OR/15/047 The IGB groundwater system

From Earthwise

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.

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[1]; Kumar et al. 2013[2]). 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[3]).

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[4]; Srivastava et al. 2015[5]). 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[6]). The Haryana-Punjab basin area between the two represents a shallower over-filled region of the basin (Singh et al. 1996[4]). 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[7]).

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[4]). 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[8]; Singh et al. 1996[4]), to the progressively sand-dominated fluvial deposits (70% fine- medium sands) (Singh et al. 1999[9]; Saha et al. 2011[10]), 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[11]; Kinniburgh and Smedley 2000[12]; Acharyya 2005[13]) — 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[14]; Sinha et al. 2014[3]).
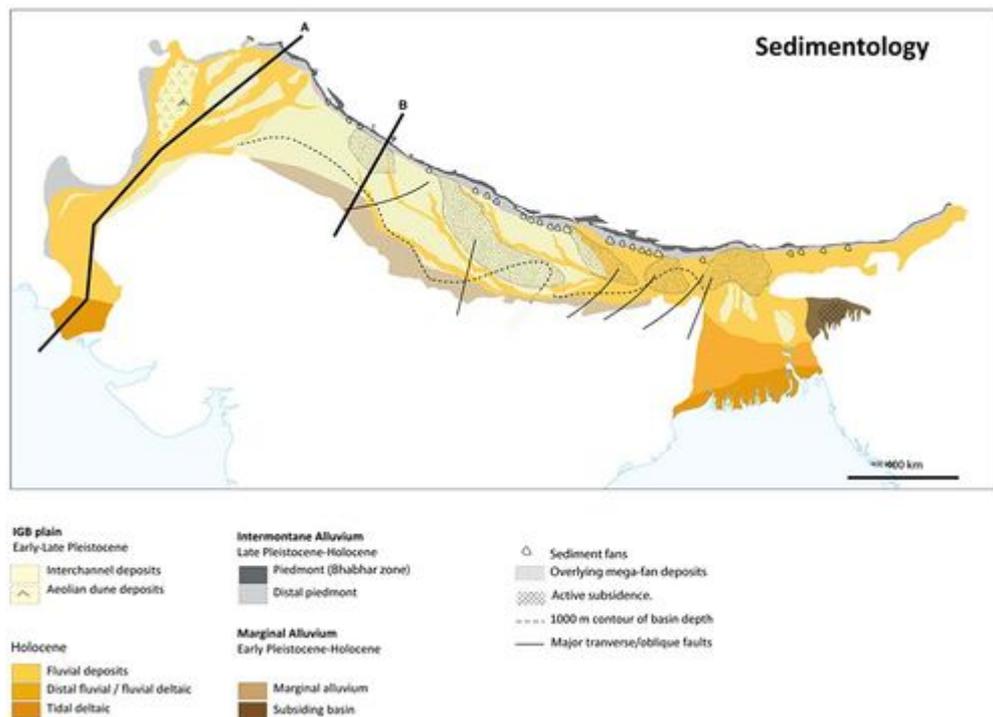
Figure 2 Typologies of alluvium sedimentology. The location of the cross sections, A and B are shown.

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[15]; 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[16]); 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 2005[17]). 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[18]; Goodbred 2003[19]; Sinha 2005[20]). 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[18]).

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)[4].

— 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[9]; Sinha 2005[20]). 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[21]). 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 2005[20]; Samadder et al. 2011[22]).
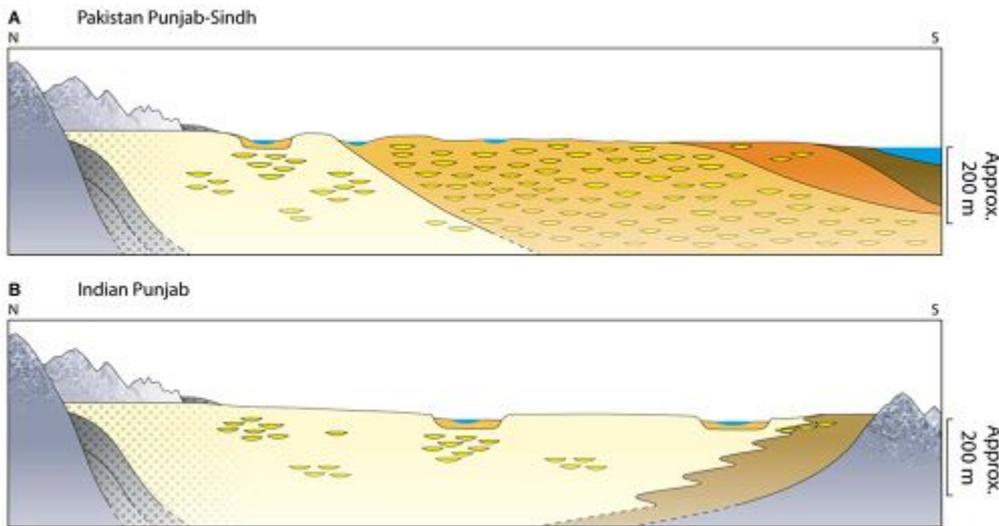

Figure 3 Schematic cross-sections of the IGB within the Indus (A) and upper Ganges basin (B), illustrating the systematic variations in alluvium sedimentology.

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 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)[23], Ahmad et al. (1993)[24], 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.
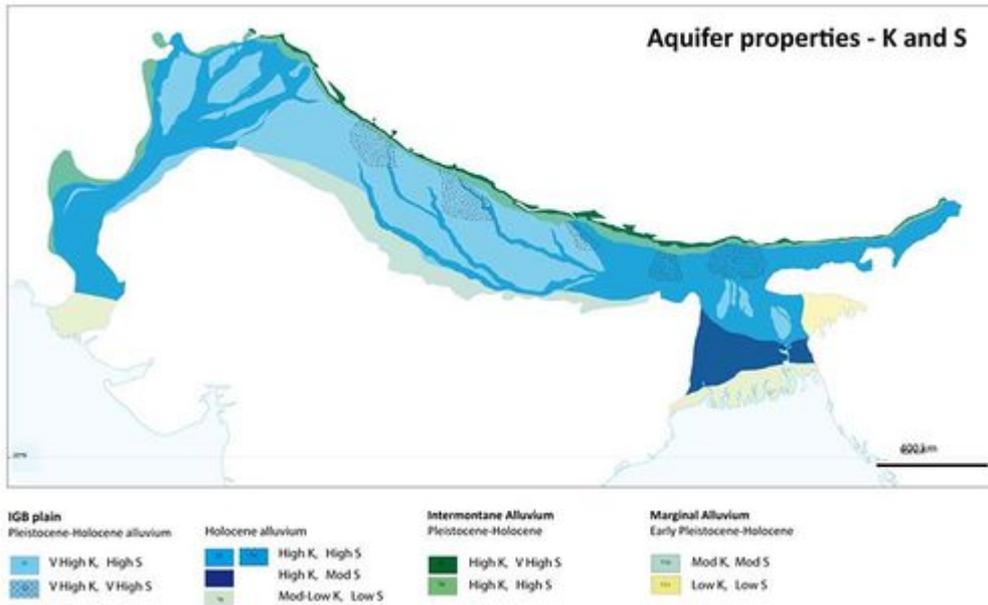
Figure 4 Aquifer properties of the IGB aquifer system vary systemically on a basin-scale with the sedimentological characteristics of the Plio-Pleistocene – Holocene alluvium.

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[25]). 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[26]) 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.
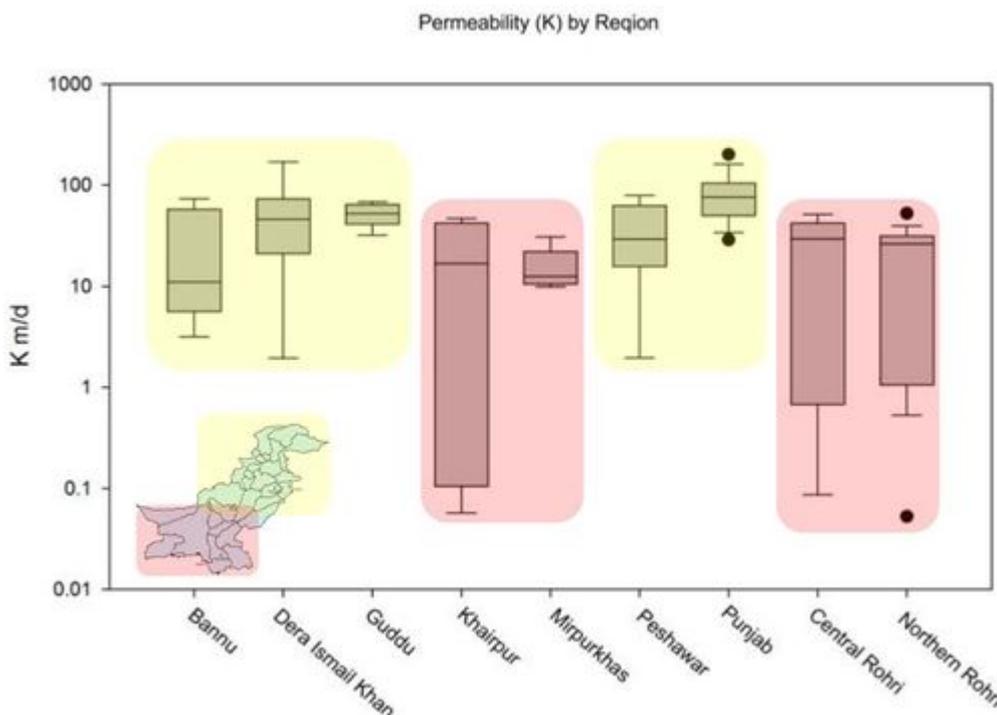

Figure 5 Estimated permeability from pumping tests in the Indus.

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[27]) and compared with available published values of specific yield across the basin (Bennet 1969[23], Mott MacDonald and Partners 1984[28], Chilton 1986[29], Ahmad 1993[30], CGWB 2010[31], Shamsudduha et al. 2011[26], Khan et al. 2014[32]). 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.
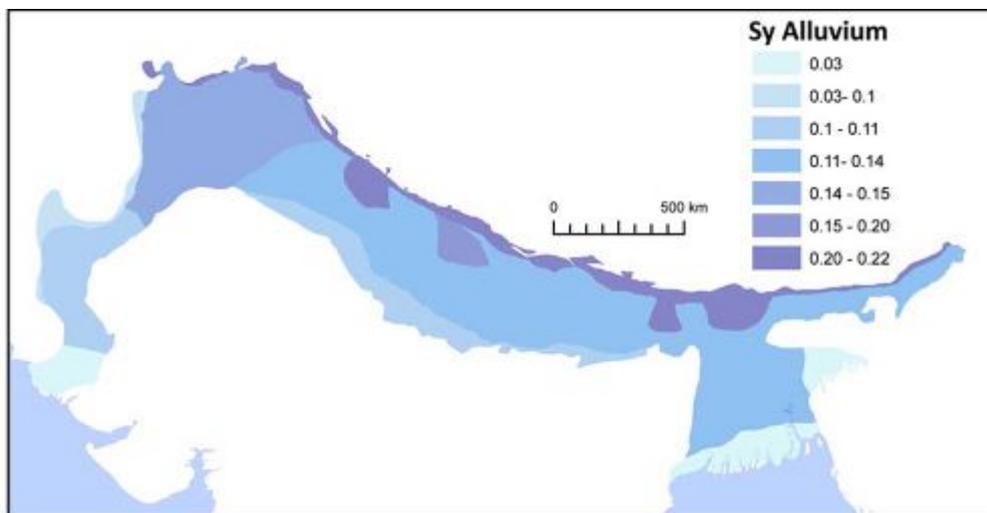

Figure 6 Variations in Specific yield across the IGB.

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 (Bennett 1969[23]), rising to 50–100 in the main Ganges basin (Sinha et al. 2009, Khan et al. 2014[32]), and 200–500 in the Lower Indus (Chilton

1986[29], Ahmad 1995[33]); 10 000 in the southern Bengal Basin and 20 000 in the coastal areas (Michael and Voss 2009[34]). Limited data from modern sediments close to the major rivers show a much lower ratio of <10 (Ahmad 1995[33]).

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[35]). 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[36]). 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. The basin has not been subject to widespread marine transgression (Schroder 1993[37]; Valdiya 2002[6]; Goodbred 2003[38]) 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[39], Schroder 1993[37]).

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[38]; Clift and Giosan 2013[40]), 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
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
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
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.
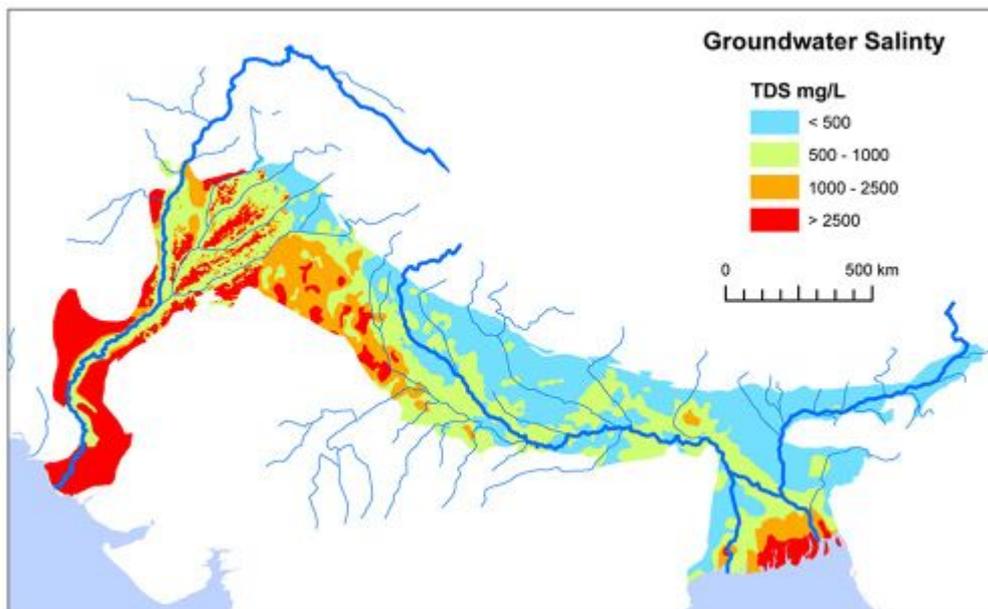

Figure 7 Distribution of groundwater salinity in the top 200 m of the IGB aquifer. Data from *WAPDA 2001*[41]*, IWASRI 2005*[42], Quereshi 2008[43], CGWB 2010[31], *Ravenscroft et al. 2009*[44] DPHE/BGS 2001[39]).

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[45]), 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 10–1000 µg/L As (Kinniburgh and Smedley 2001[46]). 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[47]; Burgess et al. 2010[48]) — one subject addressed by the Deep Groundwater Case Study.
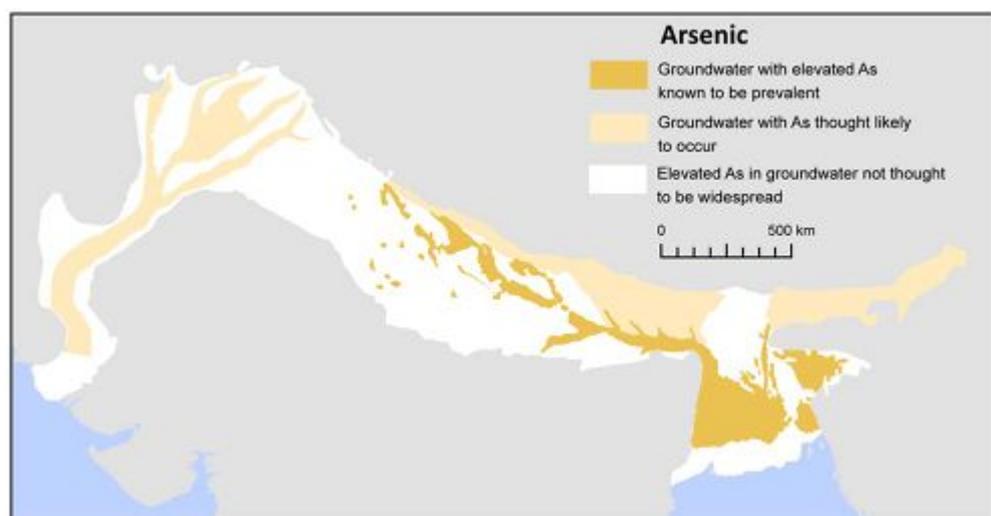

Figure 8 Known areas with elevated arsenic in the IGB Aquifer system.

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[49]) which has been modified by others (e.g. Kumar and Seethapathi 2002[50]) and tested using environmental tracers (e.g. Goel et al 1977[51], Datta and Goel 1977[52]). 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[51], Shamsudduha et al. 2011[26]).

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[43], FAO 2009, FAO 2012[53])) 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[54], Arshad et al 2009[55], Raza et al. 2013[56]). 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[56]). Studies in India (WWF 2015[57]) 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[43], Basharat et al. 2014[58]).

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[59]) 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[45]).

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[60]). 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[26]). 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[61], Chaturvedi and Srivastava 1979) and have recently been revisited (Khan et al 2014[62]).
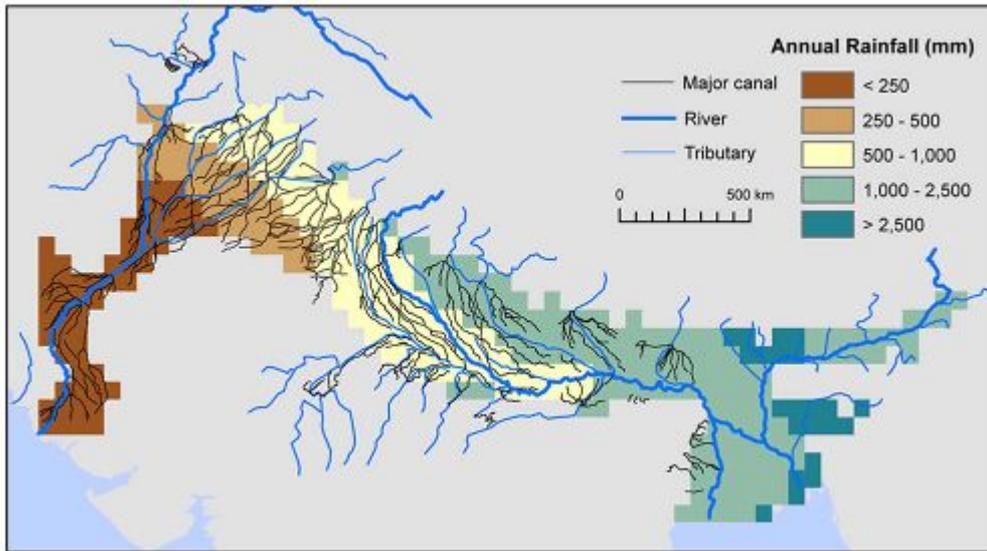

Figure 9 A combination of factors provides a highly complex pattern of recharge across the IGB. In areas with a high density of irrigation canals, such as the Upper Indus and Upper Ganges basins, leakage from irrigation canals can give annual recharge of 400 mm; where average annual rainfall is greater 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[63]).

References

1. ↑ 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
2. ↑ Kumar M R, Mishra D C 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.
3. ↑ 3.0 3.1 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.
4. ↑ 4.0 4.1 4.2 4.3 4.4 Singh I B. 1996. Geological evolution of Ganga Plain—an overview, Journal of The Palaeontological Society of India , 41; 99–137.
5. ↑ 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.
6. ↑ 6.0 6.1 Valdiya KS. 2002. Emergence and Evolution of Himlaya: reconstructing history in the light of recent studies, Progress in Physcial Geography, 26; 3; 60.
7. ↑ 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.
8. ↑ Shukla U K, Singh I B, Sharma M and Shamra S. 2001. A model of alluvial megafan sedimentation: Ganga megafan, Sedimentary Geology, 144; 243–262
9. ↑ 9.0 9.1 Singh et al. 1999. Upland Interfluve (Doab) Deposition: Alternative model to Muddy Overbank Deposits, Facies, 40; 197–211.
10. ↑ Saha D, Sahu S and Chandra P C. 2011. As-safe alternate aquifers and their hydraulic characteristics in contaminated areas of Middle Ganga Plain, Eastern India. Environ Monit Assess, 175; 331–348.
11. ↑ Goodbred A L and Kuehl S A. 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
12. ↑ Kinniburgh and Smedley. 2000. Arsenic contamination of groundwater in Bangladesh, BGS Technical Report WC/00/19 Vol 1, 656 pp
13. ↑ Acharyya S K. 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.
14. ↑ Heroy D, Kuehl S A, Goodbred Jr S L. 2003. Mineralogy of the Ganges and Brahmaputra Rivers: implications for river switching and Late Quaternary climate change. Sedimentary Geology, 155; 343–359
15. ↑ Schroder J F. 1993. Himalaya to the Sea: Geomorphology and the Quaternary of Pakistan in the Regional Context, in Schroder J F (ed) Himalaya to the Sea: Geology, *Geomorhphology and the Quaternary*, Routledge New York, pp 1–28
16. ↑ Clift P D and Giosan L. 2013. Sediment fluxes and buffering the post-glacial Indus Basin, *Basin Research*, 25; 1–18.
17. ↑ Sinha R, Gibling M R, Tandon S K, Jain V & Dasgupta A S. 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.
18. ↑ 18.0 18.1 Valdiya K S. 2002. Emergence and Evolution of Himlaya: reconstructing history in the light of recent studies, Progress in Physcial Geography, 26; 3; 60.
19. ↑ 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

20. ↑ [20.0](#) [20.1](#) [20.2](#) Sinha R, Gibling M R, Tandon S K, Jain V & Dasgupta A S. 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.

21. ↑ Saha D, Sahu S and 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.

22. ↑ Samadder R K, Kumar S and Gupta R P. 2011. Paleochannels and their potential for artificial recharge in the western Ganga plains. *Journal of Hydrology*, 400; 154–164.

23. ↑ [23.0](#) [23.1](#) [23.2](#) Bennett G D, Rehman A U, Sheikh J A and 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.

24. ↑ Ahmad, 1993. Water Resources of Pakistan. Pp355.

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

26. ↑ [26.0](#) [26.1](#) [26.2](#) [26.3](#) Shamsudduha M, Taylor R, Ahmed K M and Zahid. 2011. The impact of intensive abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh, *Hydrogeology Journal*, 19; 901–916.

27. ↑ DPHE/BGS. 2001. Arsenic contamination of groundwater in Bangladesh. Kinniburgh D G and Smedley P L (eds). British Geological Survey Technical Report WC-00-19, BGS, Keyworth.

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

29. ↑ [29.0](#) [29.1](#) Chilton P J. 1986. Pakistan Scavenger wells pilot project: an introductory note for BGS staff, BGS Technical report WD/0S/86/16, pp21.

30. ↑ Ahmad, 1993. Water Resources of Pakistan. Pp355.

31. ↑ [31.0](#) [31.1](#) CGWB 2010. Groundwater quality in shallow aquifers of India. Central Groundwater Board, Ministry of Water Resources, Delhi.

32. ↑ [32.0](#) [32.1](#) Khan M R, Voss C I, Yu W and Michael H A. 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

33. ↑ [33.0](#) [33.1](#) Ahmed, 1995. Groundwater Resources of Pakistan. 560 pp

34. ↑ Michael, H A and Voss, C I. 2009. Estimation of regional-scale flow properties in Bengal Basin of India and Bangladesh. *Hydrogeology Journal*, 17; 6; 1329–1346.

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

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

37. ↑ [37.0](#) [37.1](#) Schroder J F. 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

38. ↑ [38.0](#) [38.1](#) 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

39. ↑ [39.0](#) [39.1](#) DPHE/BGS. 2001. Arsenic contamination of groundwater in Bangladesh. Kinniburgh DG & Smedley PL (eds). British Geological Survey Technical Report WC-00-19, BGS, Keyworth

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

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

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

43. ↑ ^{43.0} ^{43.1} ^{43.2} Quereshi, Gill and Sarwar. 2008. Sustainable groundwater management in Pakistan: challenges and opportunities. Irrigation and drainage 59, 107-116
44. ↑ Ravenscroft P, Ahmed, K M and Samad M A. 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.
45. ↑ ^{45.0} ^{45.1} O Dochartaigh B E, MacDonald A M, Darling W G, Hughes A G, Li J X and Shi L A. 2010. Determining groundwater degradation from irrigation in desert-marginal northern China, *Hydrogeology Journal*, 18; 1939–1952.
46. ↑ Kinniburgh and Smedley. 2000. Arsenic contamination of groundwater in Bangladesh, BGS Technical Report WC/00/19 Vol 1, 656 pp
47. ↑ Michael H A and Voss C I. 2009. Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modelling analysis, Hydrogeology Journal, 17; 7, 1561–1577.
48. ↑ Burgess W G, Hoque M A ,Michael H A, Voss C I, Breit G N and Ahmed KM 2010 Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic. Nature Geoscience 3: 83–87
49. ↑ Chaturvedi, R S. 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.
50. ↑ Kumar C P and Seethapathi P V. 2002. Assessment of Natural Groundwater Recharge in Upper Ganges Canal Command area, Journal of Applied Hydrology, 15; 4, 13–20.
51. ↑ ^{51.0} ^{51.1} Goel P S, Datta P S, Tanwar B S. 1977. Measurement of vertical recharge to groundwater in Haryana State (India) using Tritium Tracer, Nordic Hydrology, 8; 211–224.
52. ↑ Datta P S and Goel P S. 1977. Groundwater recharge in Panjab State (India) using Tritium Tracer, Nordic Hydrology, 8; 255–236.
53. ↑ FAO. 2012. Irrigation in Southern and Eastern Asia in Figures, AQUASTAT Survey 2011, FAO Water Reports 37, Rome pp 512.
54. ↑ 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.
55. ↑ 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.
56. ↑ ^{56.0} ^{56.1} Raza A, Latif M and Shakir A S. 2013. Long-term effectiveness of lining tertiary canals in the Indus Basin of Pakistan, Irrigation and Drainage, 62; 16–24.
57. ↑ 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)
58. ↑ Basharat M, Hassan D, Bajkani A A and Sultan S J. 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.
59. ↑ Jurriens R. and Mollinga P.P. 1996. Scarcity by design: protective irrigation in India and Pakistan. ICID Journal. 45(2) (1996) pp: 31–53
60. ↑ Qureshi A S, McCornick P G, Sarwar A and Sharma B R. 2010. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. Water Resources Management 24: 1551–1569
61. ↑ Revelle R, Lakshminarayana V. 1975. The Ganges water machine. Science 188:611–616
62. ↑ Khan M R, Voss C I, Y u W and Michael H A. 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
63. ↑ Singh I B. 2007. The Ganga River. In Gupta A. (ed) Large Rivers: geomorphology and

management, Wiley, England, pp 689.

Category:

- OR/15/047 Groundwater resources in the Indo-Gangetic Basin: resilience to climate change and abstraction

Navigation menu

Personal tools

- Not logged in
- Talk
- Contributions
- [Log in](Log in)
- Request account

Namespaces

- Page
- Discussion

☐

Variants

Views

- Read
- View source
- View history
- PDF Export

☐

More

Search

Search Go

Navigation

- Main page
- Recent changes
- Random page
- Help about MediaWiki

Tools

- This page was last modified on 3 December 2019, at 11:54.