raza et al. 2013). However the losses increase with the age of the lining and experiments have shown that within 10 years the conveyance losses can rise to the same as unlined canals (Raza et al. 2013). Studies in India (WWF 2015) indicate similar losses, up to 50% of irrigation water is lost through the entire canal network with the vast majority of this water becoming groundwater recharge, and a smaller proportion evaporating. The scale of the groundwater recharge provided by irrigation canals is corroborated by the widespread evidence of groundwater table rise and subsequent waterlogging throughout the 20th century (Quereshi 2008, Basharat et al. 2014).

Irrigation field losses

Groundwater can also be recharged in irrigated areas from application of excess water to the crops, leading to infiltration of water that cannot be taken up by the plants. Across much the IGB deficit irrigation is practiced (Jurriens and Mollinga 1996) however some proportion of irrigated water is likely to return to the groundwater, particularly where flood irrigation is practiced. Although providing useful recharge, the returning water can have elevated nitrate concentrations and high salinity since the recharging water flushes out salts within the soil and if sourced from groundwater will be more mineralised in the first place(e.g. Ó Dochartaigh et al 2010).

Recharge by the major rivers

The Indus, Ganges and Brahmaputra major river systems form important water resources in the IGB region in themselves, with large annual surface water discharges – Figure 10. Prior to development of widespread irrigation across the IGB, recharge through losses from the river system were a major source of recharge, particularly in the Indus River system where rainfall decreases downstream. The influence of groundwater recharge from the Indus River is observed today by the presence of fresh water in a 50 km buffer zone around the major rivers. In some places the influence is wider due to migration of the river channels. Reducing river flows in the Lower Indus have arguably had an impact on the salinity of the groundwater in the Sindh and consequently the ecology of the mangrove swamps (Qureshi et al 2010). Groundwater recharge also occurs close to the Ganges River System during the monsoon season, where extensive flooding infiltrates to the shallow aquifer. For much of the year, however, the Ganges river system receives water from groundwater as baseflow, rather than provides recharge.

Induced recharge

There is growing evidence that increased pumping in areas with shallow water-tables and permeable soils can increase groundwater recharge by creating additional space to store rain or river water (Shamsudduha et al. 2011). This behaviour has led some to investigate the possibility of deliberately lowering groundwater levels in the dry season to increase infiltration during the monsoon to help control flooding and increase the water available for irrigation. These ideas were first published in the 1970s within an idea called the *Ganges Water Machine* (Revelle and Lakshminarayana 1975, Chaturvedi and Srivastava 1979) and have recently been revisited (Khan et al 2014).

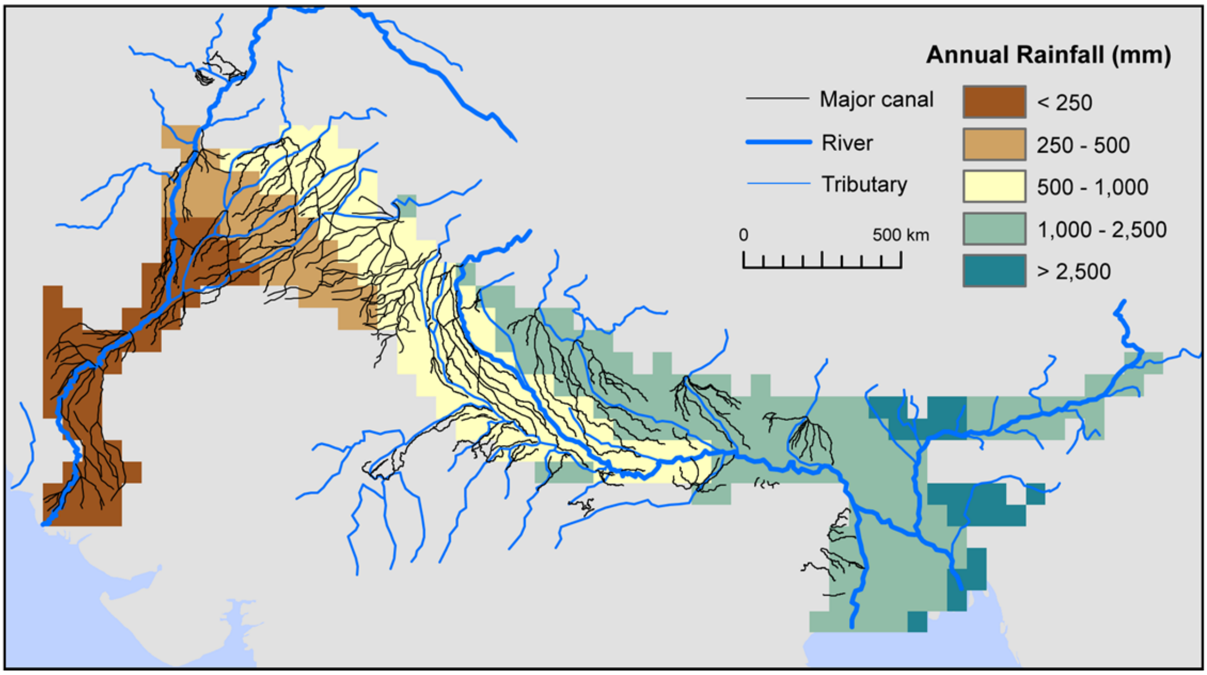


Figure 9 – A combination of factors provides a highly complex pattern of recharge across the IGB. In areas with a high density of irrigation canals, such as the Upper Indus and Upper Ganges basins, leakage from irrigation canals can give annual recharge of 400 mm; where average annual rainfall is greater than 1000 mm, rainfall recharge generally dominates. Rainfall recharge can occur even where annual rainfall is as low as 250 - 500 mm due to the high intensity of individual rainfall events and the permeable soils. Recharge directly from rivers is particularly important on the River Indus where rainfall decreases significantly downstream, but can also be important in the Ganges, particularly during flood events.

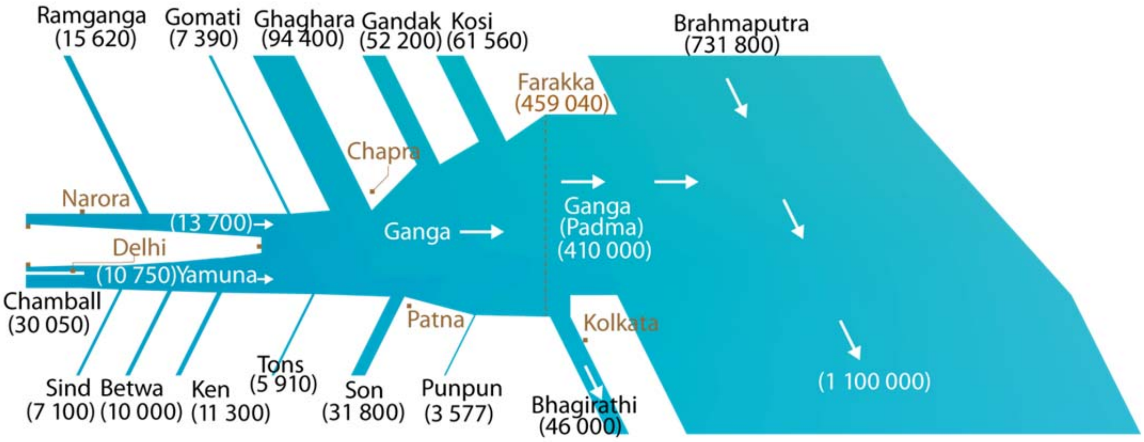


Figure 10 – Schematic of the Ganges and Brahmaputra river systems and their average annual discharge (m^3/yr) (adapted from Singh et al 2007).

4 Typologies

As described in Chapter 3, the aquifer properties, water chemistry and groundwater recharge vary throughout the Indo Gangetic Basin groundwater system. Much of the spatial variation at the basin scale is predictable and relates to the geological and climatic history of the area, and more recently to some of the irrigation practices. These systematic changes in the groundwater resource across the basin are described by seven major typologies, which present the significant differences in the groundwater resources in the different areas. Three minor typologies at the margin of the basin accompany these large over-arching major typologies. Each typology is summarised below with a block diagram and the extent of the typology shown in Figure 11. Table 1 summarises the main differences and characteristics of the typologies (see page 27).

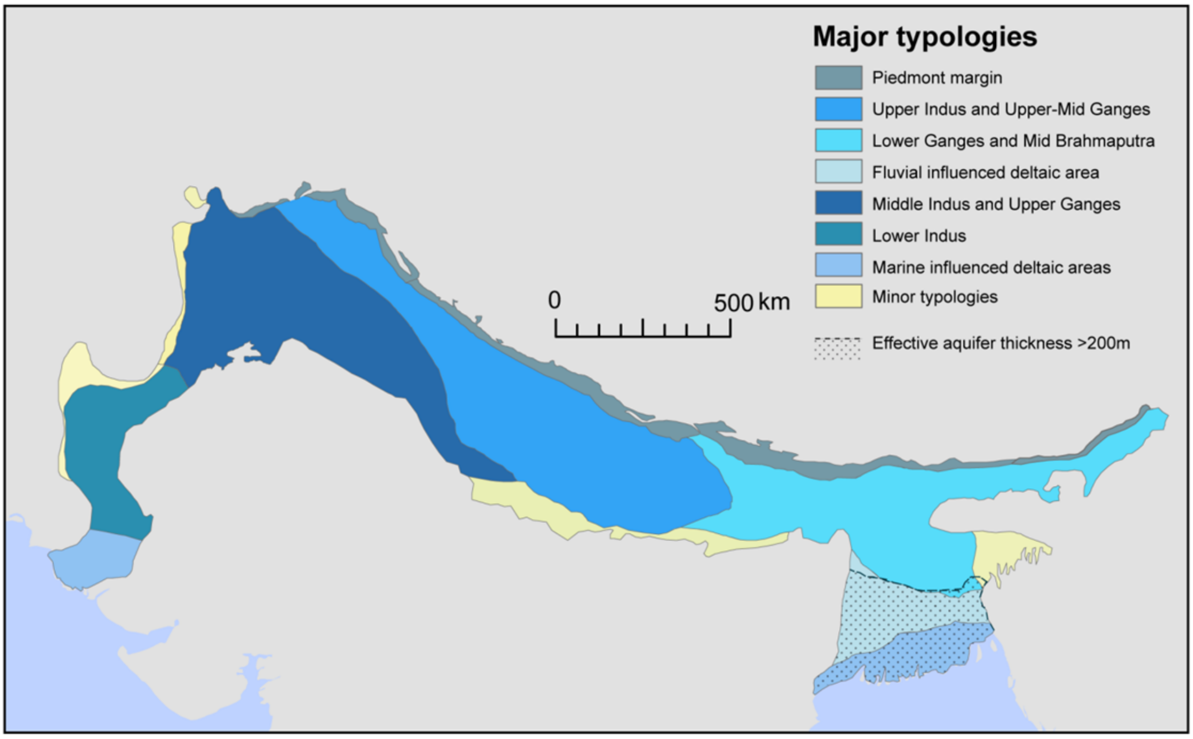
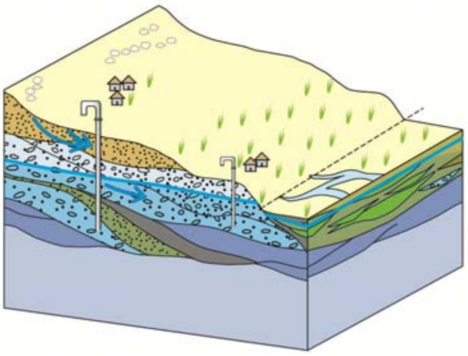


Figure 11 – The main groundwater typologies of the Indo-Gangetic basin.

Typology 1 The Piedmont

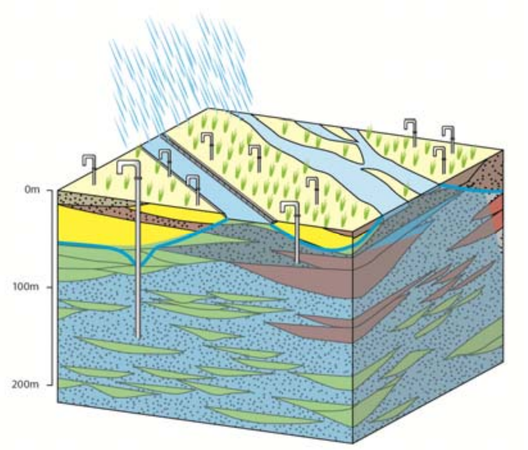
The piedmont typology lies along the northern margin of the basin at the edge of Himalayas and comprises a narrow strip 10s of km wide including the Bhabhar zone, Terai plain and intermountain valleys (see Figure) (Lovelock and Murti 1972; GDC 1986). The aquifer is heterogeneous, made up of stacked alluvial fans comprised predominantly of gravels and coarse sands eroded from the foothills of the Himalayas, and ranges from boulder to silt sized sediment (Day 1971; Singhal et al. 2010). The typology is variable in thickness, but often not more than 100 m. The permeability of the



aquifer is variable, 1 – 50 m/d, and specific yield high 20 – 30% (Lovelock and Murti 1972; GeoConsult 2012). There is little evidence for regional separation between shallow and deep, although shallow and deeper groundwater may be locally disconnected.

Rainfall in the typology is high, often >1000 mm and the aquifer is recharged through rainfall (Narula and Gosain 2013). Saline groundwater is not a major issue, but concentrations of arsenic vary considerably across the typology, related to the source of the sediment and redox conditions and concentrations can be greater than 0.05 mg/L (Shrestha et al. 2004; Gurung et al. 2005, Pokhrel et al. 2009). Much of the abstraction occurs from shallow tube wells between 0 and 50 m, where yields can be 5 – 15 l/s; higher yields are common in deeper tubewells (50 – 80 m) where yields of up to 40 L/s are reported (GeoConsult 2012). On valley sides, and in higher altitude intermontane settings, there remains widespread reliance on diffuse hillslope springs – see Box 2 (page 25).

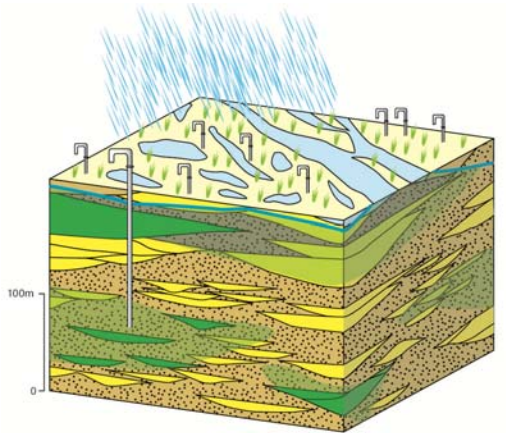
Typology 2 The Upper Indus and Upper and Mid Ganges



This major typology comprises an extensive highly permeable aquifer with good quality groundwater that runs from the Upper Indus, through the Upper Ganges and Mid Ganges Basin (Singh 1985; Sinha et al. 2005a, 2005b). The sediments are thick (possibly >200 m), generally medium to coarse grained with a high permeability – typically 30 - 50 m/d but up to 50-70 m/d locally, and high specific yield 10 – 25% (Chaudri 1966; Bennet 1969; Niwas and Singhal 1985; Shukla et al. 2001; CGWB 2007). Low permeability layers can stratify the aquifer, but these are rarely continuous over more than a few kilometres (Singh et al. 1999; Samadder et al. 2011; Srivastava et al. 2003). Overall anisotropy (Kv/Kh) varies from approximately <25 in the Upper Indus to 50 – 100 in the Middle Ganges; recent deposits next to the major rivers are less anisotropic (Malmberg 1975; Grey et al. 1979; Srivastava et al. 2003). The aquifer is highly exploited with many shallow tube wells (<100 m), hand dug wells and a growing number of deeper tube wells (100 – 150 m) (CGWB 2007.

There are many canals throughout this typology and much of the area is irrigated from both surface water and groundwater (Dhiman 2012). Rainfall is high, generally >750 mm and groundwater recharge occurs through both rainfall recharge and canal seepage (CGWB 2007). The presence of saline groundwater is not a major problem, but it may occur at shallow levels as a consequence of water logging, or in pockets at depth associated with evaporite sequences deposits under previous climates (Goodbred and Kuehl 2000; Basharat 2012). Natural elevated arsenic concentrations can occur in various localities, usually associated with younger Holocene deposits, and the groundwater can be contaminated due to the intensive agriculture and urbanisation (Lawrence 1985; CGWB 2007; Saha et al. 2011; Sinha 2011; Basharat 2012).

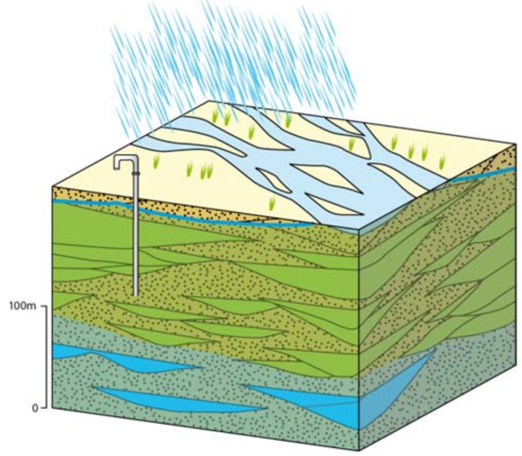
Typology 3 The Lower Ganges and Mid Brahmaputra



This typology comprises highly permeable alluvium sediments, in a series of stacked channel and interchannel deposits - similar to typology 2 (Singh 1996; Sarma 2005; DPHE 2007; Holly and Voss 2009). The aquifer tends to be highly permeable throughout, with permeability typically 40 – 80 m/d, and specific yield generally in the range 10 – 20% (Bennet 1969; Kinniburgh and Smedley 2000). The aquifer is often greater than 200 m thick. Since the aquifer runs along the front of the Himalayas, it still receives sediment input along it length (apart from on the elevated Pleistocene Tract regions) and anisotropy is likely to be similar to Typology 2, in the range 25 – 100 (Michael and Voss 2009). Low permeability units are unlikely to be extensive, extending to several kilometres (Kinniburgh and Smedley 2000). A series of mega fans comprising coarse highly permeable form the upper sequence of parts of this typology, improving its aquifer properties (Shukla et al. 2000).

Rainfall across this typology is high with annual rainfall >1000 mm and canal irrigation is limited to a relatively small area fed from the Rivers Kosi and Ghandak (CGWB 2010). Groundwater recharge is therefore dominated by rainfall recharge and also seasonal flooding from the rivers. Potential recharge is high, and there is evidence that actual recharge is limited by the availability of space in the aquifer to receive it (Shamsudduha et al. 2011). Groundwater levels can be shallow or even at ground surface, causing long periods of flooding. Groundwater salinity is not a widespread issue within this typology, but elevated arsenic concentrations are common in localised areas associated with the Holocene deposits (Harvey et al. 2006; Shah 2008; Kumar et al. 2010; Bhattacharya et al. 2011). Groundwater is widely used, particularly within Bangladesh.

Typology 4 The fluvial influenced deltaic area

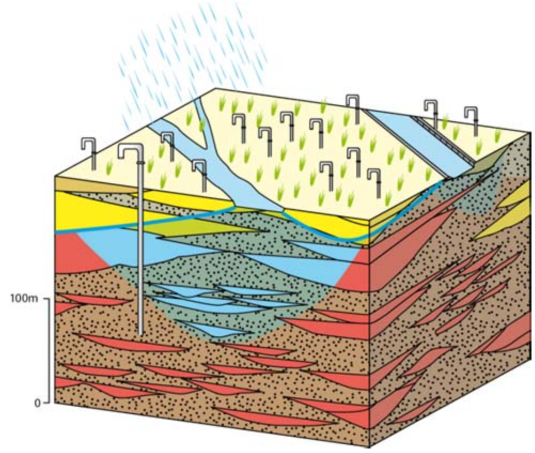


The fluvial influenced deltaic area is dominated by extremely high concentrations of arsenic in shallow (generally <100 m deep) groundwater. The sediments comprise alluvium sediments deposited in fluvial to deltaic and tidally influenced setting, and therefore have a greater proportion of silts and fine sands then typologies further upstream (Jones 1985; Allison et al 2003; DPHE 2007; Holly and Voss 2009). The geological setting gives a complex highly heterogeneous aquifer. Permeability can be low – typically 10 – 25 m/d and specific yield is <10%

(Mott MacDonald and Partners 1982, 1986; Kinniburgh and Smedley 2000; Mukherjee et al. 2007). Low permeability units are continuous over 10s of kilometres and as a consequence the aquifer is highly anisotropic, with mean horizontal permeability 10,000 times greater than vertical permeability (Michael and Voss 2009).

Rainfall across the typology is high, greater than 2000 mm and increasing from west to east – potential recharge is therefore dominated by rainfall recharge and actual recharge is limited by the space in the aquifer to receive the water and also by the presence of low permeability soils in some places (CGWB 2007; Shamsudduha et al. 2009). Elevated arsenic concentrations in shallow groundwater are widespread, with very high concentrations (>200 µg/L) common (Kinniburgh and Smedley 2000; Acharyya 2005; Harvey 2006; Mukherjee et al. 2011). At depth (>150 m) groundwater can have lower arsenic concentrations, due to the complex history of deposition, historic flushing, redox conditions and the presence of the pervasive low permeability layers which limit the downward movement of the shallow groundwater. The deeper groundwater, however, receives little modern groundwater recharge (Kinniburgh and Smedley 2000; Shah 2008; Hoque and Burgess 2009; Fendorf et al. 2010; Burgess et al 2010).

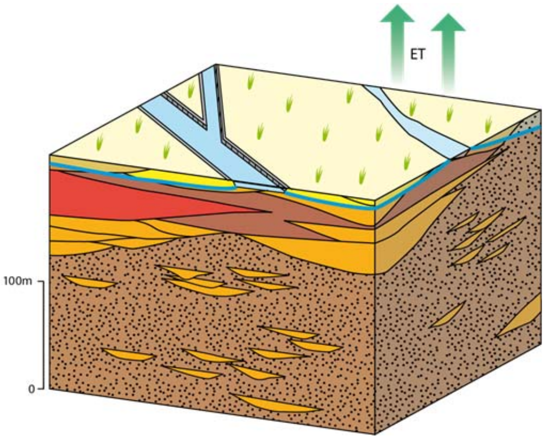
Typology 5 Middle Indus and Upper Ganges



The Middle Indus and Upper Ganges typology comprises a highly permeable aquifer stretching across the drier area of the middle Indus basin and into the Upper Ganges basin. The aquifer comprises a thick sequence of stacked channel and interchannel alluvial sediments (Singh 1996; ISWARI 2005). The permeability of the aquifer is generally high, often 30 – 50 m/d, locally up to 50 - 60 m/d, with high specific yield, 10 – 20% and regional anisotropy, 25 – 100, although much lower in the recent deposits next to modern river channels (Bennet 1969; Mott MacDonald and Partners 1982). Evaporite deposits are common within the alluvial stratigraphy at depth leading to areas with saline groundwater.

Rainfall across this typology is highly seasonal with often less than 25 wet days within a year and average annual rainfall is less than 500 mm. Therefore, although rainfall recharge can occur, it does not dominate. Historically, the aquifer was recharged from the rivers, and large, thick (>100 m) fresh water lenses occur close to the rivers (Mott MacDonald and Partners 1985). At the present day, the aquifer is recharged both from the rivers, and the extensive canal network (Basharat 2012). River flow has diminished due to the high volume diverted to the canal network. In general groundwater salinity is < 1000 mg/L close to the rivers, and >2500 mg/L away from the influence of the rivers (ISWARI 2005). Recharge from seepage from the canals can lead to a partial flushing of the shallow groundwater, but also to waterlogging and increased salinization in some areas. Elevated natural fluoride and arsenic concentrations and nitrate from agricultural practices are also common (Gupta et al. 2005).

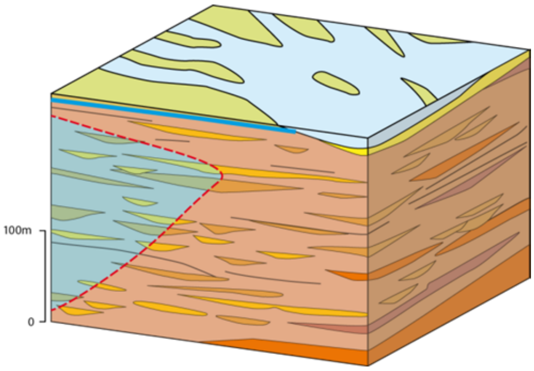
Typology 6 The Lower Indus



The Lower Indus Basin, found within the Sindh in Pakistan is dominated by the presence of saline groundwater (IWASRI 2005). Salinity is especially widespread at depth, and there is a greater probability of finding good quality groundwater at shallower depths. The aquifer comprises alluvial sediment with a high proportion of fine sands and silts (Mott MacDonald and Partners 1985; Schroder 1993). However, despite this, the average permeability remains generally in the range 1 – 20 m/d, and specific yield 5 – 15% (Bennet 1969; Mott MacDonald and Partners 1990). The increased presence of laterally extensive silt layers does decrease the regional vertical permeability and anisotropy is in the region of 100 – 500. Evaporite sequences in the sediment are common.

Rainfall in the Lower Indus is low, < 250 mm, and evapotranspiration is high and, therefore, groundwater recharge from rainfall is negligible (IWASRI 2005). Historically, groundwater was recharged from flow from the Indus River and this led to thick lenses >50 km wide of fresh water around modern and paleo river channels (Basharat et al. 2014). However, river flow in the Lower Indus has significantly reduced in the last 40 years due to irrigation and diversions, and recharge from the river is restricted to a smaller area next to the main Indus channel. Groundwater is recharged from the canal network leading to exensive water logging (Mott MacDonald and Partners 1994). This has lead to the development of thin freshwater lenses in some locations, but also increased phreatic salinisation where the water table is very shallow. Groundwater salinity is mostly > 2500 mg/L. However, next to the Indus, and in localised area, freshwate lenses can exist and groundwater can be <1000 mg/L (Mott MacDonald and Partners 1985; IWASRI 2005).

Typology 7 The marine influenced deltaic areas



A marine groundwater typology exists within the coastal margins of both the Indus and Ganges-Brahmaputra river systems. Permeability of these aquifers tends to be low <10 m/d, specific yield <5% and anisotopy very high, 20,000, as a result of the aquifer being composed of highly stratified silt and clay sediments which were deposited in deltaic or marine-influenced settings (Mott MacDonald and Partners 1985; Kinniburgh and Smedley 2000; Michael and Voss 2009). Shallow groundwater is not used in the coastal regions; here, deep groundwater, below the occurrence of excessive salinity, is a vital resource, especially in the large coastal towns (Taylor et al. 2014).

In Bangladesh, rainfall is high and there is much river water, allowing for recharge in the shallow groundwater both from rainfall and river infiltration (Shamsudduha et al. 2009). Deeper groundwater in this typology receives little modern recharge due to the low vertical permeability (Michael and Voss 2009). In Pakistan, rainfall is negligible and river flow significantly diminished leading to a rapid decline in the availability of freshwater, with a corresponding imapct on the mangrove ecosystems (Basharat et al. 2014). Therefore in Pakistan the groundwater is extensively saline in this typology, both from the influence of sea water intrusion through the creeks and also from terrigenous impact described in Typology 6. The saline water in the coastal areas of Bangladesh is more complex (Alison et al. 2003; Kinniburgh and Smedley 2000). Shallow groundwater can be saline far inland from the impact of storm surges, and deeper groundwater (>100 m depth) can have much lower salinity due to its partially isolation from the modern influence of the sea due to the presence of clay and silt and the high anisotropy.

Minor Typologies

There are several minor typologies identified across the IGB alluvial aquifer system, including the southern marginal alluvium in the Ganges basin, the western Indus basin piedmont, and the Sylhet trough in Bangladesh and deeper groundwater within the Bengal Basin.

Deeper groundwater in the Bengal Basin

Within the Bengal Basin deep groundwater (from 150 – 350 m) is an important resource. Across the rest of the IGB alluvial aquifer system groundwater is rarely used below 150 m (hence the restriction of much of this report to discussing the shallowest 200 m). However, due the widespread contamination of shallow groundwater with arsenic and the evidence of low arsenic concentrations in groundwater > 150 m (DPHE/BGS 2001) in much of the Bengal Basin, deeper groundwater is routinely exploited to find groundwater of good quality. The likely extent of this deeper groundwater is shown in Figure 11 (DPHE 2006, Michael and Voss 2008, Burgess et al. 2010). The hydraulic properties of these older sediments are variable, again dependent on intersecting sand and gravel layers within the more permeable silts. Many deeper tubewells intersect sufficiently permeable strata to sustain yields of >10 L/s and the groundwater system has been successfully modelled with an effective horizontal hydraulic conductivity of 40 m/d (Michael and Voss 2008).

The deeper groundwater is not subject to recent recharge (Hoque and Burgess 2012) and therefore effective monitoring of abstraction is required to manage abstraction, and to ensure substantial groundwater abstraction from the deep aquifer is sustainable for decades or centuries to come (Ravenscroft et al. 2013). Careful monitoring is also required to ensure the quality of the deeper groundwater is sustainable in the long term – as abstraction alters the hydraulic gradients within the aquifer and may locally draw down younger groundwater into the aquifer. This is examined as a case study within this current project – see Box 3 (page 26).

The Southern Marginal Alluvium

Located south of the Yamuna River along the southern edge of the upper and central Ganges basin, the marginal alluvium represents a genetically distinct typology composed of sediment sourced from Precambrian and Basaltic trap rocks south of the IGB (Heroy et al.

2003). The effective thickness of the aquifer typology is also substantially less - ranging from over 200 m in the north, to 100 m or less at the southern edge (Singh 1996). The permeability and specific yield of the marginal aquifer is, however, comparable to that within the upper and central Ganges basin (typology 2), as a result of similar processes of fluvial deposition, comparable sediment coarseness, and proportion of sand-dominated to silt and mud-dominated deposits (Saha et al. 2010). The groundwater quality of the typology is generally good, with large freshwater potential. Shallow groundwater is locally saline >1000 mg/l at the western limit of the typology as a consequence of water logging, or in pockets at depth associated with evaporite sequences deposits under previous climates.

The Sylhet Basin

The Sylhet Basin occupies a distinctive region in east Bangladesh of tectonic subsidence, and forms a discrete typology in the IGB aquifer system of significantly lower aquifer permeability <10 m/d and specific yield <5%. The typology is composed of a high proportion of silts, muds and clays (>60%) deposited in low energy fluvial and wetland settings in the basin (Johnson and Alam 1991). Channel deposits are often separated by significant thicknesses (tens of metres) of muds, and individual channel deposits have to be targeted in groundwater development (Johnson and Alam 1991). Depth to groundwater is very shallow (<3 m bgl), with water logging characteristic of the typology. Lower aquifer units are semi-confined or confined and typically have a piezometric head which is above the water-level in the upper aquifer units (Kinniburgh and Smedley 2000).

Groundwater abstraction is limited within the typology, probably as a result of the abundant rainfall. Actual groundwater recharge can be low, due to the lack of spare capacity within the aquifer to receive the recharge. There are locally elevated concentrations of arsenic within shallow groundwater and methane concentrations can also be elevated (Kinniburgh and Smedley 2000).

Western Indus Basin piedmont

The Western Indus piedmont forms a relatively narrow band of coarse high permeability deposits along the western margin of the Indus basin comparable in many respects to the Himalaya piedmont along the northern margin of the IGB. The typology is composed of poorly sorted gravels and coarse sands, with a minor component of silts. The typology is variable in thickness, but often not more than 100 m. In contrast to the Himalaya piedmont, average annual rainfall is less than 500 mm in the western Indus, and rainfall recharge is much more limited. Groundwater is generally saline, but with local exceptions. Localised recharge occurs from rivers and spate irrigation systems along the piedmont. Depth to groundwater is variable, and locally deep (>50 m).

Box 2 - Case study: Groundwater resilience in the Middle Hills of Nepal

Groundwater resources in the Middle Hills of the Himalaya perform a major role in supplying domestic and irrigation water and also in regulating flows in the major rivers in the basin (Andermann et al 2012). However, the significance of groundwater in this region is often unrecognised, and hydrological research has largely focussed on the glaciers with negligible field study of the groundwater. In this case study we undertake fieldwork within the Middle Hills of Nepal to investigate groundwater occurrence and use and also monitor its sensitivity to seasonal variability.

Case study objectives:

The groundwater resources in two contrasting catchments in the Middle Hills were investigated: Ramche at an elevation of 2000 – 3000 m, with subsistence terraced farming; and Madanpokhara which is largely below 1000 m, with expanding commercial agriculture. Springs, tubewells and streams within the two catchments were investigated using a combination of water use surveys, flow measurements, and sampling for inorganic chemistry, stable isotopes ($\delta^{18}O$ and $\delta^{2}H$), groundwater residence time indicators (CFC and SF_6) and noble gases. Groundwater sampling was conducted both pre- and post-monsoon. Several springs were monitored weekly for 1 year for flow and variations in stable isotopes. Preliminary results from the study are given in Bricker et al (2014).

Key results:

There is widespread dependence on springs for water supply in the Middle Hills, **particularly at higher altitudes. Diffuse high altitude springs showed a wide variability in flow throughout the year, but discrete, geologically controlled springs had more stable flow.** Groundwater residence time indicators (CFC and SF_6) indicate a mean residence time of 10-20 years for baseflow in the springs, and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) suggest this water is recharged locally. This evidence of decadal ages for groundwater suggests some in-built resilience to annual changes in precipitation.

Increased use of shallow groundwater resources in Madanpokhara in the last 5-10 years through the installation of hand-drilled tubewells in floodplain deposits, has reduced reliance on spring flows, and increased the resilience of communities to climate change. There has been increased agricultural development and inward population migration, but the resource is potentially vulnerable to over-exploitation. Concentrations of iron and manganese in excess of the Nepal Drinking Water Quality Standards were measured at some tubewells.

A) Typical terrace farming on hillslopes in the middle hills; B) shallow tubewell with handpump in Madanpokhara ©NERC 2014

Box 3 - Case study: Deep groundwater in Bangladesh and West Bengal

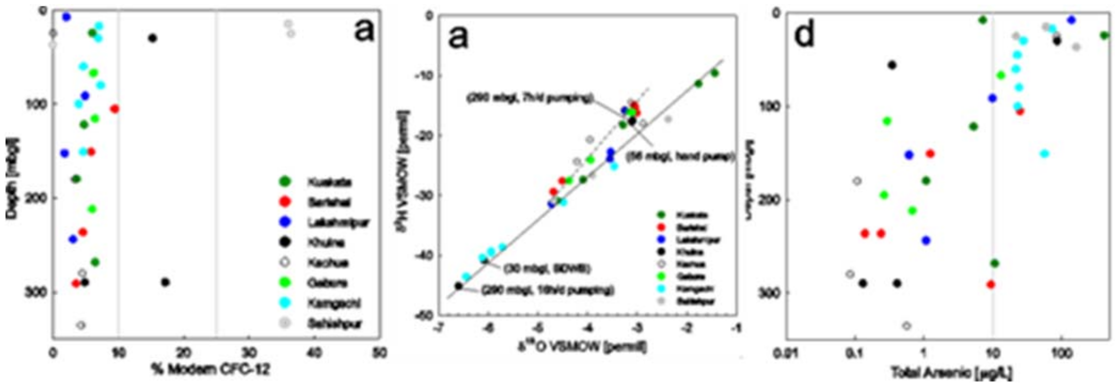
Deep groundwater (beyond 150 m depth) provides a strategic water supply for tens of millions of people in the Ganges-Brahmaputra-Meghna (GBM) delta region of Bangladesh and West Bengal as an alternative to shallow As contaminated groundwater. This case study generated new evidence of aquifer hydraulics in the GBM delta and the influences of both intensive deep groundwater abstraction (>150 m) and climate change.

Case study objectives: The study instrumented a series of nested piezometers to monitor high frequency variations in groundwater head at different depths both close to the coast and further inland. Repeated groundwater sampling was undertaken in both pumping and non-pumped tubewells (see Fig 1) for a suite of environmental tracers – including groundwater age tracers CFCs and SF_6, stable isotopes and noble gases. Preliminary results from the study are given in Taylor et al (2014).

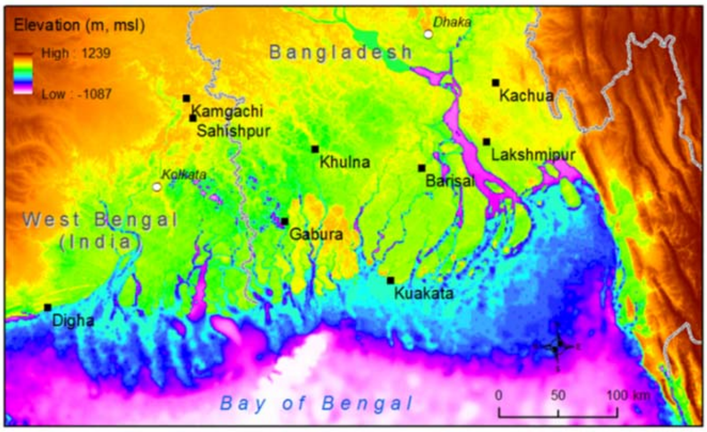
Key results:

Variations in deep groundwater head in the delta, remote from intensive abstraction, are dominated by the elastic response of the aquifer sediments to surface water loading. In coastal sites this is dominated by the rhythmic effect of tides, and further inland the response is dominated by monsoon flooding

The chemical tracers provide evidence that prolonged, intensive deep groundwater pumping modifies groundwater flow locally to that tubewell altering the sources of recharge and inducing a proportion of modern water to the deep abstraction tubewell.



Depth profiles for groundwater residence time tracer CFC-12 (left) and dissolved arsenic (right), with plot of $\delta^{18}O$ v $\delta^{2}H$ annotated to illustrate depth and regime of pumping at Khulna; regression line for shallow sites (<100 mbgl) shown as a solid line, regression line for deeper sites (>100 mbgl) shown as a dashed line



Location of study sites in GMB delta region

Table 1 – Summary of the main characteristics of the different groundwater typologies

	Hydrogeological properties	*Hydrochemistry characteristics*	*Recharge*	*Development status*
Piedmont margin	Variable spatial extent and aquifer thickness, often ≤100 m. K variable (1 – 50 m/d); Sy high (20 – 30 %)	Salinity not significant, arsenic variable, and can be >0.05 mg/L	Predominantly rainfall recharge (average annual rainfall >1000mm)	Low-moderate abstraction - (yield 5-15 l/s) Reliance on springs in hillslopes
Upper Indus and Upper-Mid Ganges	Extensive, highly permeable aquifer, at least 200 m thick High K (30 – 50 m/d, up to 70 m/d locally); Sy high (10 – 25 %)	Locally saline groundwater and local elevated arsenic. Contamination from intensive agriculture and urbanisation	Recharge occurs through both canal leakage and rainfall Extensive canals within typology, and average annual rainfall >750 mm	Highly exploited –many shallow tubewells (<100 m) and hand dug wells. Growing number of deeper tube wells
Lower Ganges and Mid-Brahmaputra	Extensive, highly permeable aquifer, at least 200 m thick. High K (40 – 80 m/d); high Sy (10 – 20 %) Water levels often very shallow, or at ground surface causing flooding	Salinity not significant. Local elevated arsenic concentrations in shallow groundwater	Rainfall recharge, and seasonal flooding from rivers High annual rainfall >1000 mm; canal irrigation limited	Groundwater is exploited but variable –many shallow tube wells (<100 m) and hand dug wells. Water-levels often shallow however.
The fluvial influenced deltaic area of the Bengal basin	Aquifer contains higher proportion of fine sands and laterally extensive low permeability silts. K and Sy can be moderate (10 - 25 m/d and <10 % respectively	Widespread high arsenic in shallow groundwater (>200 µg/L). Lower arsenic in deeper groundwater (>100 m)	Predominantly rainfall recharge (average annual rainfall high >2000mm)	Moderate to high groundwater abstraction Increasing focus on using deeper groundwater (>150 m).
Middle Indus and Upper Ganges	Extensive permeable aquifer within low rainfall region High K (30 – 50 m/d); and high Sy (10 – 20 %)	Extensive salinisation of groundwater (>2500 mg/L) away from rivers Locally elevated arsenic, fluoride, and nitrate.	Aquifer recharge predominantly from rivers and canal leakage Limited rainfall recharge with low, seasonal annual rainfall (<500 mm, <25 wet days).	High groundwater abstraction, falling water – tables and increasing salinity.

The Lower Indus	Moderately permeable aquifer within arid region. High proportion of fine sands and low permeability silts in aquifer; K (1 – 20 m/d), Sy (5 – 15 %)	Extensive salinisation of groundwater (>2500 mg/L) away from rivers. Some shallow thin freshwater lenses exist. Locally elevated natural arsenic, fluoride, and nitrate	Recharge almost entirely from canal leakage and irrigation returns. Annual rainfall <250 mm; and high evapotranspiration.	Limited groundwater abstraction for productive purposes but some for drainage.
The marine influenced deltaic areas	Low permeability aquifers in coastal regions composed of highly stratified silts and clays Moderate – low K (<10 m/d) and Sy (<5%)	*Pakistan coast:* groundwater extensively saline *Bangladesh coast:* shallow groundwater saline deeper groundwater can have much lower salinity	*Pakistan coast:* limited recharge from rivers and canals; negligible rainfall recharge *Bangladesh coast:* high rainfall recharge potential and river flow infiltration	Limited or no shallow groundwater abstraction; deeper non-saline groundwater is a vital resource to coastal towns in Bangladesh

5 Groundwater abstraction and groundwater levels

The IGB alluvium aquifer system is subject to considerable pressure, both from land use and groundwater abstraction, and changes to the hydrology from rainfall, river flow and irrigation. In this chapter we present datasets on the current groundwater abstraction across the IGB, and discuss how this is driven by agricultural activity. We also present data on groundwater level variations across the basin, interpreted from collating existing datasets across the IGB and a new statistical analysis of groundwater level data.

5.1 Groundwater abstraction

Figure 12 shows a map of the estimated groundwater abstraction across the IGB alluvial aquifer system and Table 2 gives the volume of groundwater abstracted from each typology. The methodology for compiling this dataset is discussed in Chapter 2. The total groundwater abstraction is estimated as 205 km^3 per annum. Approximately 122 km^3 is estimated from within India, 48 km^3 from the IGB within Pakistan, 34 km^3 from Bangladesh and less than 1 km^3 from within Nepal[3]. Over 90% of the abstraction is for irrigation and is therefore related to the agricultural practices. There are two main cropping seasons within the basin: the *kharif* from July to October during the monsoon and the *rabi* season from October to March. In some areas a third crop is grown from April to June.

Table 2 – Estimated abstraction from each typology

Typology	*Annual Abstraction In 2010 (km^3)*
T1 The Piedmont margin	8.9
T2 Upper Indus and Upper-Mid Ganges	72.9
T3 Lower Ganges and Mid Brahmaputra	38.5
T4 Fluvial influenced deltaic area	12.7
T 5Middle Indus and Upper Ganges	58.5
T6 Lower Indus	4.9
T7 Marine influenced deltaic areas	3
T8 Minor typologies	5.2

The main crops produced are rice, wheat, cotton and sugar cane. Figure 13 shows the different distribution of these crops across the aquifer and the most recent available information on the production of each crop (2011/12 and 2012/13). Production from the IGB comprises > 50% of the production of rice and sugar cane in Asia and two thirds of the region's wheat production. Rice, cotton and sugarcane are mainly grown in the *kharif,* and wheat and pulses during the *rabi* season. Both are irrigated. The third crop between April and June can also be irrigated, and the ability to cultivate this third crop may be related to the availability of irrigation water. Research using remote sensing in the Indus basin has indicated that actual water use by cotton is 500 – 650 mm, rice 350 – 470 mm, wheat 320 – 400 mm and sugar cane 840 – 1100 mm (Bastiaanssen et al. 2002) – in all cases at least 25% lower than the water requirements published by the FAO (Doorenbos and Kassam 1979).

---

[3] Compare with estimated global groundwater abstraction of 800 – 1000 km^3 (Margat and van der Gun 2013, Wada 2010) and total groundwater abstraction in the UK of <2.5 km^3

This practice of deficit irrigation over much of the basin has significant implications for the water resources, not only reducing the overall volume of groundwater used, but also limiting the salt flushed into the groundwater, and retaining the salt within the soil. Vegetables are grown in many parts of the basin and have higher water demands.

Groundwater abstraction for irrigation is seasonal. For much of the central basin, abstraction is highest during the *kharif* season (June to October) even though rainfall and surface water are most available at this time. Abstraction reduces during the *rabi* season, and reduces again during February and May. Groundwater abstraction is generally increasing annually across the basin as access to pumps and energy increases, and surface supplies become less reliable. Although reliable figures are difficult to come by, it is estimated that abstraction could be increasing across the basin annually at a rate of 2 – 5 km^3 per year (Shah 2007, 2009, CGWB 2011, Quereshi et al. 2008, FAO 2013).

Groundwater forms an important part of municipal supply across the IGB alluvial aquifer system, with many cities reliant on groundwater for much of their supply, including Delhi, Dhaka, and Lahore. For example abstraction in Dhaka is estimated at approximately 0.8 km^3 per year (DWASA 2012) and Lahore 1.1 km^3 per year (Basharat and Rizvi 2011). Since abstraction is localised to within the urban areas it leads to local unsustainability and falling water tables (Chatterjee et al. 2009)

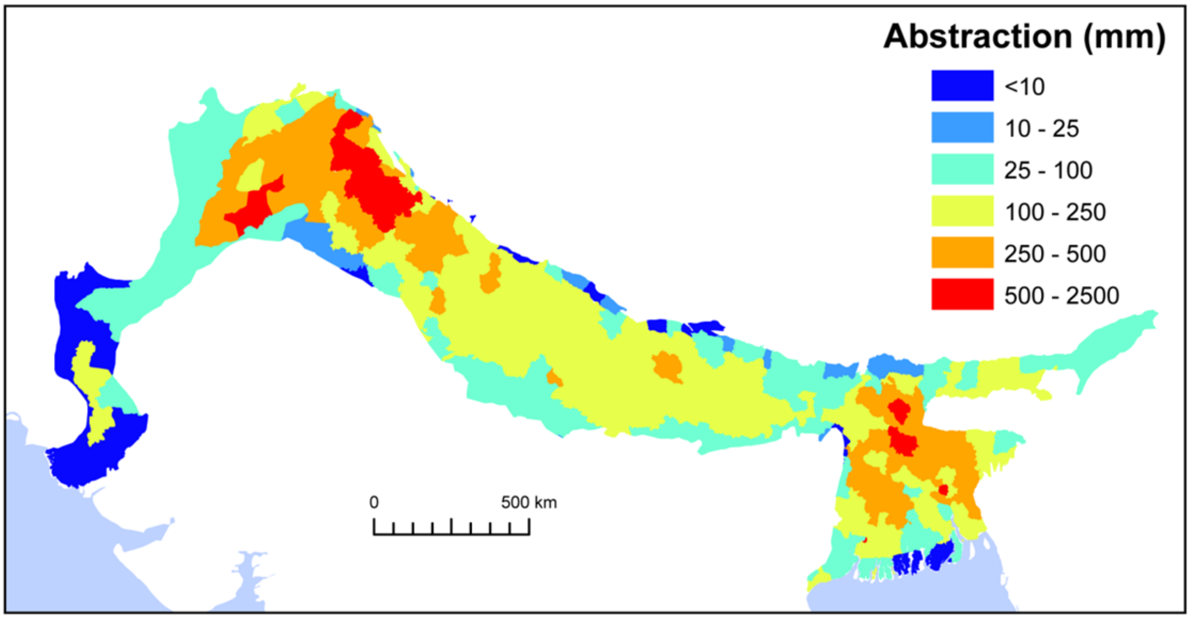


Figure 12 – Map of estimated groundwater abstraction across the IGB aquifer system in 2010. The total for the basin is 205 km^3*. Sources discussed in the Methods Section.*

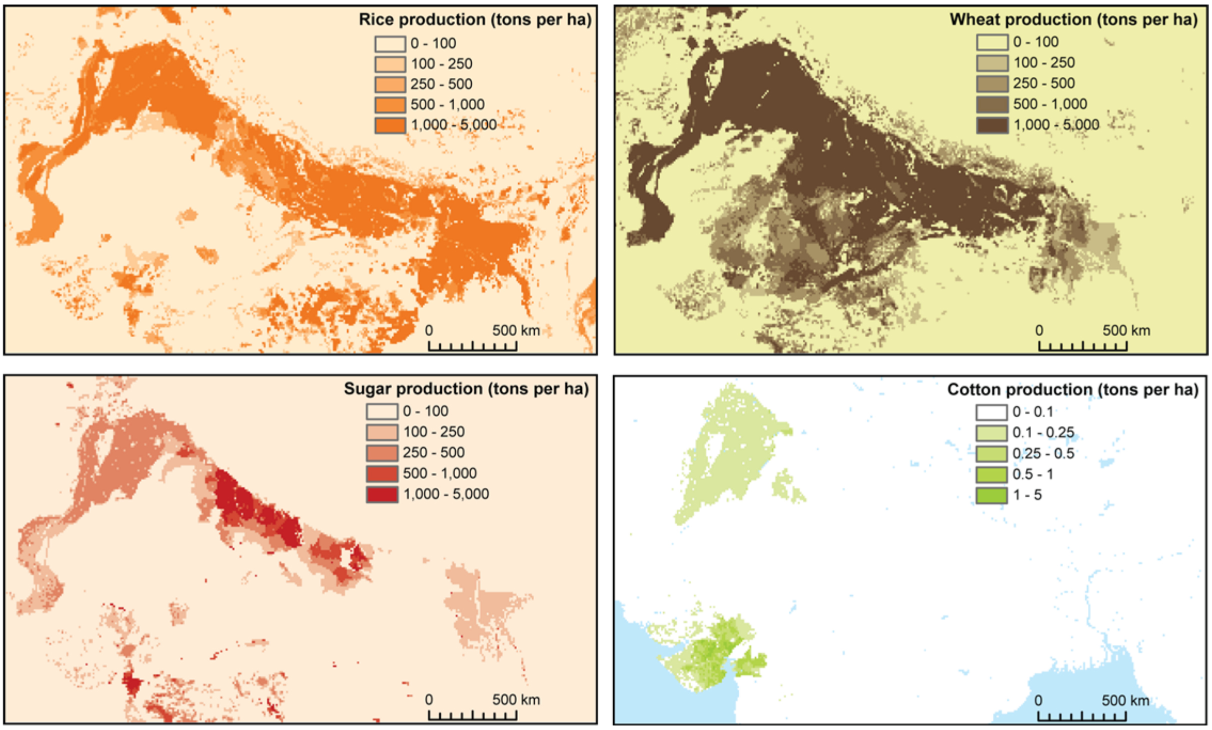


Figure 13 – Distribution of rice, wheat, sugar cane and cotton production across the IGB (Portmann et al. 2010). Rice: 122,000 tons (Pakistan 9,400, India 57,000, Nepal 5,100, Bangladesh 50,500); wheat 94,000 tons (Pakistan 23,500, India 67,700, Nepal 1,800, Bangladesh 1,000); sugar cane 229,000 tons (Pakistan 60,000, India 161,400, Nepal 2,800, Bangladesh 4,500); and cotton 3015 tons (Pakistan 2,215, India 765, Bangladesh 35 (source FAO STAT 2015, GOI 2013)

5.2 Groundwater levels

There has been much discussion about the change in groundwater levels across the basin with significant changes in groundwater level inferred from studies at different scales, using different data sources. Most notable are the estimates of groundwater-level changes from terrestrial water storage based on large-scale satellite measurements of gravity changes (e.g. Rodell et al. 2009; Tiwaru et al. 2009; Shamsudduha et al. 2012; Murray 2013; Chen et al. 2014). The resolution of these satellite based gravity measurements are, however, too coarse a resolution (400 x 400 km) to capture the significant local variations in groundwater level changes present across the basin. These large-scale remotely sensed studies are also often poorly constrained by local groundwater measurements, with some notable exceptions where good quality tubewell data are accessible (Shamsudduha et al. 2012). However, for much of the basin the quality of groundwater monitoring data is poor, and has not been easily accessible. There is also a paucity of deep groundwater-level data (>100 m depth) across most of the basin region.

Within this current study we developed a map across the IGB alluvial aquifer of trends in groundwater levels using exclusively ground based measurements. This map has been developed by spatial interpretation of groundwater levels from various published national assessments as a basemap, which were reinterpreted by using a subset of monthly and quarterly water-levels from >2300 shallow tubewells (0 – 100 m) across the basin to give the average depth of groundwater across the basin, and average seasonal variation in groundwater-levels. The 2300 subset of monitoring points were a subset of higher quality water levels monitoring points that had undergone some QA screening. Using these data enabled narrower categories of groundwater level variation to be mapped. The results are presented in Figures 14 to 16.

Overall, groundwater-levels are shallow across the basin, typically <5 m below ground level (bgl), with seasonal variation of a few metres. Against this, significant variations are evident, concurrent with areas of highest abstraction, and different recharge processes. In the Indian Punjab where abstraction is over double that in the rest of the basin, groundwater-levels are significantly deeper – over 40 % of the borehole records indicating groundwater is 20 – 50 m bgl, with seasonal fluctuations significantly greater than 5 m. Linear long term trend analysis of monthly time series of groundwater-level data, show this has equated to an average decline in groundwater level of up to 0.75 m/yr over the last 20 years – Figure 14. Downstream within the middle and lower Ganges, depth to groundwater systematically reduces to be <5 mbgl, with increasing rainfall recharge and lower abstraction – Figure 15. Long term trends of annual groundwater-level change become increasingly weaker from -0.15 m/yr in the Middle Ganges, to -0.02 to +0.05 m/yr in the Lower Ganges. In the Indus, a similar systematic downstream change is observed, but driven by canal leakage effects in the arid climate – Figure 15. Long term trends of annual groundwater-level change from -0.45 m/yr in the Middle Indus, to >+0.10 m/yr in the Lower Indus, reflecting the much lower abstraction and water-logging issues within the lower basin.

Greater detail to these trends can be seen in Figure 16, which presents 30 year time series rainfall and groundwater-level data from typical individual borehole hydrographs for different parts of the basin. In addition to the general trends outlined above, clear seasonal groundwater changes relating to abstraction can be seen in the individual hydrographs, against the long-term declining, stable or rising groundwater-level trends in different parts of the basin. The time series data also indicate that the significant long-term trend of groundwater-level decline in the Punjab are unlikely to be driven by climatic change, since the tlong-term average rainfall is consistent over the 30 year time series (see hydrographs A and B, Figure 16).

On a local scale, greater diversity is present within these large-scale trends, highlighting the true complexity of the system, and the sensitivity of the system to differences in local abstraction and recharge. Within the Indian Punjab, for example, there are still some areas of rising long-term trends in groundwater-level (against the overall trend of significant depletion in the region) and most likely as a consequence of canal leakage. Within the Bangladesh and Bengal deltaic region where the deeper aquifer exists, the deeper groundwater is confined, and the piezometric head (groundwater-level under pressure) cannot be simply be equated to increasing or decreasing recharge.

The recent observations of generally falling groundwater levels are part of a longer evolution of groundwater within the basin. Observation wells were first installed in irrigated parts of the basin in 1870 and the data for some wells are still available – Figure 17. These records demonstrate that for many decades, rising groundwater levels of up to 40 m was a major problem, due to the redistribution of river water from the major tributaries to the interfluve areas for irrigation. These rising groundwater levels caused water-logging in many areas and institutions were developed in the early 20th century to help manage water-logging and drainage. Figure 17 illustrates the current decline in groundwater levels now present in the Lower Bari Canal command area in Pakistan, due mainly to private abstraction for irrigation. In other parts of the IGB however, most notable in the Lower Indus, groundwater levels are still shallow and water logging remains an important concern.

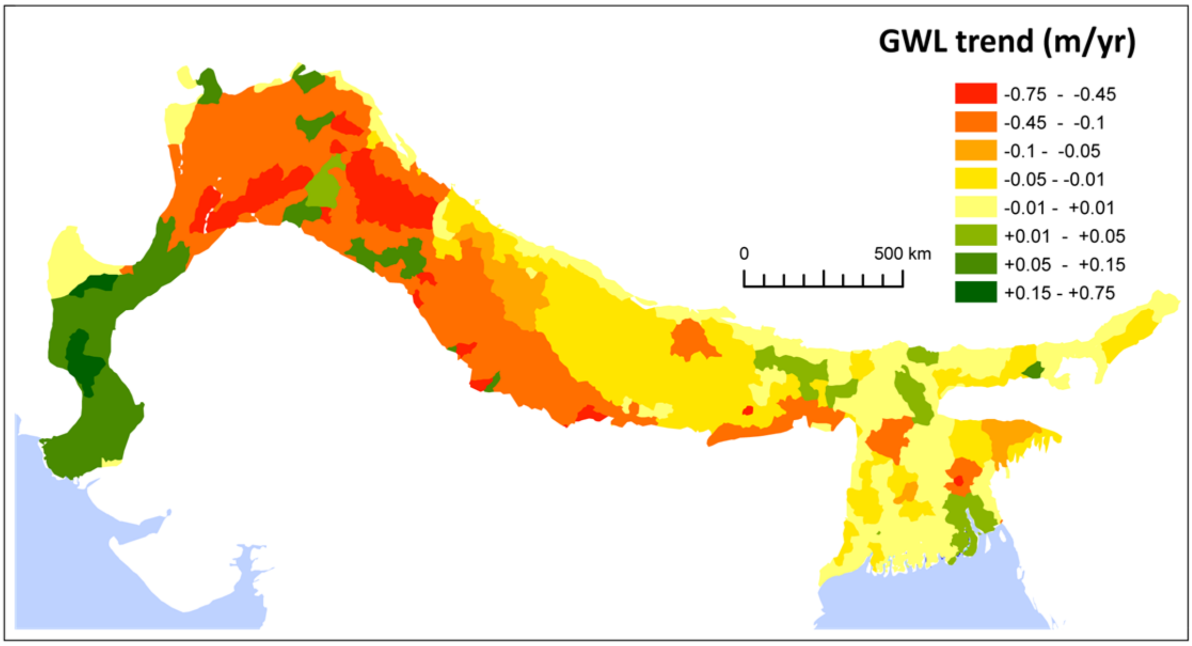


Figure 14 – Long term trends of groundwater-level change from high resolution 25 year time series data sets.

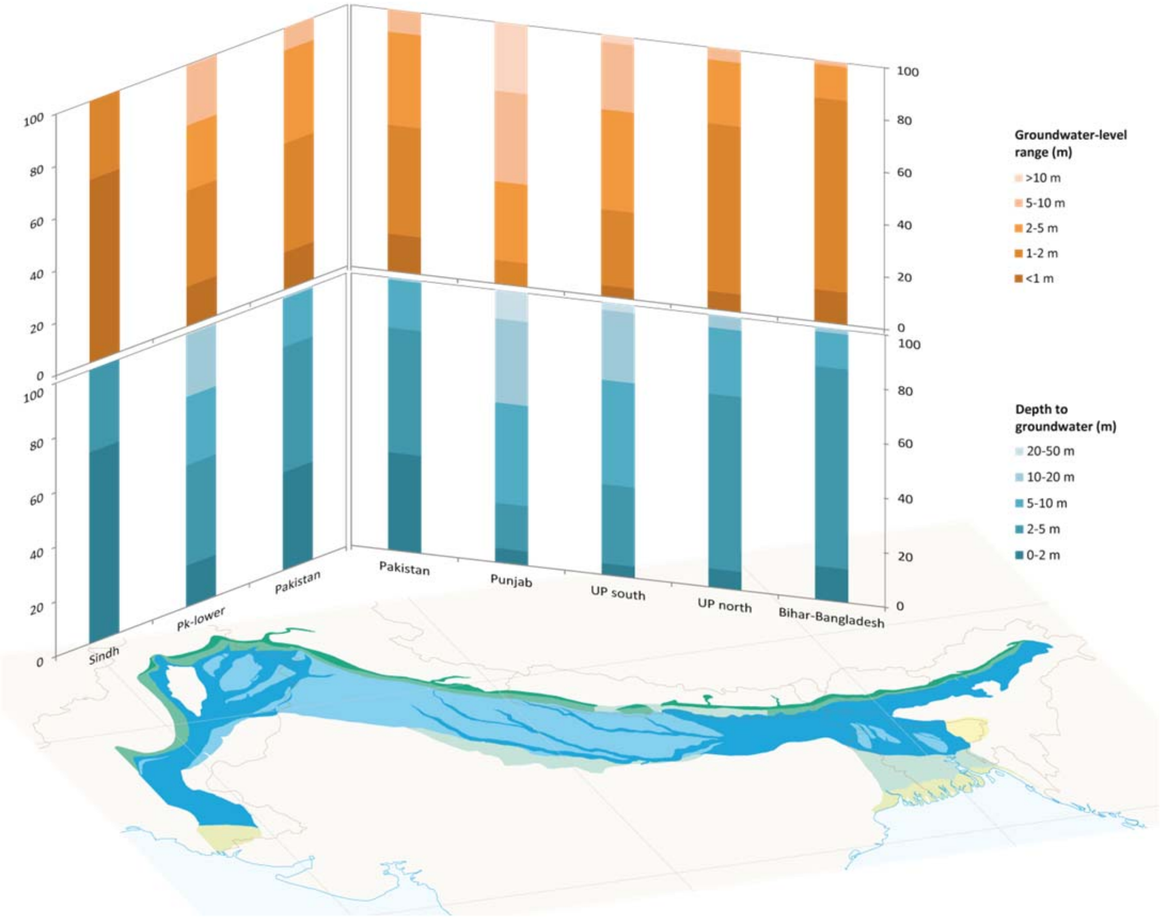


Figure 15 – Systematic changes in depth to groundwater and seasonal variance

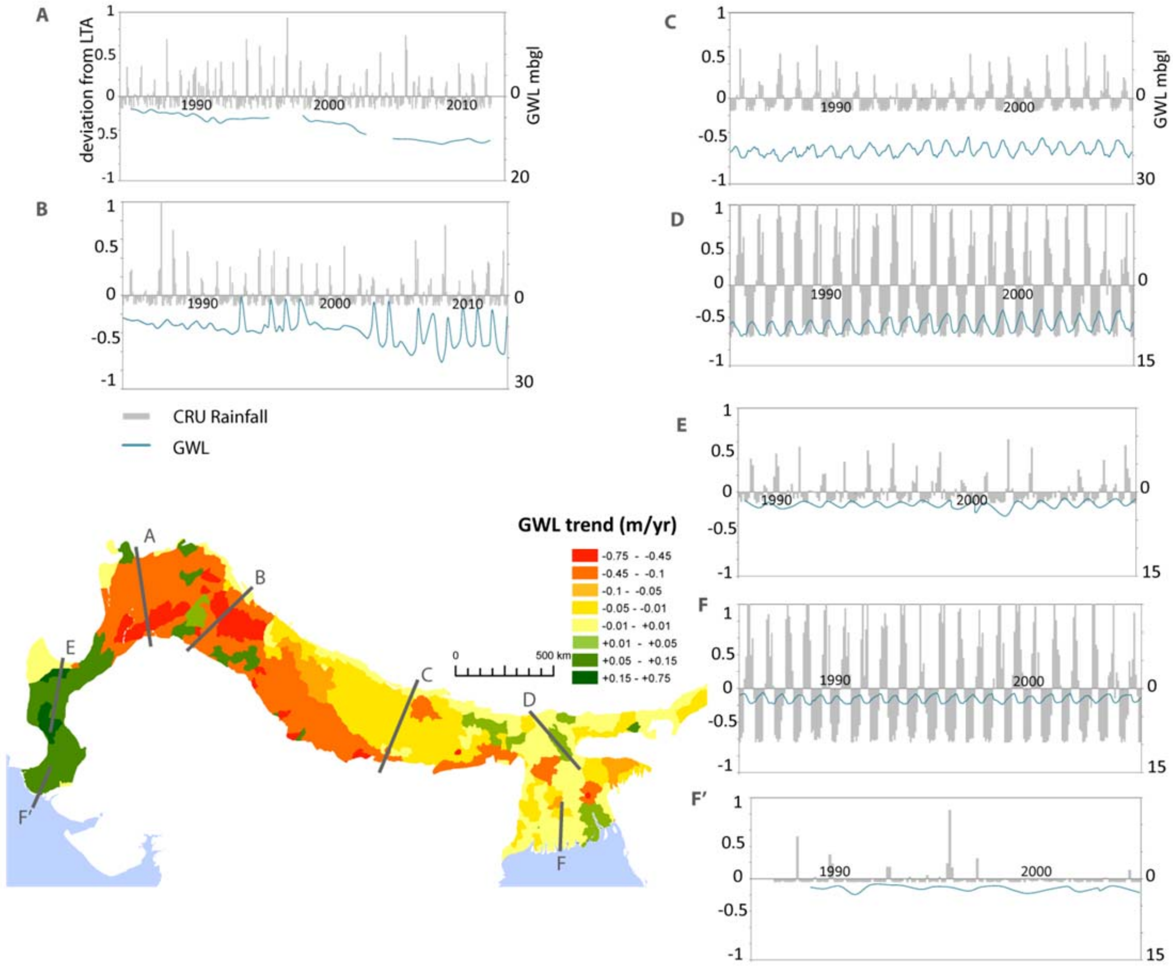


Figure 16 – Thirty year time series rainfall and groundwater-level data from typical individual borehole hydrographs for different parts of the basin. Monthly rainfall data is shown as deviation from the long-term average.

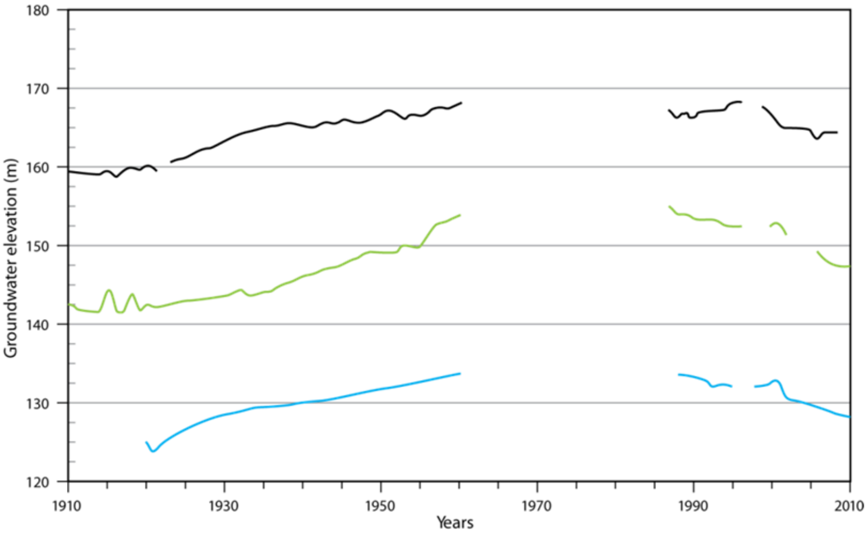


Figure 17 – Groundwater hydrographs from the Lower Bari Doab Canal irrigation area, Punjab, over 100 years. (Source: Basharat and Tariq (2013))

6 Resilience to future climate and abstraction

Reliably forecasting the future nature of the Indian monsoon is proving difficult, with many Global Climate Models disagreeing on the impact of future emissions scenarios on both the timing and magnitude of rainfall (Gosht et al. 2012). However, progress is being made by the climate modelling community, and some of the key processes driving climate variability are being identified, uncovered and modelled (Turner et al. 2012). From the perspective of groundwater, we need to understand how changes in the climate will impact on both abstraction and recharge. Looking at the issue from this perspective, there are some common elements of forecasts that could impact groundwater. There is a likelihood of increased storminess, with higher intensity rainfall as the energy in the climate system increases (IPCC 2013; Jiménez-Cisneros et al. 2014). The timing of the start of the monsoon may also change. Temperature is highly likely to increase markedly, although this will be moderated in the basin by local effects of irrigation and evapotranspiration (Harding et al. 2013). The increasing unreliability of rainfall and higher temperature are likely to exacerbate the demand for groundwater helping to sustain the rapid expansion of groundwater use (currently estimated at 2 – 5 km^3 per year).

Groundwater recharge in the basin is controlled by: rainfall recharge (where the forecast increase in intensity of rainfall may lead to increased recharge, Taylor et al. 2013); and leakage from canals and rivers. Future estimates of river flow are only as reliable as the future estimates of precipitation, which as discussed above are highly uncertain. For the Ganges, glacier melt comprises less than 10% of flow (Immerzeel et al. 2010), much of which occurs during the monsoon period; therefore it is likely that future changes in glacier melt will not be a controlling influence on groundwater recharge. The situation in the Indus is different, with a much higher proportion of flow related to glacier melt. In the medium term this is likely to lead to higher river flows as the rate of melting of the glaciers increases (Jiménez-Cisneros et al. 2014). In the long term, when the contribution from glacial melt will reduce, it is postulated that increases in precipitation and snowmelt will compensate (Immerzeel et al. 2010), although the uncertainty in future precipitation forecasting reduces the reliability of such predictions. A greater and more tangible risk to groundwater recharge are programmes to line tertiary canals and limit localised leakage and therefore limit recharge.

With such uncertainty about future precipitation and a likelihood of continued annual increases in abstraction (given the continuation of the drivers and incentives, such as energy subsidies, leading to groundwater abstraction) the *resilience* of the groundwater systems to change is a useful lens through which to examine the groundwater resource. Groundwater resilience to change is governed by the volumes of freshwater, the permeability of the aquifer system and the likely long term recharge (Foster and MacDonald 2014).

6.1 Groundwater storage volumes and trends

The usable groundwater resource in the IGB is a function of the depth of the aquifer, the specific yield of the sediments (a measure of the drainable groundwater, related to the porosity) and the salinity of the groundwater. For this analysis we have limited the depth of the aquifer to 200 m, partly because so little information on aquifer properties or salinity is available below that depth, and also because so few boreholes currently abstract water from below 200 m except in the Bengal Basin.

Overall groundwater storage in the top 200 m of the IGB alluvial aquifer system is estimated at approximately 30,000 km^3 ± 10,000 km^3. For comparison, the estimated annual surface water flow from the Indus and Ganges-Brahmaputra-Meghna is approximately 1,100 km^3 (FAO Aquastat 2014). The groundwater storage comprises 11,800 km^3 of high quality fresh water with TDS < 500 mg/L, 11,500 km^3 of water with TDS 500 – 1000 mg/L, 3,000 km^3 with TDS 1000 – 2500 mg/L and 3,300 km^3 with water of the poorest quality with TDS>2500 mg/L. Groundwater abstraction comprises 205 km^3 across the basin (in 2010), with much of it being abstracted from the freshwater areas: 159 km^3 from storage with TDS < 1000 mg/L, 32 km^3 from TDS 1000 – 2500 mg/L and 13 km^3 from TDS > 2500 mg/L. Therefore, this large store of groundwater offers a significant buffer against short term changes in climate, with several decades of abstraction within the aquifer, even if recharge were to cease. However, declining groundwater levels can have a devastating impact on ecosystems, river flows and users of shallow groundwater, many of whom will not be able to access deeper groundwater.

Figure 18 shows the estimated current annual change in groundwater storage across the basin, estimated from the groundwater level map developed for the basin as part of this study. A complex picture of groundwater storage changes emerges governed both by the abstraction and the recharge. Highest depletion of storage is occurring in parts of the Indian Punjab, Haryana and Punjab Region in Pakistan where annual mass change of > 100 mm equivalent of groundwater is occurring. If such trends of depletion continued, the groundwater resources in the upper 200 m in North West India and parts of the Punjab in Pakistan could be depleted to less than 50 % of their volume within 50 years. Similar trends are not observed in northern Bangladesh despite high abstraction, due to much greater natural recharge.

Groundwater accumulation also occurs– most notably in the Sindh, where groundwater has been accumulating at a rate of > 10 mm per year. This is reflected in the water-logging and corresponding salinity problems experienced in the Sindh. Groundwater accumulation also occurs across other parts of the basin – often close to where rapid depletion also occurs. This is a consequence of canal irrigation, where high leakage can cause rising groundwater levels and water-logging within one part of the canal command, and rapid depletion further downstream.

Across the entire basin, the annual change in groundwater storage is estimated at approximately 10 km^3. As discussed above, this integrates much complexity and variability within the IGB alluvial aquifer system, with some areas depleting and others accumulating. This compares well with the estimate of groundwater depletion using GRACE from Rodell et al. (2009) who estimated 18 km^3 depletion per year for the states of Rajasthan, Punjab and Haryana, with the majority of the depletion occurring in Rajasthan. Interpretation of GRACE data by Tiwari et al. (2009) inferred a much higher rate of depletion (approximately 50 km^3 per annum); however this work again had much of the depletion occurring outside the IGB alluvial aquifer system (e.g. within the poorer aquifer systems of Rajasthan) where recharge is negligible, and also indicated significant depletion in Bangladesh which was difficult to reconcile with observations (Shamsudduha et al. 2012). More recent work on the GRACE data by Chen et al (2014) suggests average depletion of 20 km^3 per year across the region (again with significant depletion outside of the IGB alluvial aquifer system), with several years actually showing net accumulation. Using GRACE within this region to infer groundwater storage change is challenging: for example accounting for the significant changes in mass balance from ongoing tectonic activity, erosion and sedimentation; the large surface water flows within the river systems, the changes in moisture in the atmosphere, and the change in mass from snow and ice melt. Constraining and disaggregating the bulk estimates of mass change from GRACE to give groundwater storage changes required additional information and data. It is hoped that the groundwater storage changes developed here from analysis of the best available regional observational groundwater level data and specific yield information will be a useful tool to the further development and interpretation of GRACE data in the region.

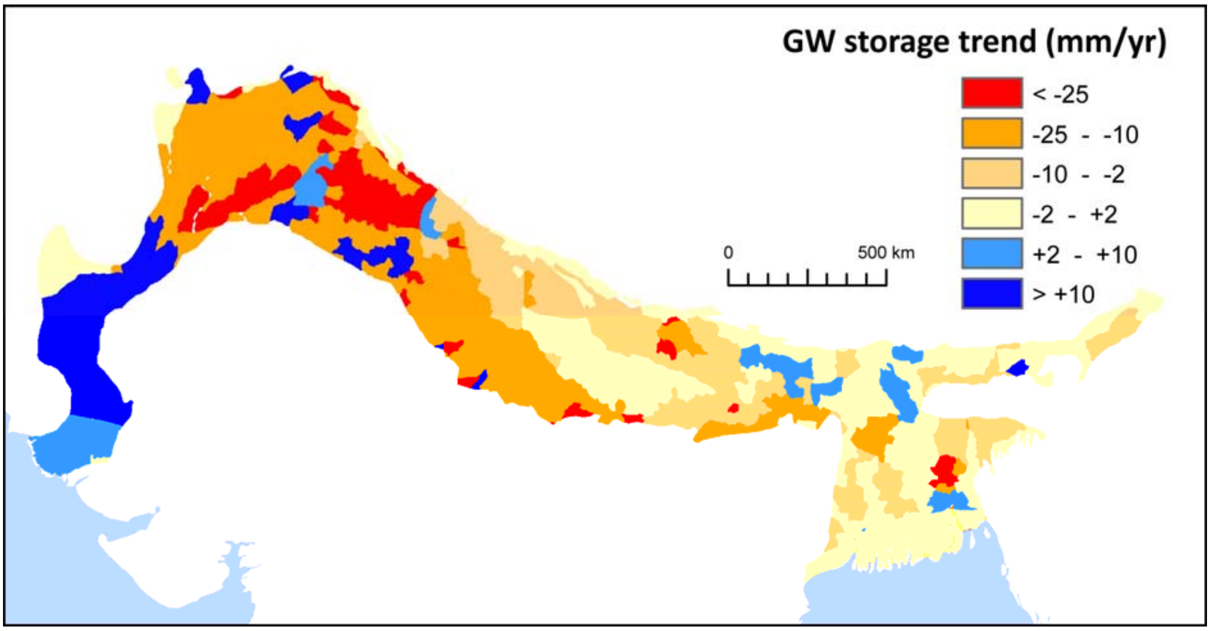


Figure 18 – The estimated annual change in groundwater storage estimated from the average annual measured change in annual water levels.

6.2 Groundwater Recharge

As discussed earlier, groundwater recharge for the IGB alluvial aquifer is difficult to estimate given the combination of factors controlling it, from rainfall volumes and intensities to canal leakage in some areas, irrigation returns, river inundation and even abstraction. To help map out changes in groundwater recharge, we have estimated net groundwater recharge across the basin, calculated from the difference between the annual abstraction and the estimated water mass storage changes. The net recharge is therefore the average annual water being added to the system (or a reduction in natural discharge to rivers) to stop groundwater being depleted even more rapidly. The maps of both the estimated abstraction and water mass change are subject to uncertainty, although we have been careful to use the best possible available field data, triangulated and cross checked with other sources where available. Overall, given an annual abstraction of >200 km^3 and an estimated annual depletion in storage of 10 km^3, net recharge to the basin is high. However this masks the considerable variability.

Figure 19 shows the net recharge estimated for the basin. The map indicates substantial net groundwater recharge in areas of high irrigation suggesting that abstraction is increasing net recharge by reducing natural discharges to rivers, creating storage space within the aquifer and also returning some abstracted groundwater as recharge. So for example, net groundwater recharge has been significantly enhanced in the Indian States of Punjab and Haryana, in parts of the Punjab region of Pakistan and also in northern Bangladesh. There are likely to be different mechanisms for increasing net groundwater recharge in each case. In Northern Indian Punjab (Upper Indus and Upper –Mid Ganges typology), high rainfall recharge occurs and recycling of pumped groundwater irrigation water (see Box 4, page 39); while in the southern Indian Punjab and Pakistan (Middle Indus and Upper Ganges typology), the net groundwater recharge can only be accounted for if we account for the large volumes of canal leakage. For example, given an estimated annual flow in the canal systems of the Indus of 120 km^3 and an estimated leakage to groundwater of 50%, then recharge of 60 km^3 per year could be occurring. Estimating canal flows in the Ganges canal systems is more difficult since data are not publically available; however, given a design capacity of approximately 300 km^3 and similar leakage to the Indus systems, recharge could be highly significant. In Bangladesh, groundwater levels are shallow, and increased abstraction has been shown to create space within the aquifer for additional recharge during the monsoon (Shamsudduha et al. 2012).

A caveat must be added to the above discussion, in that it is reliant on the quality of the existing groundwater level data for the basin. Although every effort has been made to QA and check the datasets used, there is still an absence of reliable representative groundwater level data across the IGB alluvial aquifer system. Only with improved groundwater level monitoring networks can more confident analysis be undertaken; as discussed above, it is unwise to rely on unconstrained large scale remotely sensed gravity data.

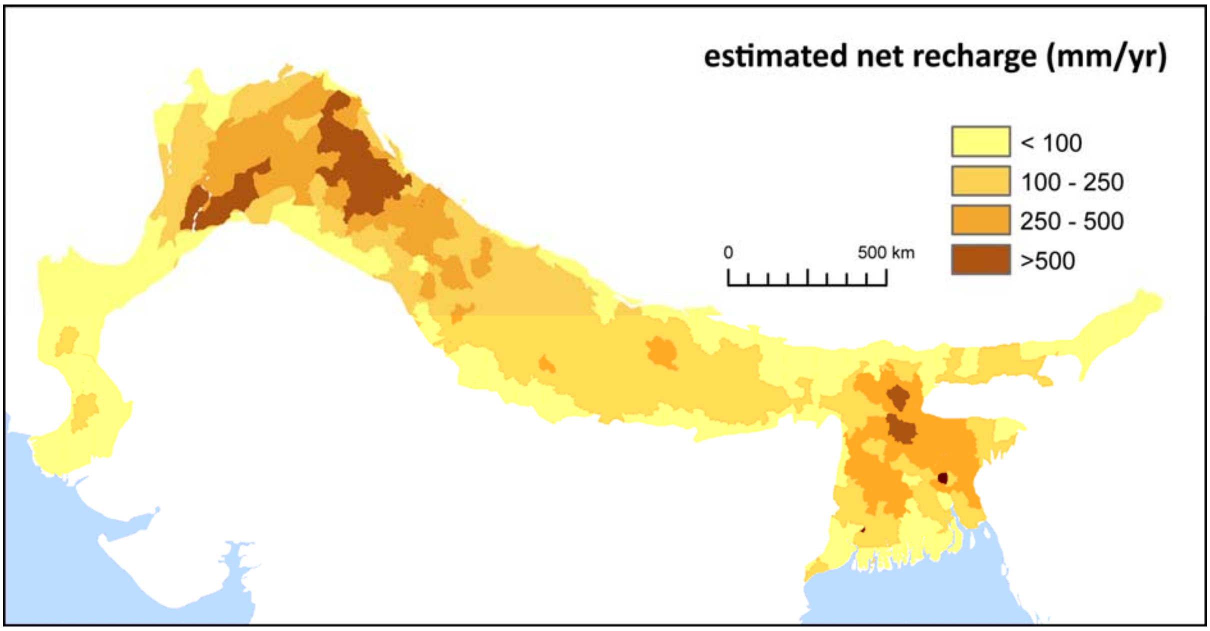


Figure 19 – Net recharge, calculated by subtracting the calculated annual water storage change from the abstraction. Net recharge will be equivalent to the groundwater recharge minus natural discharge to rivers.

Box 4 - Case study: Groundwater response to abstraction and recharge processes in Northern India

Punjab in northwest India is a key area for India's food production (e.g. rice, wheat and sugar) and both groundwater and surface water are intensely used for irrigation. Groundwater levels have been observed to be falling up to 80 cm per year in some places and pre monsoon groundwater levels can be > 20 mbgl. As a consequence deeper tubewells are now being drilled to abstract groundwater from depths of 150 m, augmenting abstraction from shallower tubewells. Understanding groundwater recharge processes and the connections between shallow and deeper groundwater will be vital to help manage the groundwater abstraction and reduce the impacts of unsustainable abstraction.

Case study objectives: A focussed hydrogeological study was carried out in the Bist-Doab area of northern Punjab, northwest India, to gather new evidence on recharge processes, groundwater quality, groundwater residence times, and the connectivity of shallow and deep groundwater. The study analysed 20-year records of groundwater level variations and undertook repeated sampling of shallow and deep piezometers using a suite of environmental tracers – including groundwater age tracers CFCs and SF_6, stable isotopes and noble gases (recharge source tracers). Nineteen paired shallow (8-50 mbgl) and deep (76-160 mbgl) tubewells were sampled both pre and post monsoon to provide new evidence on groundwater recharge and flow processes across a range of hydrological settings. Detailed results from the study are given in Lapworth et al (2015).

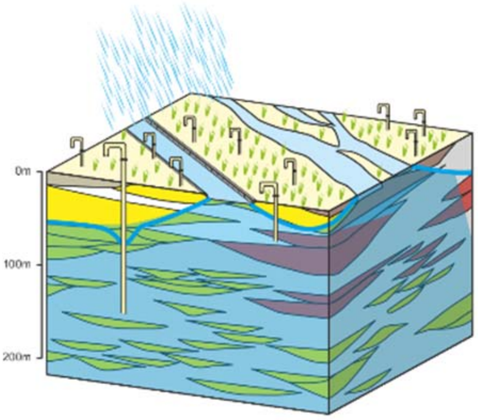
Key results:

Groundwater levels are not declining throughout the study area: but mostly at the end of the canal command areas, with more stable groundwater levels throughout other parts of the catchment.

The widespread occurrence of modern tracers in deep groundwater (>60% of sites had modern fractions >0.1) suggests that there is low aquifer anisotropy here and that deep aquifers are recharged by a significant component of modern (<75 years old) recharge via vertical leakage.

Stable isotope and noble gas results at all depths indicated modern meteoric conditions, with little evidence of widespread recharge from canal leakage in this area. Groundwater recharge is dominated by rainfall in this northern part of the Punjab.

Groundwater recharge:
Evidence from stable isotopes show that groundwater recharge is dominated by meteoric sources rather than canal leakage.



Groundwater residence times:
The shallow part of the aquifer system (0-50mbgl) has mean residence times between 1-50 years. The deeper part of the aquifer system (70-160mbgl) has mean residence times between 40-170 years.

Pumping enduced vertial leakage:
Widespread occurrence of modern tracers in deep groundwater, >60% of sites had modern fractions >0.1.

Groundwater quality:
Highest SEC (500-1200 μS/cm), and nitrate (0-40 mg/L) concentrations were found in shallow groundwater. Higher trace element concentrations (e.g. median U >15 μg/L) found at depth due to greater water rock interactions. Arsenic and fluoride concentrations were below WHO guideline values for both the shallow and deep groundwaters.

*SEC (Specific Electrical Conductivity)

So what of recharge to the IGB alluvial aquifer in the future? The climate forecasts do not suggest widespread and rapid reduction in precipitation volumes across the basin. Given the evidence that rainfall recharge can occur even where precipitation is low (<350 mm) and may be linked to intensity of rainfall events, significant rainfall recharge is likely to carry on within the bounds forecast for future climate variability. River flow is also not forecast to be severely impacted by climate change, or even glacier melting. However, river flow, particularly in the Indus, has been significantly impacted by diversions for irrigation, with severe impacts for the quality of water particularly in the Sindh. Canal leakage forms an important component of groundwater recharge, particularly in drier areas. Programmes to line tertiary canals, if not accompanied by a reduction in groundwater abstraction could have a much greater impact on groundwater recharge than any direct influence from climate change. Another area to focus on is returns from irrigation to the groundwater. Using more efficient irrigation methods may reduce this loss, and therefore reduce net groundwater recharge.

6.3 Degradation

The degradation of water quality is arguably the greatest threat to the IGB aquifer. Within the Indus Basin and parts of the Ganges, water management practices have led to significant degradation in groundwater quality, and continue to do so. Three of the most pressing issues are: increased salinization of the groundwater resources, contamination from agriculture and urban centres, and the mobilisation of arsenic and other naturally occurring contaminants. In this section we discuss salinization and agricultural contamination, arsenic and urban issues are considered separately below.

Irrigation and abstraction has led to considerable salinization of groundwater in the Mid Indus, Upper Ganges typology, and the Lower Indus groundwater typology – Figure 20. Canal leakage and irrigation returns, although useful for groundwater recharge, have also degraded the quality of the groundwater through water-logging and subsequent phreatic salinization. It is possible that increased groundwater abstraction has been reducing this trend by lowering groundwater levels, however, high abstraction has also mobilised older, deeper saline water into shallow depths. This is evident in Mid Indus /Upper Ganges typology where high abstraction is being accompanied by increasingly saline water. In the Indus, the reduction of outflow of water at the Kotri Barrage means that there is little or no natural outflow from the basin. Therefore, the salts generated from weathering of the rocks in the Himalaya are all retained within the basin, leading inevitably to an increase in salt concentration in the groundwater. Within the

Figure 20 - intensive agriculture within the Upper Ganges typology

lower Indus, much of the groundwater is already saline, and the shallow freshwater lenses are highly vulnerable to abstraction.

Intense groundwater abstraction is also accompanied by increases in the use of fertilizer, pesticide and herbicides. Elevated nitrate concentrations are found within the Punjab (Lapworth et al. 2014), and have been drawn down to >100 m depth by deep pumping. Elevated nitrate concentrations are also likely to be associated with the presence of other agriculturally derived contaminants. Recycling of groundwater through abstraction, irrigation and irrigation returns has also been shown to intensify this process (Ó Dochartaigh et al, 2010), with increasing concentrations of solutes and contaminants within irrigation returns derived from groundwater. Routinely monitoring groundwater quality enables trends in degrading quality to be identified and strategies developed to try to mitigate the problem.

6.4 Resilience of deep groundwater abstraction (in the Bengal Basin) against contamination by arsenic and salinity

The potential vulnerability of deep wells to contamination by arsenic and salinity drawn down over time from shallow and intermediate levels is critical to the security of water supply in Bangladesh (Burgess et al. 2010). Michael and Voss (2008) have concluded from a regional modelling study of the Bengal basin that deep groundwater "could provide arsenic-safe drinking water to >90% of the arsenic-impacted region over a 1000-year timescale, if its utilization is limited to domestic supply". In a similar region a modelling study of SE Bangladesh, UCL (2013) have concluded that "deep groundwater abstraction for public water supply in southern Bangladesh is in general secure against ingress of arsenic for at least 100 years".

Locally, deep groundwater is vulnerable to arsenic or salinity even under present pumping patterns, but these impacts are manageable through a programme of monitoring that could provide many years advance warning of impending problems. Despite concern for sustainability of the deep groundwater resource, there is little empirical evidence for an adverse impact on quality or water levels that can be attributed to deep groundwater pumping. In the Pakistan Punjab, there is evidence of upconing of deeper saline groundwater from abstraction. Across the basin, arsenic exceeds 10 μg/L in 18% of deep wells (Burgess et al. 2010), but whether this is a result of breached well casings or hydrological response to pumping remains uncertain. Empirical re-appraisal of 46 deep wells in south-central Bangladesh (Ravenscroft et al., 2013) shows groundwater composition at >150 m depth has remained largely unchanged for the 13 years between 1998 and 2011 and with no deterioration inferred over the operating lifetimes of the deep tubewells concerned, between 20 and 43 years.

Therefore, the deeper groundwater resources in the Bengal basin have a high general resilience to change induced by climate or pumping: they are largely divorced from the modern climate, with negligible modern recharge, and at a regional level there appears little evidence of widespread changes in arsenic concentrations. However, at a highly localised level, around individual wells, the heads induced by pumping, and disruption to the aquifer system during drilling can lead to localised contamination at depth / localised contamination pathways. Therefore routine monitoring both of the regional aquifer system and individual pumping wells is paramount.

6.5 High abstraction from cities

Groundwater from the IGB alluvial aquifer system sustains many of the region's cities, notably, New Delhi, Dhaka and Lahore. Although urban groundwater has not been a focus of this study, given that the total volumes abstracted are small compared to irrigation, and urban groundwater is a highly complex issue, the resilience of the water supplies to these cities is of major concern. The high density of the abstraction (e.g. for Dhaka an estimated 0.8 km^3 within 300 km^2 DWASA 2012) and the mixture of private and public water supplies, means groundwater is locally becoming highly depleted in these cities with groundwater levels falling rapidly (>100 m depth in some locations) and bringing with it a set of issues, such as subsidence, declining yields, increased costs (Morris et al. 2003) – Figure 21. In tandem with the high abstraction is pervasive, and widespread, contamination of groundwater from both domestic water (sewerage) and industrial waste (Foster and Choudhary 2009). The stratification of the aquifers protects some of the deeper groundwater from contamination, but shallow groundwater, often used for private water supply, can by highly contaminated. Therefore, continued good quality groundwater supply in the largest cities will be difficult to sustain in the long term, without developing large protected wells fields outside of the urban areas and building groundwater protection into land use planning. A systematic assessment of the scale and significance of existing groundwater pollution in city regions is also required, together with a robust evaluations of private water well use and the role of institutions in relation to urban groundwater use and protection (Foster and Choudhary 2009; Foster et al. 2010).

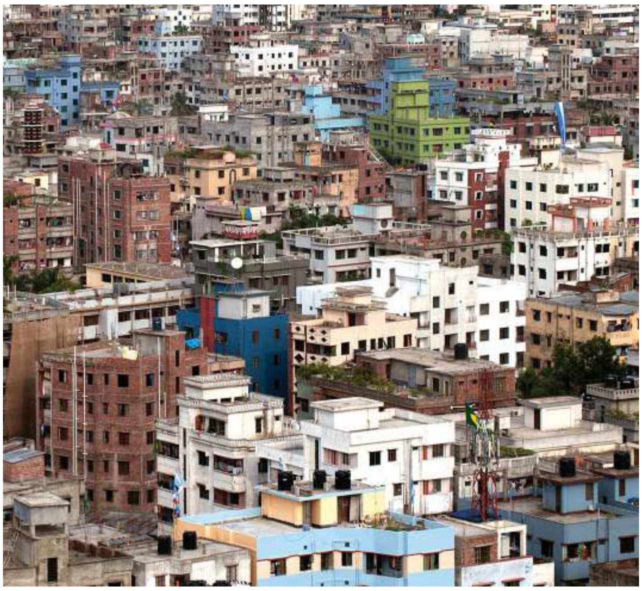


Figure 21 – Competing high abstraction rates from public and private water supply in Dhaka Mega City (Source: UN 2015)

7 Conclusions

Groundwater abstraction and water management practices within the IGB aquifer system pose a much greater risk to the future of groundwater within the basin than direct impacts from climate change. Recent changes in groundwater storage show an evolution driven by the presence of surface water irrigation canals and groundwater abstraction. Surface water irrigation has led to rising groundwater levels, and subsequent salinization in parts of the Indus and Upper Ganges basins and reduced river flows driven by canal diversions (particularly in the Indus) has reduced freshwater recharge in drier areas. The high groundwater abstraction (estimated 205 km^3) has led to significant depletion in some parts of the basin, most notably northwest India and the Punjab in Pakistan, and also induced greater recharge in wetter areas, for example in the Bengal Basin. Policies, such as the widespread lining of canals to reduce leakage, will impact the groundwater resources, which have come to rely on the large additional recharge that canal leakage provides.

The direct impacts of climate change are likely to be minor in comparison, with forecast total rainfall volumes and river flows likely to change only incrementally, and intense rainfall events which drive groundwater recharge, becoming more common. Indirect impacts of climate change may be more important, with concerns over the timing of the start of the monsoon, and increasing temperatures leading to a greater demand for groundwater.

The large volumes of groundwater within the aquifer system provides it with a significant buffer to external changes, and therefore should enable conjunctive surface water and groundwater management strategies to be developed. Of greater concern than widespread depletion of groundwater is the degradation of water quality. Increased salinization of groundwater is occurring through irrigation, water-logging and mobilisation of deeper groundwater by abstraction. The large reduction of outflow from the Indus River has led to salts generated from the weathering and erosion of the Himalayas to be retained within the aquifer. The increased use of fertilizers, pesticides and herbicides across the aquifer, coupled with the recycling of groundwater irrigation water are also leading to noticeable contamination.

The groundwater typologies developed in this study allow a new lens through which to view the groundwater resources of the IGB and their resilience to change. Each typology has its own unique set of challenges and opportunities for groundwater development, and the aquifer characteristics determine how the groundwater will respond to current and future drivers. In the first instance, the typologies could be used to help prioritise groundwater monitoring and investigation, before the eventual development of different management strategies. For example, within the Upper Ganges and Middle Indus, falling water tables and salinization associated with widespread unsustainable abstraction is the major concern, whereas in the Middle Ganges there may be plenty opportunities for increased groundwater abstraction; and in the Bengal Delta area monitoring and protection of the deeper good quality groundwater is a priority.

References

Acharyya SK. 2005. Arsenic levels in groundwater from Quaternary Alluvium in the Ganga Plain and Bengal Basin, Indian subcontinent: insights into influence of stratigraphy. Gondwana Research, 8; 1; 55-56.

Agrawal GD, Lunkad SK, Malkhed T 1999. Diffuse agricultural nitrate pollution of groundwaters in India Water Sceince and Technology 39 (3) 67-75

Ahmad, 1993. Water Resources of Pakistan. Pp355.

Ahmed, 1995. Groundwater Resources of Pakistan. 560 pp

Ahmad, S, Mulk S and Amir M. 2002. Groundwater Management in Pakistan. First South Asia Water Forum Kathmandu Nepal. Printed by Pakistan Water Partnership

Allison MA, Khan SR, Goodbred Jr SL & Kuehl SA. 2003. Stratigraphic evolution of the late Holocene Ganges-Brahmaputra lower delta plain, Sedimentary Geology, 155; 317-342

Amini M. et al. 2008. Statistical Modelling of Global Geogenic Arsenic contamination in groundwater, Environmental Science and Technology, 42; 3669–3675

Andermann, C., Longuevergne, L. Bonnet, S., Crave, A., Davy, P. and Gloaguen, R. 2012. Impact of transient groundwater storage on the discharge of Himalayan rivers. Nature Geoscience, 5(2): 127-132

Arshad M, Ahmad N, Usman M, Shabbir S. 2009. Comparison of water losses between unlined and lined watercourses in Indus Basin of Pakistan, Pakistan Journal of Agricultural Sciences, 46; 4, 280-284.

Basharat M. 2012. Spatial and temporal appraisal of groundwater depth and quality in LBCD command - issues and option. Pakistan Journal of Eng. And Applied Science, 11; 14-29.

Basharat M, Hassan D, Bajkani AA and Sultan SJ. 2014. Surface water and groundwater Nexus: groundwater management options for Indus Basin Irrigation System, International Waterlogging and Salinity Research Institute (IWASRI), Lahore, Pakistan Water and Power Development Authority, Publication no. 299, pp 155.

Basharat M and Rizvi SA, 2011. Groundwater Extraction and Waste Water Disposal Regulation-Is Lahore Aquifer at Stake with as Usual Approach? In proceedings of World Water Day -2011 "Water for Cities-Urban Challenges" organized by Pakistan Engineering Congress, Lahore, Pakistan: Pp 135-152.

Basharat M and Tariq AR. 2013. Long-term groundwater quality and saline intrusion assessment in an irrigated environment: a case study of the aquifer under LBDC irrigation system, Irrigation and Darinage, 62; 510-523, doi: 10.1002/ird.1738.

Bastiaanssen WGM, Ahmad MD, Chemin Y 2002. Satellite surveillance of evaporative depletion across the Indus Basin. Water Resource Research 38 (12) 1273 doi:10.1029/2001WR000386

Bennett GD, Rehman AU, Sheikh JA, Ali S. 1969. Analysis of pumping tests in the Punjab region of west Pakistan, Geological Survey Water-Supply Paper 1608-G, prepared in cooperation with the W Pakistan Water & Power Dec Authority under US AID

Bhattacharya P, Mukherjee A, Mukherjee AB. 2011. Arsenic contaminated groundwater of India. In Nriagu J (ed): Encyclopedia of Environmental Health. Elsevier BV (Netherlands). 150-164 (Modified from Chakraborti et al. 2004).

Bricker SH, Yadav SK, MacDonald AM, Satyal Y, Dixit A and Bell R. Groundwater resilience Nepal: Preliminary findings from a case study in the Middle Hills, British Geological Survey Open Report, Groundwater Science Programme, OR/14/069, 58 pp.

Burgess WG, Hoque MA ,Michael HA, Voss CI, Breit GN and Ahmed KM 2010 Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic. Nature Geoscience 3: 83-87

CGWB. 2007. Ground Water Scenario, India. CGWB, Ministry of Water Resources, Government of India. Faridabad BM Jha (ed).

CGWB. 2009. Dynamic groundwater resources of India 2009, CGWB, Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India, pp 299

CGWB 2010. Groundwater quality in shallow aquifers of India. Central Groundwater Board, Ministry of Water Resources, Delhi.

CGWB 2012. Aquifer systems of India. Central Groundwater Board, Ministry of Water Resources, Delhi.

CGWB. 2012. Ground Water Year Book - India. CGWB, MoWR, Government of India, Faridabad

CGWB. 2014. Ground Water Year Book 2012-13 - India. CGWB. 100 pp

CGWB. 2014. Water Quality Issues and Challenges in Punjab, CGWB, Ministry of Water Resources, Government of India report, March 2014, pp 182.

Chaturvedi, RS. 1973. A note on the investigation of ground water resources in western districts of Uttar Pradesh. Annual Report, U. P. Irrigation Research Institute, 1973, pp 86-122.

Chatterjee R, Gupta BK, Mohiddin SK, Singh PN ,Shekhar S and Porohit R 2009. Dynamic groundwater resources of National Capital Territory, Delhi: assessment, development and management options. Environmental Earth Sciences, 59: 669-686

Chaudhri. AU. 1966. Analysis of Hydrologic Performance tests in unconfined aquifers, MSc thesis, The University of Arizona.

Cheema MJM, Immerzeel WW and Bastiaanssen Wgm 2014. Spatial quantification of groundwater abstraction in the irrigated Indus Basin. Groundwater 52: 25-36

Chen J, Li J, Zhang Z and Ni S. 2014. Long-term variations in Northwest India from Satellite gravity measurements, Global and Planetary Change, 116; 130-138.

Chilton PJ. 1986. Pakistan Scavenger wells pilot project: an introductory note for BGS staff, BGS Technical report WD/0S/86/16, pp21.

Clift P D and Giosan L. 2013. Sediment fluxes and buffering the post-glacial Indus Basin, Basin Research, 25; 1-18.

Clyma W, Ali A and Ashraf M. 1975. Watercourse Losses, in Proceedings of CENTO Panel Meeting of the Optimum Use of Water in Agriculture. Nuclear Institute of Agricultre and Biology: Faisalabad, Pakistan, March 15, 1975.

Datta PS and Goel PS. 1977. Groundwater recharge in Panjab State (India) using Tritium Tracer, Nordic Hydrology, 8; 255-236.

Davies C, Best J & Collier R. 2003. Sedimentology of the Bengal shelf, Bangladesh: comparison of late Miocene sediments, Sitakund anticline with the modern tidally dominated shelf, Sedimentary Geology 155; 271-300.

Day JBW. 1971. A preliminary assessment of gw resources of the Tarai East of the Dauney Hills, Nawal Parasi District, Nepal, IGS report WD/71/7, pp 19.

Dhiman SC. 2012. Aquifer systems of India, Central Ground Water Board, Ministry of Water Resources, Gov of India, pp111

DPHE. 2007. Final Report on Development of Deep Aquifer Database and Preliminary Deep Aquifer Map, DPHE, Government of the People’s Republic of Bangladesh, pp 173.

DPHE/ BGS. 2001. Arsenic contamination of groundwater in Bangladesh. Kinniburgh DG & Smedley PL (eds). British Geological Survey Technical Report WC-00-19, BGS, Keyworth

Döll P and Fiedler K. 2008. Global-scale modelling of groundwater recharge, Hydrology and Earth Systems Science, 12; 863-885.

Doorenbos, J. & Kassam, A.H. 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33. Rome, FAO.

FAO. 1992. The use of saline waters for crop production, FAO Irrigation and Drainage Paper 48, United Nations, Rome, pp 128

FAO. 2012. Irrigation in Southern and Eastern Asia in Figures, AQUASTAT Survey 2011, FAO Water Reports 37, Rome pp 512.

FAO AQUASTAT 2014. Food and agriculture organization of the United Nations (Accessed Feb 2015)

Fendorf S, Michael HA, van Geen A 2010. Spatial and temporal variations of groundwater arsenic in south and southeast Asia, Science 328 1123-1127 DOI: 10.1126/science.1172974

Foster S and Chaudhary NK. 2009. Lucknow City – India: Groundwater Resource Use and Strategic Planning Needs, GW-MATE Case Profile Collection, in Sustainable Groundwater Management: Lessons from Practice, World Bank, pp 8.

Foster S. and MacDonald AM . 2014 The 'water security' dialogue: why it needs to be better informed about groundwater. Hydrogeology Journal, 22; 7, 1489-1492.
Foster S, van Steenbergen F, Zuleta J and Garduno H. 2010. Conjuctive use of groundwater and surface water – from spontaneous coping strategy to adaptive resource management. GW-MATE Strategic Overview Series 2: World Bank, Washington DC, pp 26.

France-Lanord C. 1993. Evolution of the Himlaya since Miocene time: isotopic and sedimentological evidence from the Bengal Fan, Geological Society London Special Publications, January 1993, doi: 10.1144/GSL.SP.1993.074.01.40

Garduño H , Foster SSD 2010. Sustainable groundwater irrigation -- approaches to reconciling demand with resources. GW-MATE Strategic Overview Series, 4, World Bank, Washington DC.

Geoconsult. 2012. Study of tube well inventory of 22 Terai and Inner Terai Districts, Nepal, Government of Nepal Ministry of Iririgation Groundwater Resources Development Board, Katmandu, 69 pp.

Goel PS, Datta PS, Tanwar BS. 1977. Measurement of vertical recharge to groundwater in Haryana State (India) using Tritium Tracer, Nordic Hydrology, 8; 211-224.

Government of India (GoI). 2012. All India Report on Input Survey 2006-07. New Delhi: Agriculture Census Division, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India

Government of India (GoI) 2013. State of Indian Agriculture 2012-13. Ministry of Agriculture, Government of India, New Delhi.

Goodbred AL & Kuehl SA. 2000. The significance of large sediment supply, active tectonism and eustasy on margin sequence development: late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta, Sedimentary Geology, 133; 227-248

Goodbred S L. 2003. Response of the Ganges dispersal system to climate change: a source to sink view since the last interstade, Sedimnetary Geology, 162; 1-2, 83-104. *continuity of sed dep processes

Goodbred SL, Kuehl SA, Steckler MS, Sarker MH. 2003. Controls on facies distribution and stratigraphic preservation in the Ganges-Brahmaputra delta sequence. Sedimentary Geology, 155; 301-316.

Grey DRC, Bath AH & Oliver D. 1979. Tubewell deterioration in salinity control and reclamation projects, Pakistan, IGS report, WD/OS/79/20, pp24.

Groundwater Development Consultants (GDC). 1994. Reassessment of the GW Development strategy for Irrigation in the Terai, Vol 6 Maps, April 1994.

Gupta SK, Deshpande RD, Agarwal M & Raval BR. 2005. Origin of high flouride in groundwater in the North Gujurat-Cambay region, India, Hydrogeology Journal, 13; 596-605

Gurung JK, Ishiga H & Khadka MS. 2005. Geological and geochemical examination of arsenic contamination in groundwater in the Holocene Terai Basin, Nepal, Environ Geology, 49; 98-113.

Halcrow-ACE, 2003. Exploitation and regulation of fresh groundwater-Main Report. ACE-Halcrow JV Consultants, Gulberg III, Lahore, Pakistan. DWAS 2012. Annual Report of 2011-12 Dhaka Water Supply & Sewerage Authority, Dhaka

Harding RJ, Blyth EM, Tuinenburg OA and Wiltshire A. 2013. Land atmosphere feedbacks and their role in the water resources of the Ganges basin, Science of the Total Environment, 468-469, S85-92.

Harvey CF et al. 2006. Groundwater dynamics and arsenic contamination in Bangladesh, Chemical Geology, 228; 112-136.

Heroy D, Kuehl SA, Goodbred Jr. SL. 2003. Mineralogy of the Ganges and Brahmaputra Rivers: implications for river switching and Late Quaternary climate change. Sedimentary Geology, 155; 343-359

Hoque MA and Burgess W. 2009. Provenance and travel time of groundwater pumped from 'arsenic safe' depths in the aquifer of southern Bangladesh: aquifer representation to assess

Hoque MA and Burgess WG 2012. ^{14}C dating of deep groundwater in the Bengal Aquifer System, Bangladesh: implications for aquifer anisotropy, recharge sources and sustainability. Journal of Hydrology 444-445: 209-220

Immerzeel WW. Pellicciotti F and Bierkens M.F.P. 2013. Rising river flows throughout the twenty-first centrury in two Himalayan glacierized watersheds, Nature Geoscience, Letters, doi: 10.1038/NGEO1896

IPCC. 2013. Climate Change 2013: The Physical Science Basis, pp 1535

IPCC. 2014. Climate change 2014: Impacts, Adaptation, and Vulnerability, IPCC Working Group II report – Freshwater Resources, pp 232-257.

IWASRI 2005. Drainage Atlas of Pakistan, International Water Logging and Salinity Research Institute, Lahore.

Jain SK (ed) 2009. Special Issue on West Bengal, Bhu-Jal News - Quarterly Journal of Central Ground Water Board Volume No.24 , Number 1, Jan-March 2009

Jiménez-Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila. 2014. *Freshwater resources*. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

Johnson, Y.J., Alam, A.M.N., 1991. Sedimentation and tectonics of the Sylhet Trough, Bangladesh. Geological Society of America Bulletin, 103; 1513–1527.

Jones PH. 1985. Geology and Groundwater Resources of Bangladesh, World Bank South Asian Region, 60 pp.

Jones P D and Harris I. 2013. University of East Anglia Climatic Research Unit; CRU TS3.21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2012). NCAS British Atmospheric Data Centre, 24th September 2013. doi:10.5285/D0E1585D-3417-485F-87AE-4FCECF10A992.

Jurriens R. and Mollinga P.P. 1996. Scarcity by design: protective irrigation in India and Pakistan. ICID Journal. 45(2) (1996) pp: 31-53

Khan MMH, Aklimunnessa K ,Kabir M, Mori M 2007. Determinants of drinking arsenic-contaminated tubewell water in Bangladesh. Health Policy and Planning 2: 335-343

Khan MR, Voss CI, Yu W and Michael HA. 2014. Water resources management in the Ganges Basin: A comparison of Three Strategies for Conjunctive use of groundwater and surface water, Water Resources Management, doi:10.1007/s11269-014-0537-y

Khan S, Rana T, Gabriel HF, Ullah MK. 2008. Hydrogeologic assessment of escalating gw exploitation in the Indus Basin, Pakistan, Hydrogeology Journal, 16; 8; 1635-1654.

Kinniburgh & Smedley. 2000. Arsenic contamination of groundwater in Bangladesh, BGS Technical Report WC/00/19 Vol 1, 656 pp

Kumar CP and Seethapathi PV. 2002. Assessment of Natural Groundwater Recharge in Upper Ganges Canal Command area, Journal of Applied Hydrology, 15; 4, 13-20.

Kumar MR, Mishra DC and Singh B. 2013. Lithosphere, crust and basement ridges across the Ganga and Indus basins and seismicity along the Himlayan front, India and Western Fold Belt, Pakistan, Journal of Asian Earth Sciences, 75; 5, 126-140.

Kumar P, Kumar M, Ramanathan AL & Tsujimura M. 2010. Tracing the factors responsible for arsenic enrichment in groundwater of the middle Gangentic Plain, India: a source identification perspective. Envion Geochem Health. 32; 129-146.

Lapworth DJ, Gopal K, Rao MS, MacDonald AM. 2014. Intensive Groundwater Exploitation in the Punjab – an evaluation of resource and quality trends, British Geological Survey Open Report, Groundwater Science Programme, OR/14/068.

Lapworth DJ, MacDonald AM, Krishan G, Rao MS, Gooddy DC and Darling WG., 2015. Groundwater recharge and age-depth profiles of intensively exploited groundwater resources in northwest India. Geophysical Research Letters, *Submitted*.

Lawrence AR. 1985. the problem of the high nitrate groundwater in the phreatic aquifer of Delhi, India, IGS report, WD/OS/85/8, pp 18.

Lovelock PER & Murti PK. 1972. Results of the Spring 1972 Groundwater survey in Nawalur, South Central Nepal. IGS report, WD/72/7, pp44.

MacDonald & Partners. 1982. Second Tubewell Project, Final report Vol III, Groundwater, 53 pp.

MacDonald & Partners. 1986. Phase One Completion Report, Annexure I: Project Well Data, Kishorganj & Dhaka Regions, Government of the Peoples Republic of Bangladesh, Bangladesh Agricultural Development Corporation, 134 pp.

Mahanta et al. 2012. Mineralogy, grain size and sediment composition as factors controlling telease and mobilisation of Arsenic in an aquifer regime of the Brahmaputra floodplains, northeastern India, JNU Indo-Australia Workshop 2013.

Malmberg GT. 1975. Reclamation by tubewell drainage in Rechna Doab and adjacent areas, Punjab region, Pakistan, Geological Survey Water-Supply Paper 1608-O, prepared in cooperation with the west Pakistan Water & Power Dev Authority under US AID.

Margat, J., and J. van der Gun. 2013. Groundwater around the World, CRC Press/Balkema

Michael HA and Voss CI. 2009. Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modelling analysis, Hydrogeology Journal, 17; 7, 1561-1577.

Michael HA and Voss CI 2008. Evaluation of the sustainability of deep groundwater as an arsenic –safe resource in the Bengal Basin. PNAS 105 (25) 8531-8536

Michael HA and Voss CI. 2009. Estimation of regional-scale flow properties in Bengal Basin of India and Bangladesh. Hydrogeology Journal, 17; 6; 1329-1346.

Morris, B.L., Lawrence, A.R., Chilton, P.J., Adams, B., Calow, R. and Klinck, B.A. 2003). Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problems and Options for Management. Early Warning and Assessment Report Series, RS, 03-3. United Nations Environment Programme, Nairobi.

Mukherjee, A, Fryar, A.E., and Howell, P., 2007. Regional hydrostratigraphy and groundwater flow modeling of the arsenic contaminated aquifers of the western Bengal basin, West Bengal, India. Hydrogeology Journal, 15; 1397-1418

Mukherjee, A., Fryar, A.E., Scanlon, B.R., Bhattacharya, P., Bhattacharya, A., 2011. Elevated arsenic in deeper groundwater of western Bengal basin, India: Extents and controls from regional to local-scale. Applied Geochemistry, 26; 600-613.

Murray SJ. 2013. Present and future water resources in India: insights from satellite remote sensing and a dynamic global vegetation model, Journal of Earth System Science, 122; 1, 1-13.

Narula KK & Gosain AK. 2013. Modelling hydrology, groundwater recharge and non-point nitrate loadings in the Himalayan Upper Yamanu basin. Science of the Total Environment. Doi:10.1016/j.scitotenv2013.01.022

Nickson R, McArthur J, Burgess W, Ahmed KM, Ravenscroft P, Rahmann M 1998. Arsenic poisoning of Bangladesh groundwater. Nature 395 doi:10.1038/26387

Niwas SRI & Singhal DC. 1985. Aquifer transmissivity of porous media from resistivity data, J. Of Hydrology, 82; 143-153.

O Dochartaigh BE, MacDonald AM, Darling WG, Hughes AG, Li JX and Shi LA. 2010. Determining groundwater degradation from irrigation in desert-marginal northern China, Hydrogeology Journal, 18; 1939-1952.

Pokhre Dl, Bhandari BS and Viraraghavan T 2009. Arsenic contamination of groundwater in the Terai region of Nepal: an overview of health concerns and treatment options Environment International 35: 157-161

Portmann, F. T., Siebert, S. & Döll, P. (2010): MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, Global Biogeochemical Cycles, 24; GB 1011, doi:10.1029/2008GB003435.

Quereshi, Gill and Sarwar. 2008. Sustainable groundwater management in Pakistan: challenges and opportunities. Irrigation and drainage 59, 107-116

Qureshi AS, McCornick PG, Sarwar A and Sharma BR 2010 Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. Water Resources Management 24: 1551-1569

Ravenscroft P, Ahmed, KM and Samad MA. 2009. WORKING DOCUMENT NUMBER 9, Groundwater: Quantity and Quality Issues Affecting Water Supply. Sector Development Plan (FY 2011-25), Water Supply and Sanitation Sector in Bangladesh. Policy Support Unit, Local Government Division, Government of Bangladesh.

Ravenscroft P. 2007. Predicting the global extent of Arsenic Pollution of Groundwater and its potential impact on Human Health, UNICEF report.

Ravenscroft P McArthur JM and Hoque MA. 2013. Stable groundwater quality in deep aquifers of Southern Bangladesh: the case against sustainable abstraction, Science of the Total Environment 454-456: 627-638

Rawat S and Mukherji A 2012. The poor state of irrigation statistics in India: the case of wells and tube wells. Water P:olicy Highlight, IMWI-TATA Water Policy Programme, Gujarat, India.

Raza A. Latif M. and Shakir AS. 2013. Long-term effectiveness of lining tertiary canals in the Indus Basin of Pakistan, Irrigation and Drainage, 62; 16-24.

Revelle R, Lakshminarayana V (1975) The Ganges water machine. Science 188:611–616

Rodell M, Velicogna I and Famiglietti JS. 2009. Satellite-based estimates of groundwater depletion in India, Nature, 460; 999-1002.

Saha D, Dhar YR & Vittala SS. 2010. Delineation of groundwater development potential zones in parts of marginal Ganga Alluvial Plain in South Bihar, Eastern India. Environ Monit Assess, 165; 179-191.

Saha D, Sahu S & Chandra PC. 2011. As-safe alternate aquifers and their hydraulic characteristics in contaminated areas of Middle Ganga Plain, Eastern India. Environ Monit Assess, 175; 331-348.

Sahu S and Saha D 2014. Geomorphic, stratigraphic and sedimetnologic evidences of tectonic activity in the Sone-Ganga alluvial tract in the Middle Ganga Plain, India, Journal of Earth Systems Science, 123; 6; 1335-1347.

Samadder RK, Kumar S & Gupta RP. 2011. Paleochannels and thier potential for artificial recharge in the western Ganga plains. J of Hydrology, 400; 154-164.

Sarma JN. 2005. Fluvial process and morphology of the Brahmaputra River in Assam, India. Geomorphology, 70; 226-256.

Schroder JF. 1993. Himalaya to the Sea: Geomorphology and the Quaternary of Pakistan in the Regional Context, in Schroder JF (ed) Himalaya to the Sea: Geology, Geomorhphology and the Quaternary, Routledge New York, pp 1-28

Shah BA. 2008. Role of Qauternary stratigraphy on arsenic-contaminated groundwater from parts of the Middle Ganga Plain, UP-Bihar, India. Environ Geology, 53; 1553-1561.

Shah T 2009. Climate change and groundwater: India’s opportunities for mitigation and adaptation Env Res Letts. 4: 035005 doi:10.1088/1748-9326/4/3/035005

Shah T et al 2007 Groundwater: a global assessment of scale and significance Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture ed D Molden (London: Earthscan) (Colombo: IWMI) pp

Shah T, Singh OP, Mukherji. 2006. Some aspects of South Asias groundwater irrigation economy: analyses from India, Pakistan, Nepal Terai and Bangladesh. Hydrogeology Journal, 14; 286-309

Shah T. 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation, Enironmental Research Letters, 4; doi: 10.1088/1748-9326/4/3/035005

Shamsudduha M, Taylor R, Ahmed KM, and Zahid. 2011. The impact of intensive abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh, Hydrogeology Journal, 19; 901-916.

Shamsudduha M, Taylor RG & Longuevergne L. 2012. Monitoring groundwater storage changes in the highly seasonal humid tropics: validation of GRACE measurements in the Bengal Basin. Water Resources Research, 48; WO2508, doi: 10.1029/WR010993

Shrestha SD, Brikowski T, Smith L, Shei T-C. 2004. Grain size constraints on arsenic concentration in shallow wells of Nawalparasi Nepal. Journal of Nepal geological society, 30; 93-98.

Shukla UK, Singh IB, Sharma M & Shamra S. 2001. A model of alluvial megafan sedimentation: Ganga megafan, Sedimentary Geology, 144; 243-262

Siebert S et al. 2007. Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany/Food and Agriculture Organisation of the United Nations, Rome Italy

Singh et al. 1999. Upland Interfluve (Doab) Deposition: Alternative model to Muddy Overbank Deposits, Facies, 40; 197-211.

Singh IB. 1996. Geological evolution of Ganga Plain - an overview, Journal of The Palaeontological Society of India , 41; 99-137.

Singh IB. 2007. The Ganga River. In Gupta A. (ed) *Large Rivers: geomorphology and management,* Wiley, England, pp 689.

Singhal DC, Israil M, Sharma VK & Kumar B. 2010. Evaluation of gw resource and estimation of its potential in Pathri Rao watershed, district Haridwar (Uttarakhand). Current Science, 98; 2, 162-171.

Sinha R S. 2011. Arsenic toxicity in groundwater of Uttar Pradesh, State Water Resources Data and Analysis Centre, and State Water Resources Agency, Technical Report GWE/1/2011, pp 58.

Sinha R, Gibling MR, Tandon SK, Jain V & Dasgupta AS. 2005. Quaternary stratigraphy and sedimentology of the Kotra Section on the Betwa River, Southern Gangetic Plains, Uttar Pradesh, J of Geological Society India, 65; 441-450.

Sinha R, Jain V, Babu GP & Ghosh S. 2005a. Geomorphic characterization and diveristy of the fluvial systems of the Gangetic plains, Geomorphology, 70; 207-225.

Sinha R. et al. 2014 Craton-derived alluvium as a major sediment source in the Himalaya Foreland Basin of India, GSA Bulletin, 121; 11-12; 1596-1610.

Sinha R. Tandon SK, Gibling R, Bhattacharjee PS, Dasgupta AS. 2005b. Late Quaternary geology and alluviual stratigraphy of the Ganga basin, Himalayan Geology, 26; 1, 223-240

Sir Mott MacDonald and Partners Ltd. 1984. LBOD Stage 1 Project, Project Preparation. Annex 6.

Sir Mott MacDonald and Partners Ltd. 1985. LBOD Stage 1 Project, Additional Preparation. Final report.

Sir Mott MacDonald and Partners Ltd. 1990. LBOD Stage 1 Project, Mirpurkhas, Pilot Study: Hydrogeology, special wells, preliminary well design, well numbers and spacing. Technical report Annexes 1-6.

Sir Mott MacDonald and Partners Ltd. 1994. LBOD Stage 1 Project. Assistance to SCARPS Monitoring Organisation (SMO). July 1994. Final Report

Srivastava et al. 2015. Soils of the Indo-Gangetic Plain: a pedogenic response to landscape stability, climatic variability and antrhoppgenic activity during the Holocene, Earth Science Reviews, doi: 10.1016/j.earscirev.2014.10.010.

Srivastava P, Singh IB, Sharma S, Shukla UK & Singhvi AK. 2003. Late Pleistocene-Holocene changes in the interfluve areas of the central Ganga Plain, India. Geomorphology, 54; 279-292.

Struckmeier W and Richts A 2008. Groundwater resources of the World (1:25,000,000). World Wide hydrogeological mapping and assessment programme, UNESCO/BGR

Sukhija BS, Nagabhushanam P & Reddy DV. 1996. GW recharge in semi-arid regions of India: an overview of results obtained using tracers. Hydrogeology Journal; 4; 3; 50-71.

Taylor R. et al. 2013. Groundwater and climate change, Nature Climate Change 3; 322-329, doi: 10.1038/nclimate1744

Taylor RG, Burgess WG, Shamsudduha M, Zahid A, Lapworth DJ, Ahmed K, Mukherjee A, Nowreen S., 2014. Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction. British Geological Survey Open Report, OR/14/070. 24pp.

Tiwari VM, Whar J and Swenson S. 2009. Dwindling groundwater resources in northern India, from satellite gravity observations, Geophysical research Letters, 36; L18401, doi: 10.1029/2009GL039401.

Turner AG Annamalai H 2012 Climate change and the South Asian summer monsoon. Nature Climate Change 2 587-595

Valdiya KS. 2002. Emergence and Evolution of Himlaya: reconstructing history in the light of recent studies, Progress in Physcial Geography, 26; 3; 60.

Van Steenbergen F & Oliemans W. 2013. Groundwater resource management in Pakistan. In Proceedings of ILRI workshop: Groundwater managment: sharing responsibility for an open access resource, IRLI, pp18

Wada, Y.; Beek, L.P.H. van; van Kempen, C.M.; Reckman, J.W.T.M.; Vasak, S.; Bierkens, M.F.P. 2010. Global depletion of groundwater resources, Geophysical Research Letters, 37; L20402

WAPDA 2001. Hydrogeological map of Pakistan (scale 1:250,000). Directorate of Hydrogeology, WAPDA, Lahore.

WHO. 2003. Guidelines for drinking water quality, Third Edition, Volume 1 Recommendations, WHO Geneva, 366 pp

WWF. 2015. Problems and Prospects of saving water and energy in agriculture in Upper Ganga River Basin, Executive Summary, pp 9. (Accessed 25/2/2015: http://assets.wwfindia.org/downloads/water_and_energy_use_efficiency_study.pdf)

Yu W, Yang Yc, Savitsky A ,Alford D, Brown C, Wescoat J, Debowicz D and Robinson S 2013 The Indus Basin of Pakistan, the impacts of climate risks on water and agriculture. The World Bank, Washington.