ELEMENTA
Science of the Anthropocene

Higgins, SA, et al. 2018 River linking in India: Downstream impacts on water discharge and suspended sediment transport to deltas. *Elem Sci Anth,* 6: 20.
DOI: https://doi.org/10.1525/elementa.269

RESEARCH ARTICLE

River linking in India: Downstream impacts on water discharge and suspended sediment transport to deltas

Stephanie A. Higgins[*,†], Irina Overeem[*], Kimberly G. Rogers[*] and Evan A. Kalina[‡,§]

To expand agricultural production and address water scarcity, India is moving forward with the National River Linking Project (NRLP), which will connect 44 rivers via 9,600 km of canals. Here, we compile the first complete database of proposed NRLP dams, reservoirs and canals, including operating schedules for Himalayan infrastructure. We evaluate potential NRLP-derived changes to mean annual water discharge for 29 rivers and mean monthly water and sediment discharge for six rivers flowing to five major deltas. Sediment rating curves are used to quantify the impacts of changing water discharge within the rivers, and basin-wide trapping efficiency is established for new reservoirs. Given full implementation of the NRLP, we forecast reductions in annual suspended sediment transport to deltas of 40–85% (Mahanadi), 71–99% (Godavari) and 60–97% (Krishna) due to profound reservoir trapping and peak streamflow reductions. The Ganga before its confluence with the Brahmaputra is projected to experience a 39–75% reduction in annual suspended load. The Brahmaputra before its confluence with the Ganga is projected to experience a 9–25% reduction in suspended load, despite losing only 6% of its annual water flow. We calculate a projected corresponding aggradation decrease for the Ganga-Brahmaputra delta from 3.6 to 2.5 mm y^{-1}, which is a large enough change to drive relative sea-level rise at the delta front. At the remaining four deltas, the NRLP will exacerbate current sediment starvation. We reconstruct the annual water transfer volume proposed for the NRLP to be 245 km^3 y^{-1}, higher than previous estimates due to the inclusion of along-canal usage. If completed, the NRLP will transform watershed boundaries, with more than half of the land in India contributing a portion of its runoff to a new mouth. These impacts may have profound environmental and public health implications, particularly in the context of future climate change.

Keywords: Inter-basin water transfer; River linking; deltas; subsidence; river network; water scarcity

Introduction

To expand agricultural production and address water scarcity, India is moving forward with a large-scale civil engineering project to connect 44 rivers via a vast network of canals (Joshi, 2013; Bagla, 2014). The National River Linking Project, or NRLP, aims to increase irrigated area by 350,000 km^2 and improve food security and clean water access. India receives between 50 and 90% of its annual precipitation during the summer monsoon, during which time water is abundant and floods are common. The NRLP will store and redistribute this water in an effort to reduce temporal and spatial inconsistencies in supply. The project is intended to address the substantial challenges of food production and clean water access that India will face in the coming century – challenges that are being confronted globally as countries face rising temperatures, and increasing populations with stressed water supplies (Wallace, 2000; Battisti and Naylor, 2009; Hanjra and Qureshi, 2010). Interbasin water transfer systems are a common solution to water scarcity, and the NRLP is the largest of many new diversion schemes proposed or underway in China, Brazil, and Central Africa (Zhang, 2009; Lemoalle et al., 2012). However, large-scale river diversion projects such as the NRLP can result in far-reaching consequences for downstream river discharge and delta maintenance. For example, due to damming, diversions, and increased water usage, the Colorado, Nile, Indus and Yellow (Huanghe) rivers discharge little to no sediment today, whereas they previously accounted for 10% of the global sediment flux to the ocean (Syvitski and Milliman, 2007).

The NRLP in its current form was designed in the early 1980s, when the Indian government established the National Water Development Agency (NWDA) to manage implementation of the project. The project stalled between the 1980s and the 2010s, but it was renewed in

* Community Surface Dynamics Modeling System, INSTAAR, University of Colorado Boulder, Boulder, Colorado, US

† Department of Geological Sciences, University of Colorado Boulder, Boulder, Colorado, US

‡ University of Colorado, Boulder, Colorado, US

§ Cooperative Institute for Research in Environmental Sciences at the NOAA Earth System Research Laboratory/Global Systems Division, Boulder, Colorado, US

Corresponding author: Stephanie A. Higgins (stephanie.higgins@colorado.edu)

2012 following a Supreme Court order to proceed. The first canal was completed in September 2015; project completion is expected by mid-century. If fully realized, the NRLP will consist of 29 canals running a total of 9,600 km in length. Nine of the canals would each transfer more than 10 $km^3\,y^{-1}$ of water. This transfer capacity is greater than that of the current largest canal in the world (the Central Route of the South–North Water Transfer in China, which transfers 9.5 $km^3\,y^{-1}$; Zhang, 2009). The full system, depicted in **Figure 1**, would transfer fifty to one-hundred times the volume of the largest interbasin water transfer system in the United States and will likely constitute the largest construction project in human history.

Given the far-reaching social, economic, and environmental impacts of the NRLP, there have been innumerable calls for scientific research into nearly every aspect of the proposal (Bandyopadhyay and Perveen, 2003; Mizra, 2008; Amarasinghe and Sharma, 2008; Joshi, 2013). Sediment transport changes that may result from the NRLP have been highlighted as a significant knowledge gap (Bandyopadhyay and Perveen, 2008). Reduced sediment supply has been implicated in the sinking of many major deltas, putting vital agricultural regions, industrial areas, sea ports, diverse wetlands, and population megacenters at risk (Syvitski et al., 2009; Tessler et al., 2015). Deltas downstream of NRLP transfers include the Ganga-Brahmaputra, Mahanadi, Godavari, Krishna and Kaveri deltas. These five deltas together host a population of more than 160 million people (Higgins, 2015). All five deltas currently suffer from reduced aggradation that, together with land subsidence and global sea-level rise, place the deltas at risk of substantial elevation loss relative to sea level (Syvitski et al., 2009; ADB 2011; Tessler et al., 2015). It is therefore essential to establish how NRLP transfers may affect sediment transport to these vulnerable coastal areas.

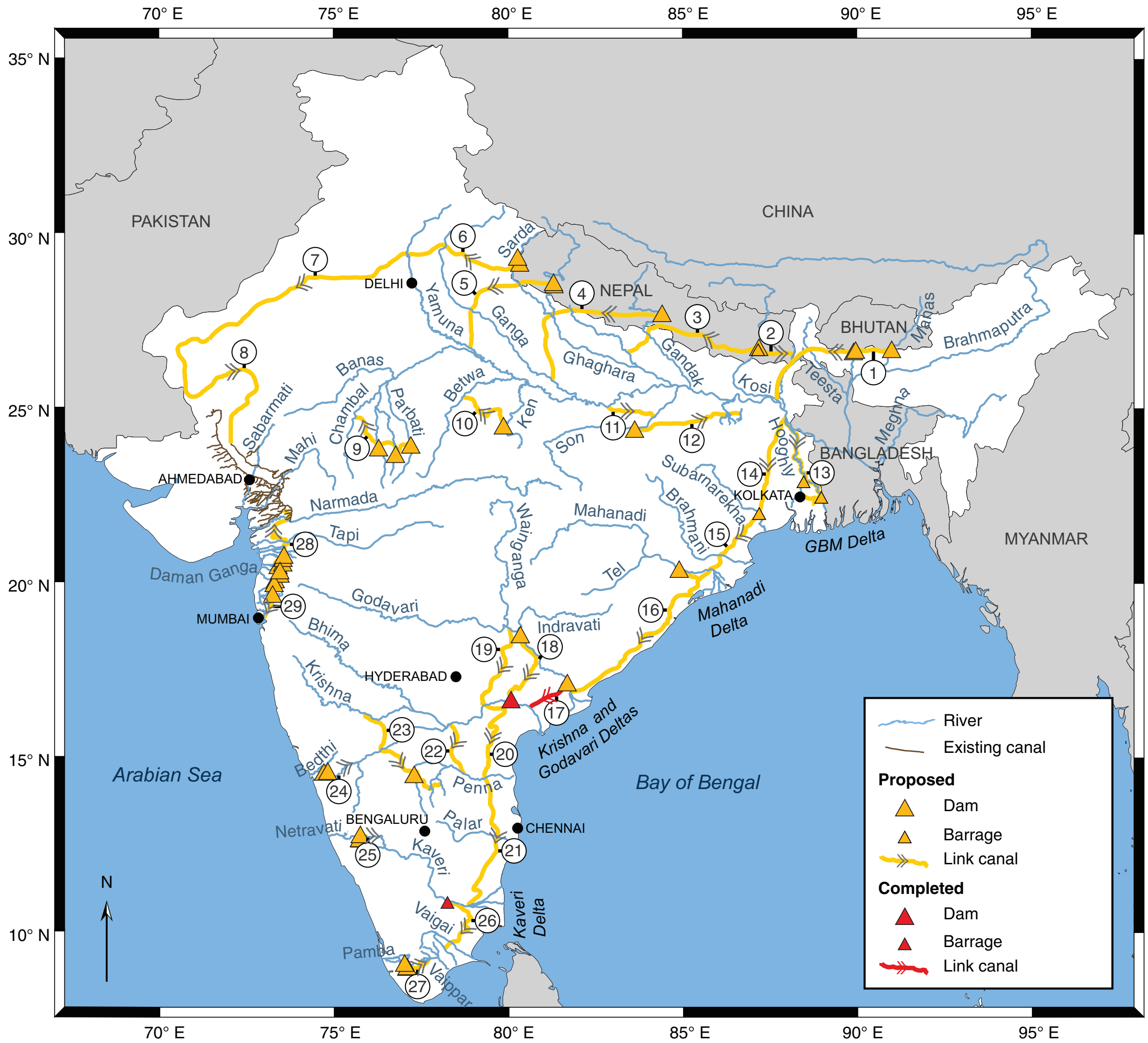

Figure 1: Proposed canals, dams and barrages associated with the NRLP. Canals, dams and barrages associated with the NRLP. Yellow indicates proposed and red indicates completed structures. Canal #17 (red) connecting the Krishna and Godavari rivers was completed in September 2015. Arrows indicate the direction of water transfer along the canals. Major river deltas in this study are labeled – the Ganges-Brahmaputra Meghna (GBM) in India/Bangladesh, and the Mahanadi, Krishna, Godavari and Kaveri deltas in India. The locations and attributes of all canals and dams are available as shapefiles and in .csv format in Supplementary Material. NWDA names for each canal are given in Table 1. DOI: https://doi.org/10.1525/elementa.269.f1

Three fundamental processes resulting from the NRLP have the potential to affect sediment transport. The first is an increase in reservoir trapping, which has already reduced sediment transport globally by 30% (Vörösmarty et al., 2003) and in India by more than 70% (Gupta et al., 2012). New reservoirs associated with the NRLP will further impound sediment, particularly in the relatively pristine Himalayan rivers. A second impact is expected to result from the storage of high flows during the wet season and their slow release during the dry season. This will affect sediment transport due to the non-linear relationship between water discharge and sediment transport capacity. Finally, increased water utilization within the basin will decrease the average water discharge of rivers, reducing their year-round transport capacity, as sediment load is a function of water discharge for rivers that are not supply-limited (Syvitski et al., 2005; Walling, 2008).

Despite the importance of these processes, efforts to quantify their impacts within the NRLP have been severely hampered by a lack of data on the specific transfer volumes and operations of the project as well as the existing conditions in the rivers, particularly for the Himalayan (northern) half of the system. The Indian government restricts access to hydrologic data for the Ganga and Brahmaputra basins, and freely available data is sparse and incomplete. Prior to this work, even water discharge changes had not been tabulated for rivers affected by multiple canals.

This paper addresses these challenges and evaluates potential NRLP-derived changes to mean monthly water and sediment discharge and delta sedimentation for the Mahanadi, Godavari, Krishna, Kaveri, and Ganga-Brahmaputra deltas. Additionally, changes to mean annual water discharge are established for 29 rivers. Displaced population estimates are updated to the current project timeline, and changes to the existing watersheds of the subcontinental river network are mapped. This work is achieved via construction of the first comprehensive database of NRLP elements, which includes data for the full Himalayan component of the project**.** A novel graph database of the river network is developed to track and calculate flow. Finally, impacts of the NRLP are discussed within the context of human and environmental requirements and future climate change.

Methods

Data

Infrastructure data

A total of 43 dams and barrages and 29 link canals are planned in the NRLP (**Figure 1**). Where possible, infrastructure data including locations and operating schedules for dams and canals have been taken directly from NWDA documents and reports (see annotated reference list, Supplementary Material). **Table 1** gives the NWDA name for each canal. For the Peninsular component, NWDA summary statements and Feasibility Reports with operating schedules are available for canals 9, 10, and 16–29 and their associated dams, with the exception of a missing summary statement for link canal 29 and a missing Feasibility Report for link canal 25. The Feasibility Report for link canal 16 is unavailable due to recent negotiations that have moved the location of the primary reservoir and revised its operating schedules. A new summary statement has been released, but a new Feasibility Report is not yet available. For link canals 10, 28, and 29, NWDA Detailed Project Reports are available with additional information on the canals and associated dams. Newer NWDA publications were selected over older publications for inclusion in the dataset.

For the Himalayan (northern) components, NWDA data are much sparser. A pre-feasibility report is available for link canal 6 and an NWDA in-house bulletin gives some information regarding the locations of dams in link canal 1. Otherwise, data on the northern canals and dams have not been released. It was therefore necessary to supplement NWDA material with data from other sources. To that end, more than 500 documents from the public domain were reviewed for potential data on NRLP infrastructure. Seventy-five sources were ultimately included in the database, which together include the most current operating specifications for the components (see Supplementary Material). For the Himalayan canals, the most comprehensive source of information came in the form of three NWDA charts obtained by Gourdji (2005; 2008) that together depict the Himalayan canals' full transfer, evaporation, utilization, and outfall volumes.

Exact latitudes and longitudes were available for approximately half of the dams and none of the link canals. Geo-location of each canal and structure was therefore facilitated by 30 NWDA schematic maps showing the approximate locations of dams, barrages, and water transfer structures in the project. These maps were digitized and georeferenced in a GIS framework (**Figure 2**). Country and state borders, water bodies, cities/place names, and existing structures provided georeferencing points. Locations were then refined using text-based descriptions in the database sources. For example, no NWDA data is provided for the Chisapani and re-regulating dams associated with link canal 5, but a World Bank study of potential dam sites describes the recommended site:

> *The study recommended a 270-meter high embankment dam located at the upstream site of the Chisapani gorge… [and] reregulating facilities located 8 km downstream. […] Although not fully assessed yet, there may also be some loss of river habitat and encroachment on the Royal Bardiya Wildlife Reserve, which is an area of special environmental significance (World Bank, 1992).*

Place names such as these were compared to Open Street Map, India-WRIS (Water Resources Information System of India) dam databases, Google Maps and DigitalGlobe/Google Earth satellite imagery, SANDRP publications, and news articles to refine structure locations and link canal routes. Where existing irrigation canals or smaller rivers were to be utilized along the link canal routes, these were extracted from Open Street Maps and joined with the routes.

Table 1: Canal numbers and corresponding NWDA names. DOI: https://doi.org/10.1525/elementa.269.t1

Canal[a]	NWDA name	Offtake river	Outfall river
1.1	Manas-Sankosh-Tista-Ganga	Manas	Canal
1.2	Manas-Sankosh-Tista-Ganga	Sankosh	Canal
1.3	Manas-Sankosh-Tista-Ganga	Raidak	Canal
1.4	Manas-Sankosh-Tista-Ganga	Torsa	Canal
1.5	Manas-Sankosh-Tista-Ganga	Jaldhak	Ganga
2	Kosi-Mechi	Kosi	Mechi
3	Kosi-Ghaghara	Kosi	Ghaghara
4	Gandak-Ganga	Gandak	Ganga
5	Ghaghara-Yamuna	Ghaghara	Yamuna
6.1	Sarda-Yamuna	Sarda	Canal
6.2	Sarda-Yamuna	Upper Ganga	Yamuna
7	Yamuna-Rajasthan	Yamuna	Canal
8	Rajasthan-Sabarmati	Canal	Sabarmati
9.1	Parbati-Kalisindh-Chambal	Parbati	Canal
9.2	Parbati-Kalisindh-Chambal	Newaj	Canal
9.3	Parbati-Kalisindh-Chambal	Kalisindh	Chambal
10	Ken-Betwa	Ken	Betwa
11	Chunar-Sone Barrage	Ganga	Son
12	Sone Dam-Southern Tributaries of the Ganges	Son	Ganga tributaries
13	Farakka-Sundarbans	Ganga	Hooghly
14	Ganga-Damodar-Subernarekha	Ganga	Canal
15	Subernarekha-Mahanadi	Canal	Mahanadi
16.1	Mahanadi (Manibhadra)-Godavari (Dowlaiswaram)	Mahanadi	Godavari
16.2	Mahanadi (Manibhadra)-Godavari (Dowlaiswaram)	Mahanadi	Godavari
17	Godavari (Polavaram)-Krishna (Vijayawada)	Godavari	Krishna
18	Godavari (Inchampalli)-Krishna (Pulichintala)	Godavari	Krishna
19	Godavari (Inchampalli)-Krishna (Nagarjunasagar)	Godavari	Krishna
20	Krishna (Nagarjunsagar)-Pennar (Somasila)	Krishna	Penna
21	Pennar (Somasila)-Palar-Cauvery (Grand Anicut)	Penna	Kaveri
22	Krishna (Srisailam)-Pennar	Kirshna	Penna
23	Krishna (Almatti)-Pennar	Krishna	Penna
24	Bedti-Varada	Bedthi	Varada
25	Netravati-Hemavati	Netravati	Hemavati
26	Cauvery (Kattalai)-Vaigai-Gundar	Kaveri	Gundar
27.1	Pamba-Achankovil-Vaippar	Pamba	Canal
27.2	Pamba-Achankovil-Vaippar	Achankovil	Vaippar
28.1	Par-Tapi-Narmada	Par	Canal
28.2	Par-Tapi-Narmada	Auranga	Canal
28.3	Par-Tapi-Narmada	Ambika	Canal
28.4	Par-Tapi-Narmada	Purna	Narmada
29.1	Damanganga-Pinjal	Daman Ganga	Canal
29.2	Damanganga-Pinjal	Vaitarna	Thane Creek

[a] Canal numbers are a convention of this study and do not correspond to those used in some NWDA figures and publications.

For the 29 link canals, the following data were compiled: locations (GIS shapefiles of route traces), annual water transfer volumes, operating schedules, en route irrigation, en route domestic and industrial usage, and transmission losses (seepage and evaporation) (**Table 2**; and supplementary canals database). For the 43 dam structures, the following data were compiled: location (latitudes and longitudes), operating specifications (days or months of operation), full reservoir level (water elevation in meters), maximum (gross) storage, minimum (dead)

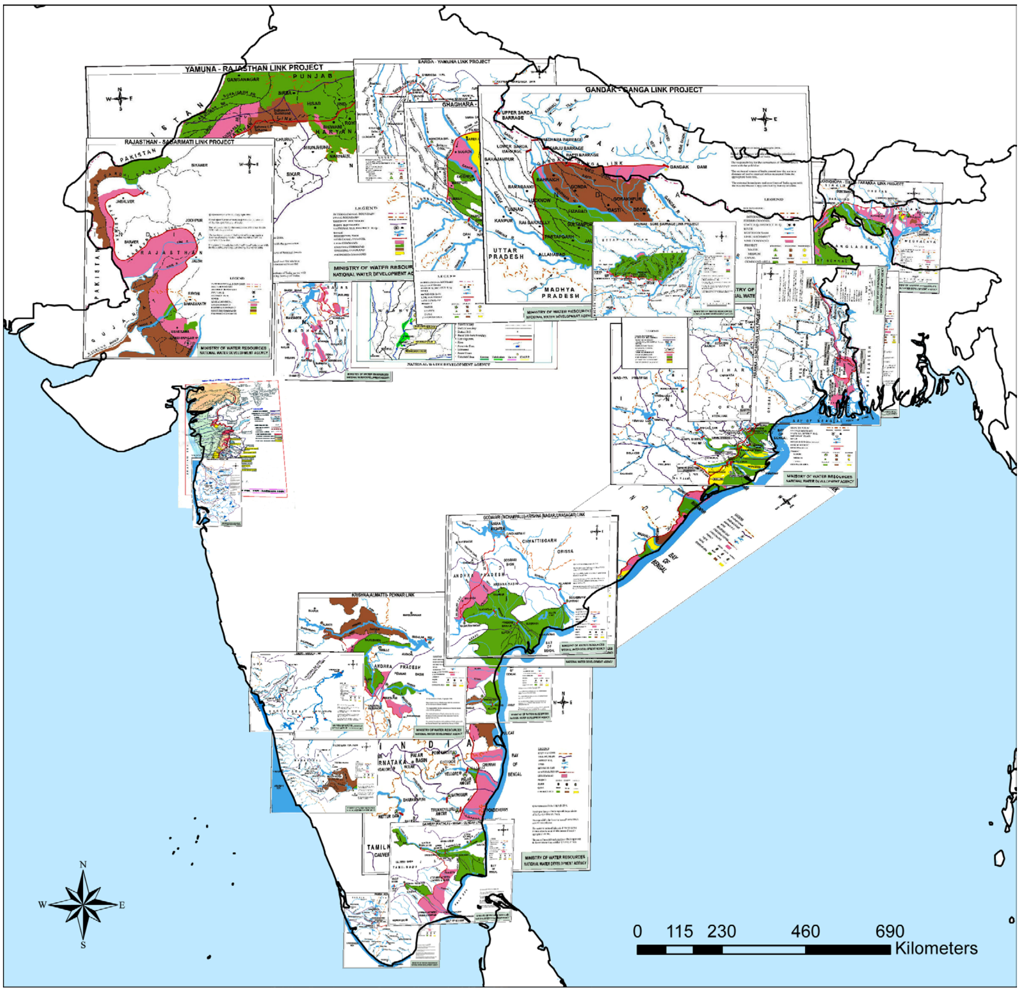

Figure 2: Geo-referenced NWDA maps. As part of database construction, 30 maps from published NWDA Feasibility Reports were geo-referenced in a GIS framework. Country and state borders, water bodies, cities/place names, and existing structures provided geo-referencing points. The maps were used in conjunction with written location descriptions in NWDA sources, Open Street Map extracts, Google Earth/Google Maps data, and other published sources to establish dam and link canal locations. DOI: https://doi.org/10.1525/elementa.269.f2

storage, submergence area, forested submergence area, and estimated displaced population (**Table 3** and supplementary dams database).

Population displacement data

NWDA estimates of displaced population for most dams in the peninsular (southern) half of the NRLP are based on census data collected between 1986 and 1993 and are therefore out-of-date for a projected construction date of 2020 or later. For dams in the Himalayas and in much of the Ganga basin, no population displacement estimates are available. We therefore estimate displaced populations for each dam location as follows. For locations where population displacement estimates have been made public, we calculate a population growth rate factor from the Center for International Earth Science Information Network (CIESIN)'s (2016) Gridded Population of the World dataset, version 4. CIESIN population data are collected at the most detailed spatial resolution available, which for India is at the district level (10 – 100 km spatial scale). At each dam location, the CIESIN (2016) projected population density for the year 2020 is divided by the population density from the year 2000 to obtain the 20–year growth rate (**Figure 3**). The 20–year growth rate is then linearly scaled to the number of years between the reported census estimate and the year 2020 in order to estimate population displacement for a 2020 construction scenario. For locations where no population displacement was available, the 2020 population densities for the dams' locations are used in conjunction with the submerged area to estimate displacement. Submerged areas were taken directly from NWDA documents and other sources (see supplementary databases for complete reference list). Uncertainty in the obtained displaced population estimates relates to both the uncertainty of the original census estimates as well as the uncertainty and consistency of the projected population density for 2020. However, we still regard this analysis as a significant improvement over the outdated reported data because of the relatively large population growth rates, which reflect an average population increase of 61% since the original census estimates.

Table 2: Selected details from canals database[a]. DOI: https://doi.org/10.1525/elementa.269.t2

Canal	Offtake vol. (10^6 m^3 y^{-1})	Trans. loss (10^6 m^3 y^{-1})	En route irr. (10^6 m^3 y^{-1})	Dom. and Ind. (10^6 m^3 y^{-1})	Outfall vol. (10^6 m^3 y^{-1})
1.1	23445	228	1212	0	0
1.2	12439	0	0	0	0
1.3	2302	0	0	0	0
1.4	2422	416	1122	0	0
1.5	2602	624	1693	0	37915[b]
2	5604	52	4644	23	883
3	7482	143	7291	48	0
4	27837	1068	25867	0	902
5	32646	939	22647	1391	7669
6.1	11680	541	1758	0	9381
6.2	11629	0	0	0	11629
7	11629	720	1950	3117	0
8	5842	538	5022	282	0
9.1	644	0	644	0	0
9.2	302	0	302	0	0
9.3	414	0	414	0	0
10	1074	68	366	49	591
11	5918	198	4790	0	930
12	2512	154	1998	360	0
13	8995	0	2000	0	6995
14	28920	1200	6680	0	21040
15	21040	580	6490	0	13970
16.1	13970	0	0	0	13970
16.2	9182	0	5011	125	4046
17[b]	5325	260	2638	162	2264
18	4370	293	412	3665	0
19	16426	562	1427	237	14200
20	12146	332	3264	124	8426
21	8565	557	3048	1105	3855
22	2310	0	0	0	2310
23	1980	0	1714	56	210
24	242	0	0	0	242
25	188	0	0	0	188
26	2252	115	1952	185	0
27.1	54	0	0	0	54
27.2	580	0	0	0	580
28.1	502	71	502	0	0
28.2	93	13	93	0	0
28.3	415	60	415	0	0
28.4	320	46	320	0	0
29.1	577	0	0	0	577
29.2	332	0	0	0	909[c]
	Totals	**9778**	**117686**	**10929**	

[a] Additional details, operating specifications, notes, status updates, information on canceled link plans, and methodological details regarding the calculation of these parameters are available in the full canals database in supplementary materials. "Offtake vol." is the annual volume pulled from the donor canal; "Trans. loss" is estimated transmission loss due to evaporation and seepage; "En route irr." is planned irrigation usage along the canal; "Dom. and Ind." is planned domestic and industrial usage along the canal; and "Outfall vol." is the annual volume discharged into the receiving canal. Values are NWDA or other government estimates and are taken from source documents listed in the supplemental database.

[b] This segment is now complete, but without the Polavaram Dam. Current discharge values without the dam are not available. These values assume completion of the dam.

[c] Outfall volume is greater than offtake volume because most water is sourced from previous segments.

Mean annual water discharge data

Hydrological data is available for southern Indian rivers via the Central Water Commission (CWC) Integrated Hydrological Data Books. Published approximately every three years, the data books contain water discharge, sediment discharge, basin properties, and water quality

Table 3: Selected details from dam database[a]. DOI: https://doi.org/10.1525/elementa.269.t3

Structure	River	Canal #	Gross storage (10^6 m^3)	Submerged area (km^2)	2020 Displaced Pop.[b]
Sankosh Lift Dam	Sankosh	1	144	8.21	131
Sankosh Dam	Sankosh	1	3919	46.26	869
Manas Dam[c]	Manas	1	10938	80	1143
Sapta Kosi High Dam Project	Kosi	2 & 3	13450	190	17847
Sapta Gandaki Dam[d]	Gandak	4	342	18	9840
Chisapani Dam	Ghaghara	5	28200	339	60000
Re-regulating Dam[c]	Ghaghara	5	125	–	–
Rupali Gad Re-Regulating Dam	Sarda	6	75	4	1316
Pancheswar High Dam	Sarda	6	11355	116	22918
Kadwan Dam	Son	9	4169	132	53613
Patanpur Dam	Parbati	9	156	29.98	9361
Mohanpura Dam	Newaj	9	616	70.51	10240
Kundaliya Dam	Kalisindh	9	583	74.76	8630
Daudhan Dam	Ken	10	2853	90	10007
Barmul Dam[c]	Mahanadi	15 & 16	1216	137.68	11261
Six additional dams	–	15 & 16	–	203.33	16631
Polavaram Dam	Godavari	17	5511	636.91	203025
Pulichintala[e]	Krishna	18	1296	143.99	43500
Inchampalli Dam	Godavari	19 & 20	10374	925.55	172138
Kalvapalli Dam	Penna	23	83	13.23	1586
Pattanadahalla Dam	Pattanadahalla	24	18	1.85	0
Shalamalahalla Dam	Shalamalahalla	24	73	8.2	1576
Kerihole Dam	Kerihole	25	–	1.2	0
Yattinhole Dam	Yattinhole	25	–	2.95	0
Hongadhalladhole Dam	Hongadhallad-hole	25	–	3.5	0
Kattalai Barrage[f]	Kaveri	26	–	5.1	–
Achankovil Dam	Achankovil	27	31	3.23	448
Punnamedu Dam	Pamba Kal Ar	27	208	4.4	0
Achankovil Kal Ar Dam	Achankovil Kal Ar	27	497	12.41	0
Chasmandva Dam	Tan	28	82	6.15	3040
Chikkar Dam	Ambica	28	142	7.42	2205
Jheri Dam	Par	28	203	8.36	2435
Paikhed Dam	Nar	28	229	9.94	4804
Dabdar Dam	Kapri	28	223	12.49	3863
Kelwan Dam	Purna	28	284	16.29	8723
Khargihill Dam	Wagh	29	461	15.58	2226
Pinjal Dam	Pinjal	29	483	19	4881
Bhugad Dam	Daman Ganga	29	426	19.03	4447
Totals			**98765**	**3416.51**	**692704**

[a] Additional details, operating specifications, notes, status updates, barrages not in this table, and methodological details regarding the calculation of displaced population for each dam are available in the full dam database in supplementary materials.
[b] Estimated displaced population for the structure if completed in the year 2020.
[c] For these structures, either live or gross storage was not given; for these cases, live storage was assumed to be 80% of gross storage, after IWM (2010).
[d] This dam site is easily confused with the "Sapta Kosi," "Kali Gandaki," and "Budhi Gandaki" sites, but it is independent of these projects.
[e] Pulichintala Project opened in 2014.
[f] Kattalai Barrage was completed in 2014.

metrics for most of the major river basins in India. These data, along with NWDA reports and peer-reviewed research on individual rivers, were used to establish current mean annual flows for most of the rivers in the Peninsular (southern) component of the NRLP.

Fewer data are available for rivers in the Himalayan component of the project. Data from the Ganga and Brahmaputra basins are classified by the Indian government and are not included in the Integrated Hydrological Data Books. Therefore, estimates from the

World Bank-supported Strategic Basin Assessment of the Ganges Basin are used for the current mean annual discharge values for the tributaries of the Ganga. The Strategic Basin Assessment is a multi-year effort by the Institute of Water Modelling (IWM) in Bangladesh to develop a shared knowledge base and analytical framework for the Ganga basin. In the Strategic Basin Assessment, a precipitation-driven numerical model was used to produce estimates of mean annual discharge for the Ganga and all its major tributaries. These estimates include operating reservoirs and irrigation withdrawals throughout the basin (IWM, 2010). For the tributaries of the Brahmaputra, mean annual discharge values are compiled from individual published sources. For the main trunks of both the Brahmaputra and the Ganga, daily discharge data were obtained from the government of Bangladesh and processed to establish both monthly and annual mean flows. These data are described in the following section.

Mean monthly water and suspended sediment discharge data

Mean monthly water discharge and suspended sediment data were obtained for six rivers leading into the five selected deltas. Gauging station locations for these datasets are given in **Table 4**. Monthly data was required for these rivers in order to assess the impacts of monsoon-season storage and dry-season transfers or releases. Given the non-linear relationship between water discharge and sediment transport capacity, reducing peak flows is expected to alter sediment transport capacity even if dry-season flows are increased proportionally.

Daily Ganga water discharge data from Hardinge Bridge and daily Brahmaputra discharge data from Bahadurabad Gauging Station were provided courtesy of the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES Project), originally from the Government of Bangladesh. Both gauging stations are located just inside the border with Bangladesh on their respective rivers, before the confluence of the two rivers. The data provided for the Ganga covered the period 1950–2011 but contains gaps in the dry season for later years. The period 1975–2000 is analyzed to provide the longest possible record with complete dry-season data beginning after the construction of Farakka Barrage, which was completed in 1975 and began diverting significant flows from the Ganga to the Hooghly for the purpose of flushing sediment near the port of Kolkata. The data provided for the Brahmaputra cover the period 1956–2011, also with gaps in recent years. The period 1975–2005 is analyzed to provide a 30–year record extending to the most recent possible year with

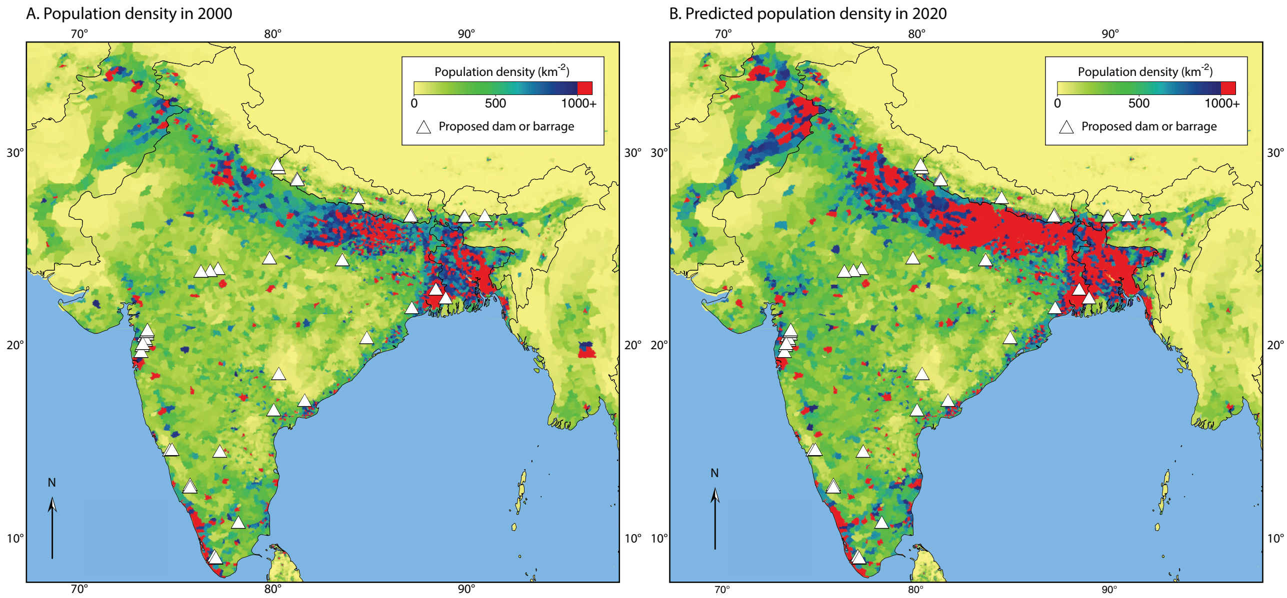

Figure 3: Scaling method for determining population displaced by dams. This figure illustrates the population density in 2000 and predicted population density in 2020 used to estimate displaced population with NRLP implementation (see text for methods). NRLP dams are shown as white triangles. DOI: https://doi.org/10.1525/elementa.269.f3

Table 4: Gauging station locations for delta simulations. DOI: https://doi.org/10.1525/elementa.269.t4

Gauging Station	Latitude	Longitude	Country	River
Bahadurabad	25.180	89.660	Bangladesh	Brahmaputra
Hardinge Bridge	24.065	89.029	Bangladesh	Ganga
Tikarpara	20.589	84.783	India	Mahanadi
Polavaram	17.256	81.657	India	Godavari
Vijayawada	16.501	80.625	India	Krishna
Upper Anaicut	10.891	78.581	India	Kaveri

complete dry-season data. Inter-annual standard deviations for each month are computed directly from the data.

Daily Godavari and Krishna discharge data from Polavaram and Vijayawada Gauging Stations were provided courtesy of the Office of the Chief Engineer, Krishna and Godavari Basin Organization. Both Polavaram and Vijayawada are the terminal gauging stations for these basins and are located just upstream of the deltas. As with the Ganga and Brahmaputra rivers, a record of at least 30 years is desirable for assessing true mean conditions in the presence of high inter-annual variability. For the Krishna river, however, a strong decreasing trend in discharge over the last 50 years renders long-term averages meaningless with respect to current conditions. Between the 1960s and today, mean annual water discharge of the Krishna fell from 62 $km^3\,y^{-1}$ to just 12 $km^3\,y^{-1}$, of which 95% comes during the monsoon season (Rao et al., 2010). The Krishna now runs dry before reaching the delta more than four months of the year. The period 2000–2015 was therefore selected to provide the longest possible period over which river discharge remained relatively stable at current conditions. Conversely, the Godavari river has shown no statistically significant change in mean annual water discharge over the last 50 years (Rao et al., 2010). A 30–year record covering the period 1980–2010 is analyzed for the Godavari. For both the Krishna and Godavari rivers, inter-annual standard deviations are computed directly from the data.

Mahanadi mean monthly water discharge was taken from Central Water Commission data at Tikarpara Gauging Station (CWC, 2015; **Table 4**). Tikarpara is the most downstream gauging station in the Mahanadi basin and is located approximately 90 km upstream from the delta apex. CWC (2015) values are a mean over the period 2000–2010. The shorter period of record was selected to minimize the influence of the Mahanadi's trend in mean annual water discharge, which has decreased by approximately 0.3 km^3 per year since the 1970s (Panda et al., 2013). Inter-annual standard deviations were not available from the CWC; instead, inter-seasonal standard deviations are taken from Panda et al. (2013). The seasons are pre-monsoon, monsoon, and post-monsoon and cover the period 1972–2005. Monsoon data in Panda et al. (2013) is further divided into June, July, August, and September. Standard deviations for these months were taken directly from Panda et al. (2013). For the remaining months, the pre-monsoon standard deviation from Panda et al. (2013) is divided by $\sqrt{5}$ for the five months January–May, and the post-monsoon standard deviation from Panda et al. (2013) is divided by $\sqrt{3}$ for the three months October–December.

For the Kaveri, monthly mean water discharge values from the Upper Anaicut (Mokkombu Dam) over the period 2001–2010 were obtained from the Asian Development Bank's (2011) report. Upper Anaicut is located 2 km upstream from the apex of the Kaveri delta, where the river splits into multiple large distributary channels including the Kollidam. Inter-annual standard deviations are computed directly from the monthly data.

Suspended sediment concentration data were obtained for the selected six rivers. A sediment rating curve was fitted to the data with the form:

$$Q_s = aQ^b, \tag{1}$$

a widely-applied form for the relation between water discharge Q in m^3/sec and suspended sediment discharge Q_s in kg/s, with two empirically-derived constants for individual rivers (Islam, 1999; Syvitski et al., 2005; Walling, 2008). 95% confidence intervals were calculated following Montgomery and Runger (2011) using a student's t-distribution (2α) in conjunction with the standard deviation of Q_s and the sum of squares of deviations of data points from their sample mean.

For the Krishna and Godavari rivers, daily suspended sediment discharge data were available along with the daily water discharge data courtesy of the Office of the Chief Engineer, Krishna and Godavari Basin Organization. The same periods of analysis were selected for sediment as for water discharge. For the Ganga and Brahmaputra rivers, sediment discharge data and pre-fitted rating curves are given for Hardinge Bridge over the period 1980–1995 and Bahadurabad Gauging Station over the short period 1989–1994 in Islam et al. (1999). Mahanadi data from the Tikarpara Gauging Station over the period 2002–2012 and Kaveri data from the Musiri Gauging Station were obtained from CWC (2012, 2015). Musiri is approximately 12 km upstream of the Upper Anaicut gauging station from which water discharge data are presented. For both the Mahanadi and Kaveri rivers, suspended sediment measurements are available only as seasonal averages: monsoon, non-monsoon and annual. A sediment rating was fit to the seasonally averaged points.

Figure 4 shows the suspended sediment data and rating curves for each of the six rivers. The rating relationships obtained are as follows: $Q_s = .0071Q^{1.51}$ for the Ganga ($R^2 = 0.68$), $Q_s = .0047Q^{1.56}$ for the Brahmaputra ($R^2 = 0.78$), $Q_s = .0006Q^{1.71}$ for the Mahanadi ($R^2 = 0.93$), $Q_s = .00008Q^{1.96}$ for the Godavari ($R^2 = 0.94$), $Q_s = .0019Q^{1.40}$ for the Krishna ($R^2 = 0.95$), and $Q_s = .0082Q^{1.26}$ for the Kaveri ($R^2 = 0.81$).

Calculating changes to water and suspended sediment discharge under the NRLP

Under the NRLP, suspended sediment discharge to deltas will be affected by changes in river water discharge and by increased sediment trapping in new reservoirs. The exact change to water discharge will depend upon canal operating schedules, utilization changes within the basin, and transmission losses (seepage and evaporation) within the canals. The new water flows will then convey new suspended loads as approximated by the individual sediment rating curve estimated from observed data for each river. Reservoir trapping will apply in the new regime. The following sections describe how we model these processes.

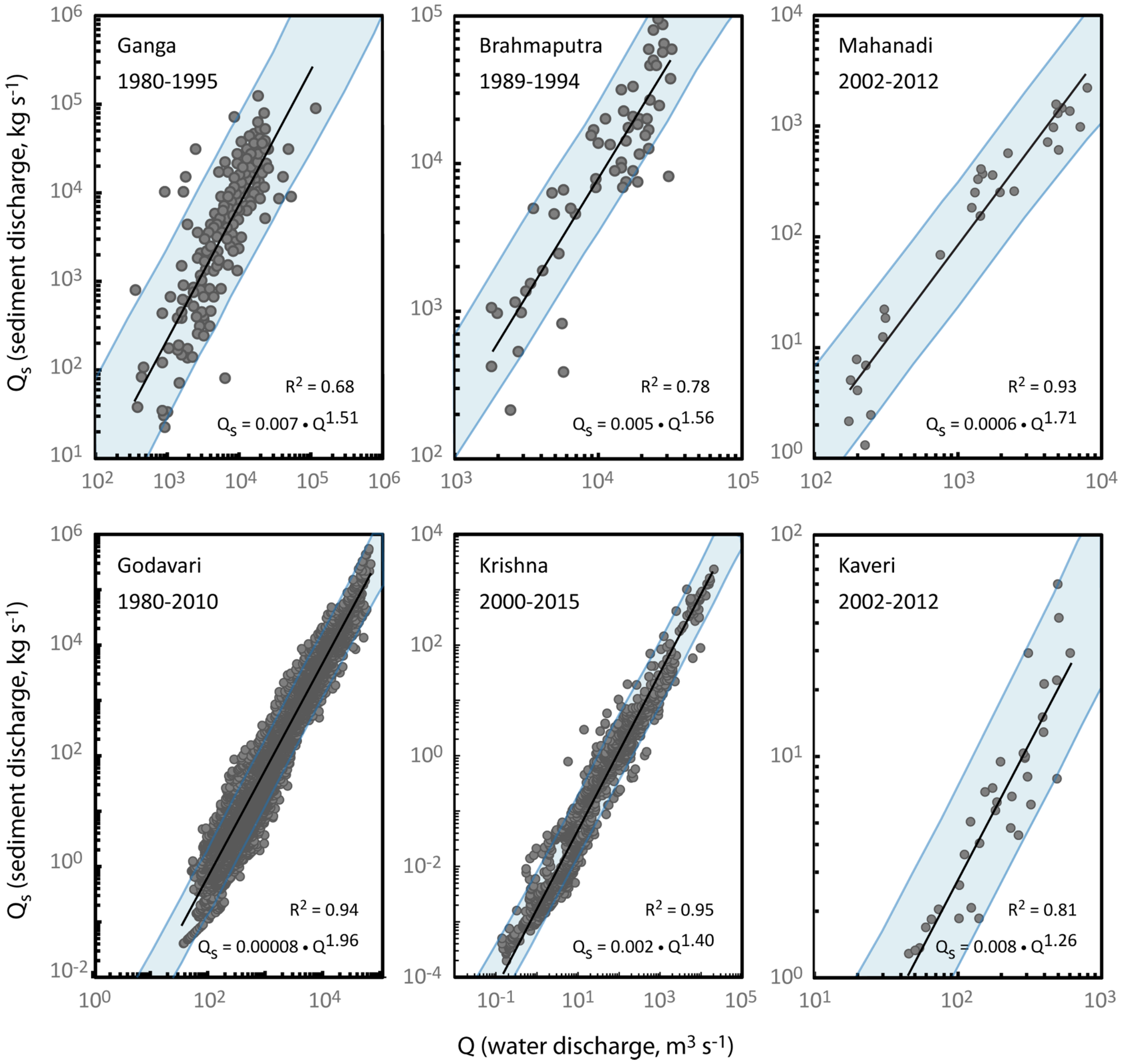

Figure 4: Sediment rating curves for six major rivers. Sediment rating curves for the Ganga, Brahmaputra, Mahanadi, Godavari, Krishna and Kaveri rivers, fitted to data from the following sources: Ganga data from Hardinge Bridge over the period 1980–1995 from Islam et al. (1999); Brahmaputra data from Bahadurabad Gauging Station over the period 1989–1994 from Islam et al. (1999); Mahanadi data from Tikarpara Gaging Station over the period 2002–2012 from Central Water Commission (2015); Godavari data from Polavaram Gauging Station over the period 1980–2010 courtesy of the Office of the Chief Engineer, Krishna and Godavari Basin Organization; Krishna data from the Vijayawada Gauging Station over the period 2000–2015 courtesy of the Office of the Chief Engineer, Krishna and Godavari Basin Organization; and Kaveri data from Musiri Gauging Station over the period 2000–2012 from Central Water Commission (2012, 2015). Light blue curves reflect 95% confidence intervals for fitted Q-Q_s relations. DOI: https://doi.org/10.1525/elementa.269.f4

Graph database construction and water flow calculations

To calculate water discharge changes resulting from the NRLP, a graph database was constructed from the text-based datasets (**Figure 5**). The database handles only those changes associated with the NRLP; we assume current regulations and transfers by existing infrastructure are reflected in gauging station data. In the graph database, canals are represented as edges, with properties of flow direction, annual transfer volume, and en route usage and loss values compiled from primary sources. Confluences, dams, barrages, and canal outfall locations are represented as nodes. Each dam node is controlled by an impoundment schedule, which removes water from the river, and a transfer schedule, which releases monthly portions of the total annual transfer volume into the canal. Losses within the canals follow the same monthly proportions. Transfers from each dam can take one of three schedules: uniform (regular transfers throughout the year); specified (specific transfer volumes per month specified by NWDA reports); or monsoon (no transfers during the monsoon months, uniform transfers during the dry season months). Impoundment schedules

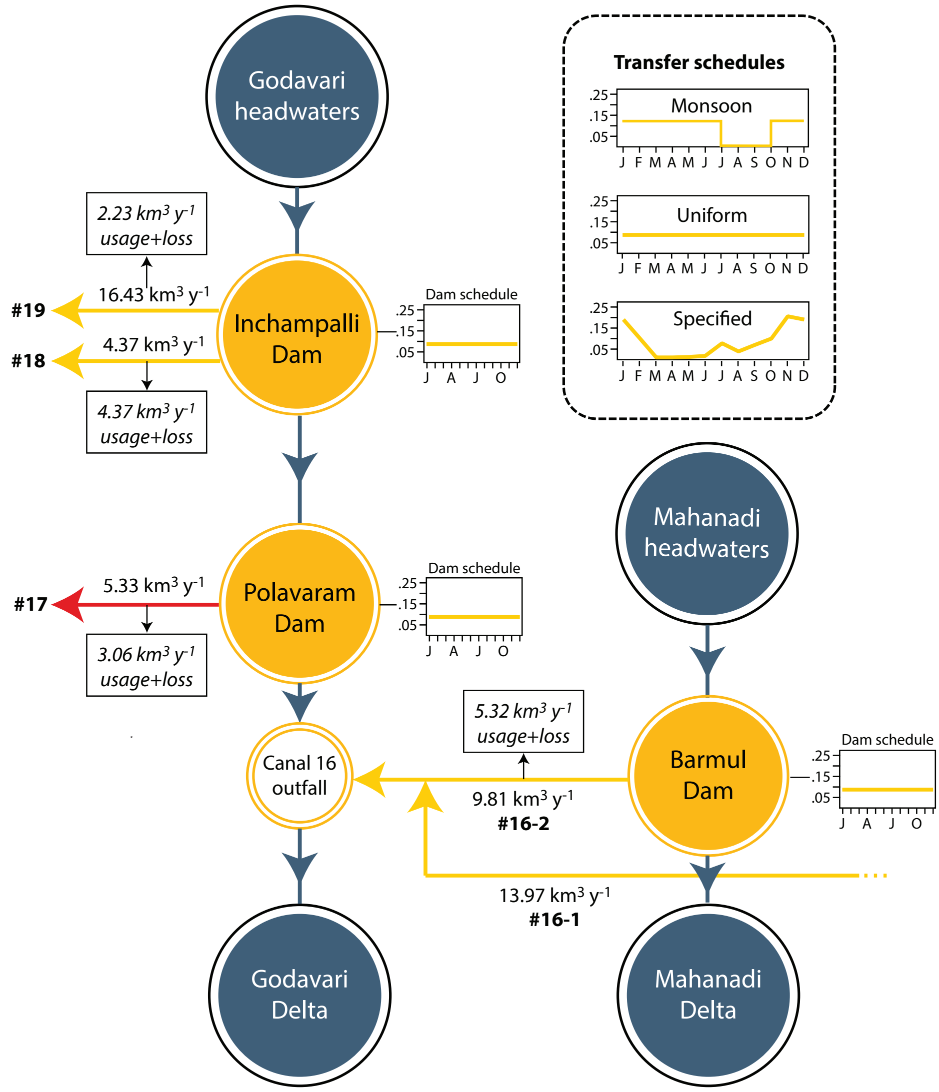

Figure 5: Schematic depiction of graph database calculations. This figure explains the structure of the graph database by depicting a portion of NRLP, containing the Mahanadi and Godavari rivers along with link canals 16–1, 16–2, 17, 18, and 19. Yellow structures are proposed and red structures are completed; canal 17 (red) was completed in 2015. Transfer volumes are properties of nodes; usage (domestic/industrial/agricultural) and losses (evaporation and seepage) are properties of canals. Transfer volumes are broken into annual transfer schedules, with a proportion of the annual total transferred each month according to source documents. Transfer schedules are monsoon (no transfer during the monsoon; uniform transfer during the dry season), uniform (regular transfers throughout the year), or specified (transfer volumes specified by the NWDA). Units are a proportion of the annual total, from 0–1. Losses and usage along the canals follow the transfer proportions. Impoundment at dam nodes occurs during monsoon months, except for dams in the Krishna basin, where a small amount of impoundment occurs year-round. To calculate changes in annual flow, annual water offtakes are transferred from donor nodes (dams) to receiving nodes (outfall points or dams) in a single step, with losses removed en route. All flow changes are then propagated to the deltas. For monthly calculations, 24 steps (12 transfers and 12 propagations) are performed. The database handles only changes associated with the NRLP; existing infrastructure is assumed to be reflected in current gauging station data values. DOI: https://doi.org/10.1525/elementa.269.f5

are the same for each dam: zero impoundment in the dry season (December–June), with the full transfer volume impounded during the remaining months. In the Krishna basin only, it was necessary to increase dry-season impoundment to 5% of the full transfer volume per month for all simulations to meet NWDA-specified transfer volumes. In all other cases, operating schedules were derived from NWDA sources and reports.

Although the graph database is not a hydrological model, it has several advantages for performing water transfer calculations. Given flow directions and operating parameters, it is capable of handling the massive complexity of a looping, interconnected, and temporally staggered system of this size. The database can be queried to examine exposure and connectivity along individual reaches. The free software can be modified by any user, with subsets of the project simulated, operating parameters modified, and new dams or canals added as the project evolves.

Changes to suspended load

The graph database was used to calculate changes to mean monthly water discharge at the apex of each of the six deltas of interest. Next, sediment rating curves were applied to mean monthly water discharge values under current conditions and under the NRLP (**Figure 4**). Change in annual suspended sediment load was then calculated from the monthly totals. In this procedure, we make the simplifying assumption that no siltation occurs within the canals. Uncertainty calculations for each part of the sediment-change calculations are described in the section "Quantifying uncertainty," below.

Sediment trapping by reservoirs

Reservoir trapping is calculated following the method of Vörösmarty et al. (2003), which uses a modified version of Brune's (1953) empirically-derived rule for determining the trapping efficiency of reservoirs. Trapping efficiency quantifies the proportion of incoming sediment permanently retained within a reservoir. Vörösmarty et al.'s (2003) method allows an estimate of basin-wide trapping efficiency for basins with multiple reservoirs. It is applied here only for new reservoirs associated with the NRLP, and we assume that existing reservoir trapping is reflected in the current sediment rating curves.

For a single basin divided into *m* regulated sub-basins, the approximate residence time of water in the reservoirs of regulated sub-basin *j* is given by:

$$\Delta\tau_{reg,j} = \frac{\sum_{1}^{n_j} V_i}{Q_j}, \tag{3}$$

Where *n* is the number of reservoirs in sub-basin *j*, V_i is the operational volume at reservoir *i*, and Q_j is the water discharge at the mouth of sub-basin *j*. The trapping efficiency for regulated sub-basin *j* is then given by

$$TE_{reg,j} = 1 - \frac{0.05}{\sqrt{\Delta\tau_{reg,j}}}. \tag{4}$$

The trapping efficiency of the full basin is given by

$$TE_{bas} = \frac{\sum_{1}^{m} TE_{reg,j}\, Q_j}{Q_m}, \tag{5}$$

Where Q_m is the water discharge at the river mouth (Vörösmarty et al., 2003).

For the Krishna, Godavari and Mahanadi rivers, all newly planned reservoirs are located on the main stems, with the most downstream reservoir located near or at the delta apex. Each of these rivers was therefore treated as one regulated sub-basin, with reservoir volumes V_i given in **Table 3**, mean annual river discharge Q_j taken at the river mouth, and basin-wide trapping efficiency for NRLP reservoirs given by Eq. 4. Reservoir volumes V_i are multiplied by a utilization factor of 0.33 to approximate annual average storage, assuming maximum storage occurs only in monsoon months. For the Kaveri river, no new reservoirs are proposed in the NRLP.

For the Brahmaputra basin, there are two regulated sub-basins associated with the NRLP: the Sankosh and the Manas. Mean annual water discharge Q_j for the Sankosh and Manas are 17.3 and 32.0 km^3 y^{-1}, respectively. For the Ganga basin, there are seven regulated sub-basins associated with the NRLP: the Kosi, Gandak, Ghaghara, Sarda, Ken and Son, each with one reservoir, and the Chambal with three reservoirs. Barrages and re-regulating dams were not included in trapping efficiency calculations. Mean annual water discharge Q_j at the dam sites are derived from primary references and are 49.9 km^3 y^{-1} for the Kosi, 32.7 km^3 y^{-1} for the Gandak, 43.8 km^3 y^{-1} for the Ghaghara, 13.6 km^3 y^{-1} for the Sarda, 12 km^3 y^{-1} for the Ken, and 13.2 km^3 y^{-1} for the Kosi (see supplementary dams database and annotated reference list for references.) For the Chambal, mean annual water discharge is 18 km^3 y^{-1}. Mean annual water discharge for the full Brahmaputra and Ganga basins at their river mouths (Q_m) are 682.6 km^3 y^{-1} and 356.0 km^3 y^{-1}, respectively. As with the previous rivers, reservoir volumes are multiplied by a utilization factor of 0.33.

From these values, basin-wide trapping efficiencies associated with new NRLP reservoirs (TE_{bas}) were established (Eq. 5). We note that these values do not represent the full trapping efficiencies within the basin, but only the additional trapping related to the construction of NRLP reservoirs. We make the assumption that trapping by existing reservoirs is already represented within the sediment rating curve. Trapping proportions were applied to the rating-curve derived suspended sediment changes to arrive at a total change in suspended sediment load for each river entering a delta.

Uncertainty for the trapping efficiency of each reservoir was derived from the bounding envelopes of Brune (1953), in which trapping efficiency is shown to vary by approximately ±10% from a de-silting to a semi-dry reservoir, or from a coarse-sediment to a fine-sediment reservoir, as highlighted in Verstraeten and Poeson (2000). It was conservatively assumed that errors in trapping efficiency measurements are not independent; a worst-case scenario estimate of trapping uncertainty was made by propagating a ±10% uncertainty for each reservoir through the basin-wide calculation.

Quantifying uncertainty on total sediment changes

In calculating uncertainty on sediment load changes resulting from the NRLP, we assume full construction of the NRLP as proposed. We assume that canals do not fundamentally alter the sediment rating curves once emplaced (beyond trapping efficiency changes from new reservoirs), and we further assume that no sediment storage occurs within the canals. We estimate sediment load changes for current mean water discharge conditions only. The change in sediment load brought about by the NRLP must be calculated independently for each flow condition, as sediment load scales non-linearly with water discharge. For a given flow condition, the uncertainty on the magnitude of the sediment-load shift from current to NRLP conditions comes from two sources: (1) uncertainty on the Q-Qs rating curve relationship (**Figure 4**), and (2) uncertainty on the trapping efficiency of new NRLP reservoirs.

For each river in **Figure 4**, the best-fit Q-Q_s relation is given, along with an envelope encompassing the range of possible Q-Q_s relations with 95% confidence. Within this envelope, the highest-exponent and lowest-exponent relation encompassing the data within uncertainty bounds can be found (i.e., highest-exponent in linear space, or highest-slope in log-log space as depicted in **Figure 4**.) These relations give the highest and lowest sensitivity to water discharge changes, where the highest-slope relation is the most sensitive and the lowest-slope relation the least sensitive to changes in water discharge. For each scenario, a 95% confidence interval for trapping efficiency is then applied to the NRLP load estimates. Both sensitivity scenarios and trapping efficiency uncertainty are included when giving 95% confidence intervals on the percent change in total annual load.

Changes to delta aggradation

Change in total annual suspended sediment load for each delta was converted to potential change in delta aggradation rate using delta area and an assumed sediment bulk density of = 1.5 g cm^{-3}. In this approximation, one-third of the total suspended sediment load is deposited on the subaerial delta, with two-thirds transported to the subaqueous or to the ocean. This proportion is considered reasonable for river systems with extensive monsoonal flooding and has been corroborated by long-term sediment budget reconstructions for the Ganga-Brahmaputra Delta and other large Asian river systems (Islam et al., 1999; Goodbred and Kuehl, 1999; Liu et al., 2009). Change in aggradation rate for each delta was therefore calculated as follows:

$$\Delta D = \frac{10^{-6}}{\rho A} \cdot \frac{1}{3} \sum_{m=1}^{12} s_m \left(Q_{s,m\,NRLP} - Q_{s,m\,current} \right), \qquad (2)$$

Where ΔD is change in delta aggradation rate (mm y^{-1}), A is delta area (km^2), ρ is sediment bulk density (g cm^{-3}), 1/3 is the fraction of sediment load deposited on the subaerial delta surface, m is month of year, s_m is seconds per month, $Q_{s,m\,current}$ and $Q_{s,m\,NRLP}$ are mean monthly suspended sediment discharge values for month m under current and NRLP conditions (kg s^{-1}), and 10^{-6} is a unit conversion factor with units of (g mm km^2 kg^{-1} cm^{-3}). Subaerial delta areas are based on the delta boundaries defined by Tessler et al. (2015). Area for the Ganga-Brahmaputra Delta includes the embanked tidal deltaplain, which is not subject to aggradation except in the case of levee breaches (e.g. Auerbach et al., 2015). Insufficient data were available to calculate changes to bed load transport or the bed load contribution to delta aggradation.

Mapping changes to existing watersheds

Changes to existing watersheds were assessed for six major rivers: the Ganga at Hardinge Bridge, and the Hooghly, Godavari, Krishna, Penna, and Kaveri Rivers at their mouths. The Mahanadi and the Brahmaputra were not included, as they are 'donors' to other rivers only. New contributing runoff regions for the other rivers were delineated using the Terrain Analysis Using Digital Elevation Models (TauDEM) package applied to the HYDRO1K dataset, a U.S. Geological Survey hydrologically-corrected 30 arc-second digital elevation model of the world. Watersheds were delineated for the offtake points of each canal and assigned as new contributing runoff regions for the rivers into which the canals outfall. The graph database described previously was used to evaluate connectivity of the network and determine exposure to new runoff regions.

Next, the percent of water exiting the basin that will be sourced from the new contributing areas was calculated. In most cases, unless operating schedules suggested otherwise, it was conservatively assumed that water entering a reservoir did not mix with the existing river water if it was to be immediately withdrawn for further transport down the system. Where water offtakes occur downstream of water deliveries, it was assumed that new and old water were removed proportionally.

An example of the calculation for the Godavari River is illustrated in **Figure 5**. We assume that the Godavari starts with its current mean annual water discharge of 89.7 km^3 y^{-1}, as all canals meet the river downstream of its confluences with major tributaries. The river loses 16.4 km^3 y^{-1} to link canal 19, 4.4 km^3 y^{-1} to link canal 18, and 5.3 km^3 y^{-1} to link canal 17, making its discharge just 63.6 km^3 y^{-1} as it nears the river mouth. At the delta, however, link canal 16 outfalls at Polavaram, carrying 18 km^3 y^{-1} sourced from the Mahanadi, the Ganga and tributaries of the Brahmaputra via Farakka Barrage. The total discharge jumps back to 81.6 km^3 y^{-1}, making the change in mean annual discharge at the Godavari only 8 km^3 y^{-1}, or 10% of flow. However, 22% of flow (18 km^3 y^{-1}) is now sourced from the watersheds of the Mahanadi, Ganga and Brahmaputra tributaries.

Results

Impacts on mean annual water discharge for Indian rivers

Figure 6 shows changes to mean annual water discharge for 29 rivers. The Ganga is projected to experience the largest reduction in absolute water discharge, primarily due to intra-basin transfers and usage. The discharge of the Ganga at Hardinge Bridge is projected to decrease by 87 km^3 y^{-1} (–24% of total annual flow), of which approximately 12 km^3 is transferred out of the basin via link canals 6, 7, and 8, and 75 km^3 is utilized or lost to evaporation within the Ganga basin. Two tributaries within the Ganga are projected to increase in mean annual discharge:

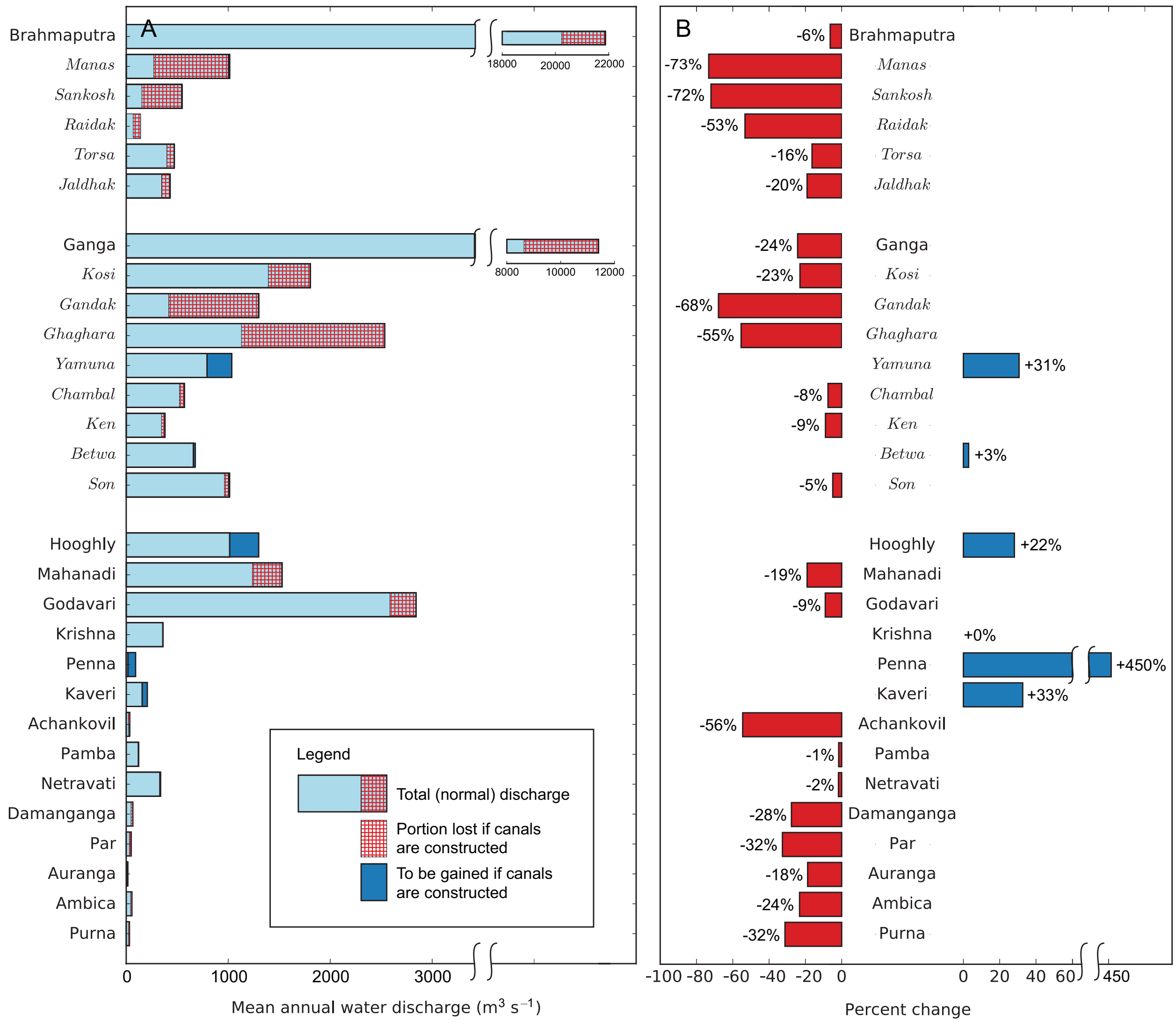

Figure 6: Changes in water discharge to Indian rivers. Graphical representations of the data in Table 5. A) Absolute changes in mean annual water discharge, with current discharge shown in light blue, the proportion of water calculated to be gained with full NRLP implementation shown in dark blue, and the proportion of water calculated to be lost with full NRLP implementation shown in hatched red. Note that the Manas, Sankosh, Raidak, Torsa and Jhaldhak are tributaries of the Brahmaputra; their losses sum to the total loss of the Brahmaputra. Similarly, the Kosi, Gandak, Ghaghara, Yamuna, Chambal, Ken, Betwa and Son are tributaries of the Ganga; their losses along with the losses to the Ganga directly sum to the value shown for the Ganga. For all rivers that are not tributaries, values are taken at the basin outlet where it enters the ocean. For tributaries, values are taken at the rivers' confluences with either the Ganga or Brahmaputra. B) As in (A), but with gains and losses represented as a percent change. DOI: https://doi.org/10.1525/elementa.269.f6

the Betwa river by 3% and the Yamuna by 31%. All other tributaries are projected to decrease in mean annual discharge, with the largest decreases seen in the Kosi (23%), Ghaghara (55%) and Gandak (68%) Rivers.

The Brahmaputra, which will contribute the largest volume of water to other river basins via withdrawals from its tributaries, is projected to experience a decrease of 43 km^3 y^{-1} (–6%), of which 5 km^3 will be used or lost within the basin and 38 km^3 will be transferred to southern basins. These transfers will reduce the mean annual water discharge of the Brahmaputra by only 6% but will decimate the tributaries themselves: the Manas and Sankosh are projected to lose more than 70% of their mean annual water discharge and the Raidak more than 50%, with the Torsa and the Jhaldak losing 16% and 20%, respectively (**Table 5**).

Southern rivers of India are the primary beneficiaries of the NRLP; however, only the Hooghly, Penna and Kaveri are projected to experience an increase in mean annual water discharge given full implementaton of the project. The Hooghly is projected to experience an increase of 22%, the Penna of 450%, and the Kaveri 33% over their current mean annual discharge. The remainder of the southern rivers are projected to either

Table 5: Changes in mean annual river discharge for 29 rivers. DOI: https://doi.org/10.1525/elementa.269.t5

River	Discharge[a] ($m^3 s^{-1}$)	Δ discharge[b] ($m^3 s^{-1}$)	Percent change
Brahmaputra[c]	**21629**	**−1369**	**−6%**
Manas	*1014*	*−743*	*−73%*
Sankosh	*547*	*−394*	*−72%*
Raidak	*137*	*−73*	*−53%*
Torsa[d]	*471*	*−77*	*−16%*
Jaldhak	*404*	*−82*	*−20%*
Ganga[c]	**11406**	**−2769**	**−24%**
Kosi	*1806*	*−415*	*−23%*
Gandak	*1299*	*−882*	*−68%*
Ghaghara	*2535*	*−1405*	*−55%*
Yamuna	*792*	*243*	*+31%*
Chambal	*570*	*−43*	*−8%*
Ken	*380*	*−34*	*−9%*
Betwa	*658*	*19*	*+3%*
Son	*1014*	*−50*	*−5%*
Direct offtakes[e]	*0*	*−202*	
Hooghly	**1014**	**222**	**+22%**
Mahanadi	**1528**	**−291**	**−19%**
Godavari	**2842**	**−257**	**−9%**
Krishna	**359**	**1**	**0%**
Penna	**17**	**75**	**+450%**
Kaveri	**156**	**51**	**+33%**
Achankovil	**33**	**−18**	**−56%**
Pamba	**121**	**−2**	**−1%**
Netravati	**336**	**−6**	**−2%**
Damanganga	**65**	**−18**	**−28%**
Par	**49**	**−16**	**−32%**
Auranga	**16**	**−3**	**−18%**
Ambica	**56**	**−13**	**−24%**
Purna	**32**	**−10**	**−32%**

[a] Current river discharge values are taken or calculated from data source indicated in supplementary material. See the annotated database reference list in supplementary materials for details of each value. Depending on data availability, the value may reflect either mean or median annual discharge.
[b] Change in annual river discharge assumes full implementation of the NRLP. Data sources are as given in Tables 2 and 3 (Dams and canals databases).
[c] For the Brahmaputra and Ganga rivers, change in annual discharge is also shown for affected tributaries (in italics). The sum of the discharge changes for tributaries is equal to the discharge change for the parent river.
[d] For the Torsa, only 75% dependable yield (the 1st quartile of discharge) was available.
[e] "Direct offtakes" reflects the sum of water taken or delivered directly to the Ganga, rather than to/from one of its tributaries.

remain stable or decrease, with the largest percent decreases occuring in the relatively smaller western rivers: the Achankovil (−56%), Damanganga (−28%), Par (−32%), Auranga (−18%), Ambica (−24%), and Purna (−32%).

Impacts on mean monthly water discharge

Mean monthly water discharge under current and NRLP conditions was established for six rivers that feed into five major deltas: the Ganga, Brahmaputra, Mahanadi, Godavari, Krishna, and Kaveri (**Figure 7**). The same NRLP-derived water discharge changes are shown against mean conditions (black curves), with one standard deviation of inter-annual variability given in blue (high-flow) and red (low-flow).

Though the rivers vary in mean annual discharge by up to two orders of magnitude, their hydrographs follow a similar pattern of low flow during the dry season and high flow during the monsoon-dominated summer months. The arrival of monsoon discharge is delayed by approximately one month for southern rivers relative to northern rivers. Inter-annual variability is high for all rivers, reflecting the strong variability in the strength of the monsoon. However, inter-annual variability is particularly high for the Krishna and Kaveri rivers. This is not entirely due to natural processes; it is partly caused by strongly varying irrigation withdrawals over the last decade. Data in this study show that both rivers ran dry for most (Krishna) or all (Kaveri) of the dry-season months over the periods of record.

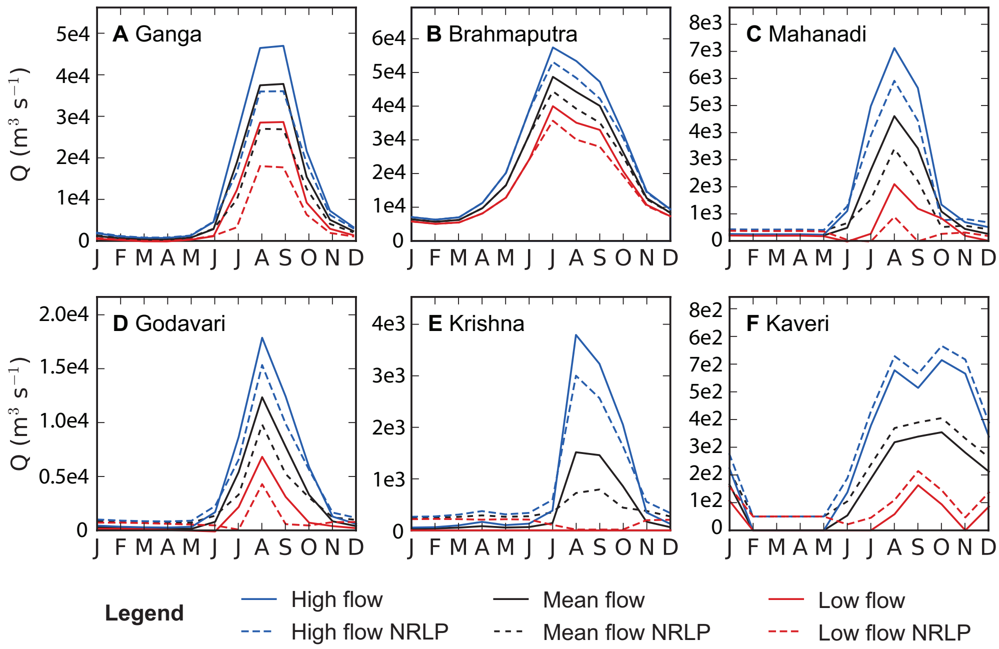

Figure 7: Estimated changes to mean monthly water discharge for six major rivers. For each river, mean monthly water discharge under current conditions is shown as a black solid line, with one standard deviation of inter-annual variability shown with solid blue and red lines. Estimated water discharge for high-, mean-, and low-flow conditions under NRLP is shown with dashed lines. Discharge falls during monsoon season for all rivers but the Kaveri under NRLP conditions; the Kaveri is projected to see a slight increase year-round. DOI: https://doi.org/10.1525/elementa.269.f7

Under the NRLP (dashed lines, **Figure 7**), monsoon-season discharge is reduced for all but the Kaveri river. This is primarily due to water impoundment in reservoirs. In general, changes to mean monthly flow will be on the order of those already seen in current inter-annual variability. However, particularly for the Ganga, future high-flow years will become similar to current mean-flow years; future mean-flow years will become similar to current low-flow years; and, if NRLP withdrawal schedules are not modified during low-flow years, future low-flow years will see unprecedented lows that fall outside of the current envelope of natural variability.

For the Ganga, water discharge will decrease from July–December, with the largest decrease occurring between July and October as water is impounded in Himalayan dams. The Brahmaputra will experience a similar decrease in water discharge from July to November, with its flow unaffected the rest of the year. As the water from the Brahmaputra is transferred to southern rivers during the dry season, some rivers will see an increase in water discharge during those months: the Kaveri will improve from no-flow to scant flow (51 $m^3\ s^{-1}$) during the dry season, and the Krishna will see its mean monthly water discharge increase from approximately 50 $m^3\ s^{-1}$ to approximately 250 $m^3\ s^{-1}$ for most of the dry-season months This will bring dry-season water discharge back to pre-1970s levels (prior to major dam construction) (GRDC, 2017), though with sediment trapping by post-1970s dams now in place (Rao et al., 2013).

Impacts on suspended sediment deliveries to deltas

Figure 8 shows the corresponding changes to monthly suspended sediment discharge calculated using the sediment ratings curves for individual rivers (**Figure 4**) and the estimated trapping efficiency of new reservoirs. Black lines in **Figure 8** give results using the best-fit rating curve, while orange and blue lines give a 95% confidence interval using the highest- and lowest-sensitivity rating curves that encompass the data. Estimated trapping efficiency increases are 36% for the Ganga, 6% for the Brahmaputra, 45% for the Mahanadi, 79% for the Godavari, 74% for the Krishna, and 0% for the Kaveri, where no new reservoirs are proposed. We note that these values do not represent the full trapping efficiencies of the basin, but only the additional trapping related to proposed NRLP reservoirs. Shading on estimated NRLP conditions is derived from uncertainty on trapping efficiency changes.

As with water discharge, the Ganga is projected to experience a year-round drop in its suspended load, with peak sediment discharge falling from 58,000 $kg\ s^{-1}$ to 23,000 $kg\ s^{-1}$ in the month of September. Similarly, peak suspended sediment discharge in the Brahmaputra will drop in same month from 97,000 $kg\ s^{-1}$ to 78,000 $kg\ s^{-1}$; in the Mahanadi from 1,700 $kg\ s^{-1}$ to 550 $kg\ s^{-1}$, in the Godavari from 8,600 $kg\ s^{-1}$ to 1200 $kg\ s^{-1}$; and in the Krishna from 50 $kg\ s^{-1}$ to 5 $kg\ s^{-1}$ despite that river experiencing no net change in mean annual water discharge. In the Kaveri, sediment discharge will increase year-round, but by a negligible amount.

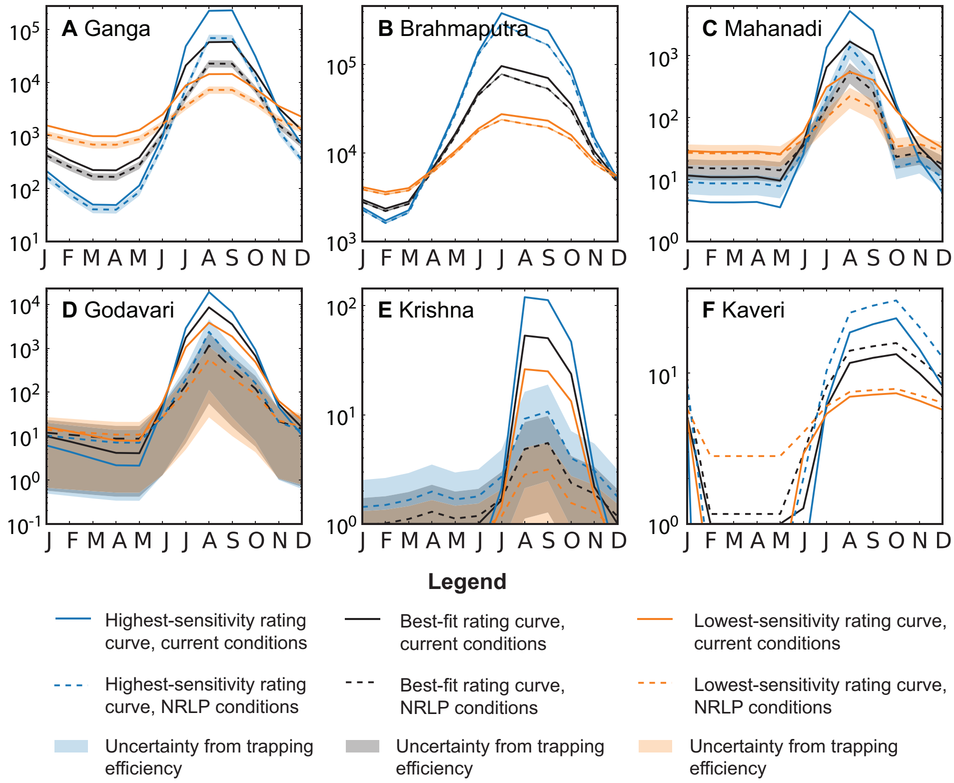

Figure 8: Estimated changes to mean monthly suspended sediment discharge for six major rivers. Estimated changes to mean monthly suspended sediment discharge calculated using sediment rating curves in Figure 4. For each river, current conditions are estimated using the best-fit rating curve of Figure 4 (solid black line.) NRLP conditions are calculated assuming the same rating curve (dashed black line), with uncertainty related to the trapping efficiency of new reservoirs given by grey shading. Highest- and lowest-sensitivity rating curves correspond to 95% confidence intervals of the fitted rating curves, with the highest-sensitivity curve showing the most sensitivity to water discharge and the lowest-slope curve showing the least sensitivity to water discharge. These curves are used to give 95% confidence intervals on the expected total annual percent change in sediment load. For each scenario, 95% confidence intervals for trapping efficiency effects are also given on the change in sediment load post-NRLP (shaded regions around dashed lines). DOI: https://doi.org/10.1525/elementa.269.f8

Total mean annual suspended sediment load for each delta is available in **Table 6**. Current conditions (Q_s) are calculated from available data, and NRLP conditions are simulated. Given full NRLP implementation, all rivers but the Kaveri are projected to experience a decrease in mean annual sediment load. With large reservoirs planned near or at their deltas, the Mahanadi, Godavari, and Krishna Rivers are projected to experience reductions of 40–85%, 71–99% and 60–97% of their annual suspended loads, respectively. The Ganga is projected to experience a 39–75% reduction in annual suspended load, and the Brahmaputra a 9–25% reduction despite losing only 6% of its annual water flow. For the Ganga, Brahmaputra, and Mahanadi Rivers, approximately two-thirds of the decrease in mean annual sediment load is due to the redistribution of flows from the monsoon to the dry season, with the remaining one-third due to trapping in reservoirs. For the Godavari and Krishna rivers, approximately half of the reduction is due to flow redistribution and half to trapping. The Kaveri is projected to experience a 7–43% increase over current conditions; however, the current suspended load is near zero, so this will have little, if any, impact on the delta.

R^2 values for fitted Q-Q_s rating curves range from 0.69–0.95 and are lowest for the Ganga and Brahmaputra Deltas, reflecting current uncertain knowledge of the sediment loads of those rivers as presented in the literature. Darby et al. (2015) notes that sediment load estimates for the Ganga range from 390–548 Mt/y, while Fischer et al. (2016) finds a suspended load of 260–720 Mt/y. For the Brahmaputra, Darby et al. (2015) notes a best estimate of approximately 475–523 Mt/y but acknowledges published values as high as 1100 Mt/y. The large uncertainties for suspended loads highlight the need for ongoing data collection on these vital international rivers.

At deltas, reduced suspended loads will translate to reduced aggradation rates, putting them at greater risk of coastal erosion and flooding (**Table 6**). For the Ganga-Brahmaputra delta, the aggradation rate is projected to drop from 3.6 to 2.5 mm y^{-1} given full implementation of the NRLP, a 30% reduction in elevation-building

Table 6: Changes in mean annual suspended sediment discharge to river deltas. DOI: https://doi.org/10.1525/elementa.269.t6

River	Mean Q_s ($Mt\ y^{-1}$)	NRLP Mean Q_s ($Mt\ y^{-1}$)	Change in Mean Q_s	Delta area (km^2)	Aggradation rate by suspended load ($mm\ y^{-1}$)		
					Historical[a]	Current	NRLP
Ganga and	420	160	–39% to –75%	88100	5.4	3.6	2.5
Brahmaputra	1000	830	–9% to –25%				
Mahanadi	9.5	3.0	–40% to –85%	5000	1.6	0.2	0.1
Godavari	38	4.9	–71% to –99%	5200	7.3	1.6	0.2
Krishna	0.35	0.06	–60% to –97%	4800	3.0	0.0	0.0
Kaveri	0.18	0.23	+7% to +43%	8000	0.9	0.0	0.0

[a] Historical data sources are Sarker (2004) for the Ganga, and Gupta et al. (2012) for the Mahanadi, Kaveri, Godavari and Krishna. The Brahmaputra is a relatively unregulated basin and was assumed to have a historical sediment load comparable to modern values.

capacity. Aggradation on the Mahanadi delta would fall to half of its current rate, and on the Godavari to just 13%. These values do not include bed load, which is typically ~10% of the suspended load and contributes additional aggradation capacity (Syvitski et al., 2003). However, little data is available to constrain bed load estimates. Both the Krishna and the Kaveri deltas, which currently receive negligible sediment loads, would continue to experience negligible aggradation under the NRLP.

Impacts on contributing runoff regions and network connectivity

Figure 9 shows the changes in watersheds for six major basins and the proportion of water that will be sourced from new areas. Given full NRLP implementation, 12% of the water discharge at Hardinge Bridge on the Ganga will be sourced from a new watershed, along with 3% at the mouth of the Hooghly. It is worth noting that more than half of the water in the Hooghly is already transferred from the Ganga via Farakka Barrage. While the NRLP will result in only 3% of the Hooghly discharge coming from the new watersheds of the Brahmaputra tributaries, it will represent an increase from 56% to 64% of discharge coming from a foreign basin.

Under the NRLP, 22% of the water discharge at the mouth of the Godavari will be sourced from a new watershed, along with 38% at the mouth of the Krishna, 95% at the mouth of the Penna, and 59% at the mouth of the Kaveri. Of all the rivers affected by the NRLP, the Penna is expected to experience the largest change in runoff source area. As a "middle-man" in the great exchange, the Penna will experience through-moving water transfers totaling more than ten times its current discharge. The effect will be to almost entirely replace the water of the Penna with water from other basins. Similarly, the Krishna is projected to experience no change in the total volume of water exiting the river mouth, but it will nevertheless experience a large change in the proportion of water that comes from its natural watershed. This is due to the compensating transfers built into the NRLP, in which rivers receive water from foreign basins to compensate for sending water further down the system.

Discussion

Transfer volumes in comparison to other water diversion systems

From the data compiled herein, it is possible to calculate the full annual transfer volume of the NRLP canals. Disregarding water that discharges into one canal and continues directly into a second, but including water that mixes with an existing river before being transferred again, the total annual transfer volume proposed for the NRLP is 245 $km^3\ y^{-1}$. This value is larger than the 174 $km^3\ y^{-1}$ reported by Bagla (2014) and Joshi (2013) because we have included utilization and intra-Ganga basin transfers (transfers between Ganga tributaries).

Among interbasin transfer systems, the NRLP is vastly larger than any existing or proposed system worldwide. The project is larger even than China's South–North Water Transfer Project, which aims to transfer 44.8 $km^3\ y^{-1}$ from the Yangtze river to the Yellow river via three mega-canals (Zhang, 2009). The Central Route of the South–North Water Transfer Project was completed in 2014 and currently moves 9.5 $km^3\ y^{-1}$ through 1,264 km of canal. The largest canals of the NRLP will be larger than any currently existing canal, including the Central Route. If fully realized, the NRLP will contain nine of the ten highest-volume canals in the world. Even if Ganga-Brahmaputra intra-basin transfers were removed from the project, The NRLP would remain the world's largest interbasin water transfer system at 129 $km^3\ y^{-1}$. By comparison, the largest interbasin water transfer system in the United States, the California State Water Project, transfers water from Northern California to Southern California in the amount of 3 $km^3\ y^{-1}$ (DWR, 2011). Additional large canals, such as the All-American Canal and the Colorado River Aqueduct, transport 3.2 and 1.5 $km^3\ y^{-1}$, respectively (Ghassemi and White, 2007), and structures in coastal Louisiana move 1–3 $km^3\ y^{-1}$ within the Mississippi delta.

The NRLP was planned with the expectation that it will bring many benefits to India. This study found that, if implemented in full, NRLP irrigation volumes would indeed exceed 100 $km^3\ y^{-1}$ and provide 11 $km^3\ y^{-1}$ of water for domestic and industrial needs. Increased domestic water supplies and more continuous availability throughout the dry season would help mitigate the risk of dehydration during heat waves, which killed 2,500 people in 2015. Hydropower will increase the standard of living. Flooding in northern India may be reduced; however, seismic hazard in the region is considerable, and the feasibility of large dams under these conditions is a matter of ongoing research.

However, the project will not benefit all people equally. We show here that dams proposed in the NRLP will submerge 3,400 km^2 of land and displace approximately 700,000 people (**Table 3**). Eleven dams will each displace 10,000 people or more, with the two highest displacements associated with dams on the Godavari: 172,000 at the Inchampalli Dam and 203,000 at the Polavaram Dam. Additional displacement may occur along canal routes, displacement which is unaccounted for here. Some displacement may be mitigated by voluntary migration in advance of construction.

Impacts on river water discharge

Though the NRLP will increase water availability within basins, we calculate mean annual water discharge at river mouths/basin outlets will decrease for 24 out of the 29 rivers studied (**Figure 6**). This will likely drive salinity incursion that may damage wetlands and contribute to the deterioration of freshwater and estuarine ecosystems (Werner et al., 2013). The decrease in river discharge would come on top of an already decreasing trend in basin outlet discharge across the subcontinent caused by increased water usage (Gupta et al., 2012). For the Krishna, mean annual discharge in the 1950s totaled 62 km^3 y^{-1}, but the modern river basin is nearly closed with a discharge of only 12 km^3 y^{-1} and no flow for several months per year (Rao et al., 2010). Despite increasing water utilization within the basin, the NRLP will not change river mouth conditions for the Krishna. Increased usage and transfers upstream will offset water flows designated for the Krishna delta.

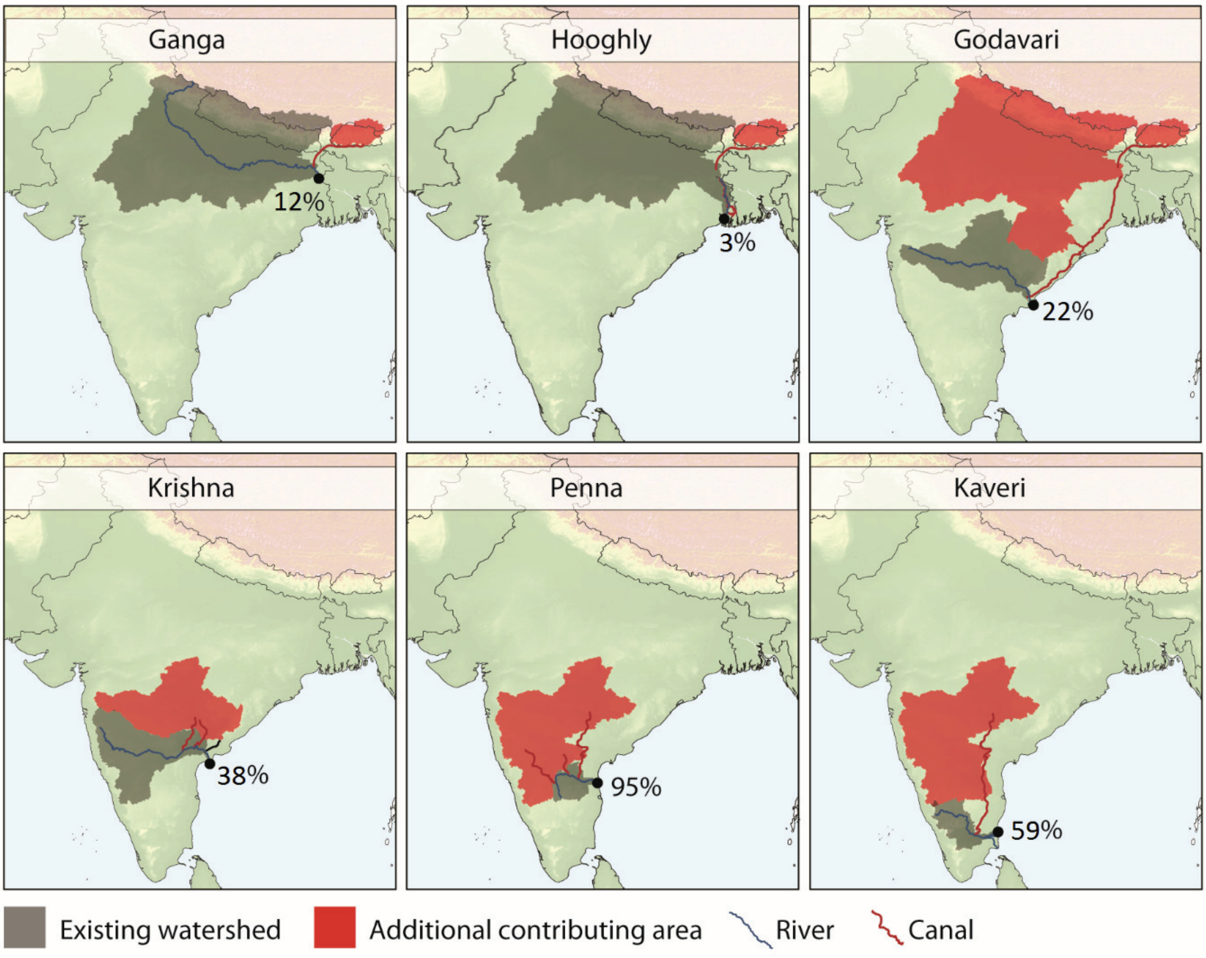

Figure 9: Changes in the watersheds of six major rivers. Changes in watersheds for six major rivers given full implementation of the NRLP. Current (existing) watershed is shown in grey, with new contributing areas shown in red. Label at the river mouth indicates the proportion of river discharge that will be sourced from runoff in the new contributing areas. The Krishna, which is projected to experience no change in the total volume of water exiting the river mouth, will nevertheless experience a large change in the proportion of water that comes from its natural watershed. This is due to the "compensating" transfers built into the NRLP, wherein a river receives incoming transfers in order to compensate for outgoing transfers sent further down the system. Note also that more than half of the water in the Hooghly is already being transferred from the Ganga watershed via Farakka Barrage. DOI: https://doi.org/10.1525/elementa.269.f9

Of the five rivers that will experience increased discharge, two (the Yamuna and Betwa) are Ganga tributaries that do not flow into the sea. The remaining three – the Hooghly, Penna and Kaveri – may see an overall decrease in salinity intrusion as freshwater is added to these systems. The NRLP will also modify the hydrographs of the major rivers by impounding flows during the monsoon season and releasing them in the dry season. For monthly flows, mean changes will be within natural variability; however, average-flow years would drop to current dry-year levels, and dry years would experience unprecedented low flows (**Figure 7**).

Impacts on sediment transport to deltas

Under the NRLP, suspended sediment load would decrease for five of the six rivers, with a scant increase for the Kaveri compared with current conditions. Approximately one-third to one-half of the reduction will come from changes to monthly water discharge, which will convey new suspended loads as approximated by the unique sediment rating curve for each river. The remaining reduction to transport is driven by sediment trapping in new reservoirs, which together have a gross storage of 98.7 km^3. We note that these values are estimates, as canals may change the sediment rating curves once emplaced; sedimentation may occur within the canals and at their offtake locations, and trapping may be partially mitigated by design features such as gates for sediment sluicing. However, given the set of assumptions herein, the NRLP will reduce sediment loads dramatically for all but the Kaveri river. In the Kaveri, the increased sediment load represents only a negligible increase over a load that is currently near zero.

Deltas are sustained by sediment deliveries, and reduced sediment loads will translate directly to decreased aggradation. For the Ganga-Brahmaputra delta, a projected aggradation decrease from 3.6 to 2.6 mm y^{-1} is enough to compromise the delta's elevation with respect to sea level. Global mean sea level is rising at a rate of 3.3 ± 0.4 mm y^{-1} and is expected to accelerate in the coming century (Church et al.,. 2013). Relative sea-level rise on the Ganga-Brahmaputra delta is currently even higher, with a mean value of 5.6 mm y^{-1} across the delta (Brown and Nicholls, 2015). Relative sea-level rise encompasses eustatic sea-level increases along with the added influence of tectonics, sediment compaction, and accelerated compaction due to human activities such as hydrocarbon extraction and groundwater abstraction. Aggradation is the only process currently countering relative sea-level rise in the near-shore portions of the Ganga-Brahmapura delta; reduced aggradation will further compromise the population of 40–50 million people living near the coast and endanger the world's largest mangrove forest, the Sundarbans.

As in all deltas, relative sea level rise rates in the Ganga-Brahmaputra delta are spatially variable, ranging from –1 mm y^{-1} from tectonic uplift, to 43 mm y^{-1} with a standard deviation of 7.3 mm y^{-1} (Brown and Nicholls, 2015). The high standard deviation reflects both differences in methodology and true differences in aggradation rates across the delta. In the Ganga-Brahmaputra delta, aggradation rates vary between active and inactive portions of the delta, and on a smaller scale rates with distance from the nearest active channel (Rogers et al., 2013). Delta aggradation rates are also affected by river floods, tides and wave conditions, as well as human activities such as embanking (Auerbach et al., 2105). In this work, estimates of aggradation changes assume uniform deposition over the entire delta, which is a simplification relative to the complex depositional environments of active delta systems. Nevertheless, these are useful calculations for giving first-order estimates of the impacts of reduced sediment loads on delta surface elevation. In reality, spatial variability of sediment deposition would concentrate the impacts into a smaller area, resulting in more dramatic reductions than reported here for the active portions of the deltas.

Table 6 shows current and NRLP aggradation rates compared to historical aggradation rates for each river. Current aggradation rates have fallen by 80–100% compared to historical rates for all but the Ganga and Brahmaputra rivers, primarily due to reservoir trapping (Sarker, 2004; Gupta et al., 2012). This has likely driven the significant shoreline erosion that has been observed at the Godavari and Krishna deltas, where 76 km^2 have been lost over the past 43 years (Rao et al., 2010). At the Kaveri delta, which hosts a population of 4.8 million people, erosion has been observed along most of the coastline (ADB, 2011). The NRLP would drive aggradation rates further downward, exacerbating existing conditions in the Godavari and Mahanadi deltas while doing nothing to increase sediment flow to the Kaveri and Krishna deltas despite nominally directing water to these areas.

Tessler et al. (2015) quantified the risk of fluvial or coastal flooding and its expected economic impacts and losses of life for 48 deltas and found the Ganga-Brahmaputra and the Krishna to be the highest-risk deltas in the world, with the Ganga-Brahmaputra, Krishna, Godavari and Mahanadi all among the ten highest-risk. The Ganga-Brahmaputra, Mahanadi, and Godavari are the 1st, 10th, and 15th most populous deltas in the world, respectively (Higgins, 2015). Under the NRLP, the risk to these populations would increase. Rare ecosystems and vital agricultural areas would become more vulnerable to storm surges, river flooding, and heightened salinity. The NRLP system has no benefit to delta surface elevation or delta aggradation rates. With respect to sediment deposition and surface elevation, the system will push the deltas further in the wrong direction.

Impacts on basin connectivity

If completed, the NRLP will transform watershed boundaries, with more than half of the land in India contributing a portion of its runoff to a new mouth. Public health impacts from changed runoff regions may be severe. Currently, 52% of rural residents use open defecation without designated toilet areas (NSSO, 2016). Fecal contamination of water sources has made diarrheal disease the third leading cause of child mortality, at more than 300,000 child deaths per year (Lakshminarayanan and Jayalakshmy, 2015).

Although fecal coliforms are short-lived, increased connectivity within the Ganga basin will expose new waterways to nearby contaminants. The Godavari would be exposed to runoff from the heavily polluted Ganga basin.

Exposure risk becomes clear when the NRLP is modeled as a full, connected system. Reservoirs on the Krishna, Godavari and Penna will host mass transfers of water moving from north to south. Mixing between river and canal waters will occur at many canal-river crossings, which in some cases will replace more than 50% of river water with water from other basins. Exact mixing proportions within reservoirs will depend upon residence time and on density differences between reservoir and canal water and may exceed the estimates in this study. They will not be smaller than these estimates unless the system is redesigned, as we have assumed zero mixing in reservoirs except when the lag between discharge and withdrawal is on the order of months.

Changes to habitat network connectivity will also have implications for invasive species management and biodiversity. As noted by Grant et al. (2012), canals 24 and 25 are expected to be particularly destructive to freshwater fish biodiversity, as they will link highly biodiverse western rivers to the much larger Krishna and Cauvery basins, allowing the spread of common species into previously isolated basins.

Climate change

Future climate change may alter the feasibility of the NRLP. Compared to the late 20th century, climate model projections for India suggest a 2–5°C increase in the mean annual temperature by the end of the 21st century (Kumar et al., 2006). This warming will accelerate evaporation and evapotranspiration and increase water demand in urban and agricultural regions (Hasson et al., 2013). Along the link canals, the NWDA estimates that approximately 9.8 $km^3\,y^{-1}$ will be lost to seepage and evaporation, which may increase in a warmer climate. The NWDA estimate does not include evaporation losses from reservoirs, which may also be substantial.

At the same time, global climate models (GCMs) suggest an increase in accumulated rainfall from the summer monsoon, particularly in western India (Kumar et al., 2006; Immerzeel et al., 2010), with some geographic and intra-annual variability evident in downscaled data (Pervez and Henebry, 2014). In the Ganga and Brahmaputra basins, basin-integrated precipitation minus evaporation (P – E) is expected to increase (Hasson et al., 2013). The combination of increased P – E and accelerated melting of snowfields and glaciers in the Himalaya will temporarily increase flows on meltwater-fed major rivers and their tributaries (Lutz et al., 2014). However, once glacier water reserves are depleted, likely by mid-century, decreased streamflows on the Ganga (–18%) and Brahmaputra (–20%) are expected, even when the projected increase in annual rainfall is taken into account (Immerzeel et al., 2010).

The NRLP is expected to further decrease streamflows, which will likely affect delta salinity conditions. Under a future rising sea level scenario, the salinity of groundwater and river channels is expected to increase (Werner et al., 2013). Climate-related salinity incursion in rivers and deltas will be exacerbated by the decrease in river mouth discharge brought about by the NRLP.

Conclusion

This study has resulted in the creation of a database and graph database model that allows calculations of changes to river water discharge for 29 rivers in India given realization of the proposed National River Linking Project. We have further created a prototype method for evaluating the impacts on suspended sediment transport given the changes in water discharge estimated from the most up-to-date empirical data. Considering the complexity and disputed nature of the project, is likely that the project will follow an evolving path to either partial or full completion. To illustrate the potential large-scale magnitude and impact of the project, this study operates the graph database model in the worst-case scenario ("all infrastructure will be realized,") but many other scenarios can be simulated and explored with this flexible model. If the NRLP is to be fully implemented as is proposed, it will decrease mean annual basin outlet discharge for 24 of the 29 affected rivers (as much as 73%), reducing freshwater deliveries to wetlands and estuaries. Additionally, more than 700,000 people will be displaced in the construction of the dams, and waterways will be exposed to new contaminants, invasive species, and disease-causing agents. Finally, the NRLP will compromise the already vulnerable deltas of the Indian subcontinent by decreasing aggradation rates as much as 87%. Additional water and sediment discharge data, particularly for Himalayan rivers, would be invaluable for refining estimates of the impacts of this colossal system.

Data Accessibility Statement

Watershed change and river/canal discharge data used in this study are included as supplemental material. They can also be accessed at https://csdms.colorado.edu/wiki/Data:NRLP_India. These data are available in csv, shapefile, and Neo4J (graph database) formats. The code used to process the data are available at the above website and on GitHub, https://github.com/sahiggin/NRLP.

Supplemental Files

The supplemental files for this article can be found as follows:

Shapefile of rivers (will also be versioned and distributed through the CSDMS data repository). CSV of the rivers database (will be distributed through the CSDMS data repository). Shapefile of dams, with all attributes (will also be versioned and distributed through the CSDMS data repository). CSV of the dam database (will also be versioned and distributed through the CSDMS data repository). Shapefile of canals, with all attributes (will also be versioned and distributed through the CSDMS data repository). CSV of the canals database (will also be versioned and distributed through the CSDMS data repository). Complete and annotated list of database references including methodological details (will be distributed through the CSDMS data repository). List of recent changes to the NRLP proposal (will be distributed through the CSDMS data repository). Neo4J database analysis code, input files and instructions document are available at https://github.com/sahiggin/NRLP.

- **Dataset.** Databases, shapefiles, and additional methodological details. DOI: https://doi.org/10.1525/elementa.269.s1

Acknowledgements

Krishna and Godavari river discharge data were kindly provided by the Office of the Chief Engineer, Krishna and Godavari Basin Organisation, Central Water Commission, Government of India. Ganges and Brahmaputra river discharge data were kindly provided by the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES Project), via the Government of Bangladesh. We thank Rochelle Worsnop for providing helpful assistance with figure design and Gabriel Ycas for productive feedback regarding study conception, methodology and philosophy. We are grateful for the thoughtful comments from Alex Kolker and an anonymous reviewer, whose feedback improved the paper.

Funding information

S.H. was supported by NASA award 10-LCLUC10-2-0038; S.H. and I.O. were supported by NSF/Belmont Forum grant G8MUREFU3FP-2201-037. I.O. received additional funding from NSF award OCE 1600287. K.R. was supported by NSF award SES 1415431. E.K. held a National Research Council (NRC) Research Associateship award at the Atlantic Oceanographic and Meteorological Laboratory (AOML) and the Earth System Research Laboratory (ESRL).

Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: SH, IO, KR
- Contributed to acquisition of data: SH, IO
- Contributed to analysis and interpretation of data: SH, IO, KR Drafted and/or revised the article: SH, IO, EK
- Approved the submitted version for publication: SH, IO, KR, EK

References

Amarasinghe, UA and **Sharma, BR** 2008 Strategic analysis of the National River Linking Project (NRLP) of India, Series 2. *Proceedings of the Workshop on Analysis of Hydrological, Social and Ecological Issues of the NRLP*, 500. Columbo, Sri Lanka: International Water Management Institute.

Asian Development Bank (ADB) 2011 TA-7417-IND: Support for the National Action Plan on Climate Change. Final Report, Appendix 4: Cauvery Delta Sub-Basin. Tamil Nadu, 131.

Auerbach, LW, Goodbred Jr., SL, Mondal, DR, Wilson, CA, Ahmed, KR, Roy, K, Steckler, MS, Small, C, Gilligan, JM and **Ackerly, BA** 2015 Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change* **5**: 153–157. DOI: https://doi.org/10.1038/nclimate2472

Bagla, P 2014 India plans the grandest of canal networks. *Science* **345**(6193): 128. DOI: https://doi.org/10.1126/science.345.6193.128

Bandyopadhyay, J and **Perveen, S** 2003 The interlinking of Indian rivers: some questions on the scientific, economic and environmental dimension of the proposal. *School of Oriental and African Studies (SOAS)/King's College London Occasional Paper 60*, 35.

Bandyopadhyay, J and **Perveen, S** 2008 Chapter 4: The Interlinking of Indian Rivers: Questions on the Scientific, Economic and Environmental Dimensions of the Proposal. In: Mizra, MMQ, Ahmed, AU and Ahmad, QK (eds.), *Interlinking of Rivers in India: Issues and Concerns*, 53–76. London, UK: Taylor and Francis. DOI: https://doi.org/10.1201/9780203894576.ch4

Battisti, DS and **Naylor, RL** 2009 Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* **323**(5911): 240–244, DOI: https://doi.org/10.1126/science.1164363

Brown, S and **Nicholls, R** 2015 Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. *Science of the Total Environment* **527–528**: 362–374. DOI: https://doi.org/10.1016/j.scitotenv.2015.04.124

Brune, GM 1953 Trap efficiency of reservoirs, *EOS Trans. Am. Geophys.* **34**(3): 407–418. DOI: https://doi.org/10.1029/TR034i003p00407

Center for International Earth Science Information Network (CIESIN) 2016 Gridded Population of the World, Version 4 (GPWv4): Population Density, Palisades. NY: NASA Socioeconomic Data and Applications Center (SEDAC). DOI: https://doi.org/10.7927/H46T0JKB

Central Water Commission (CWC) 2012 Integrated Hydrological Data Book (Non+–classified River Basins). New Delhi: Central Water Commission, 680.

Central Water Commission (CWC) 2015 Integrated Hydrological Data Book (Non-classified River Basins). New Delhi: Central Water Commission, 525.

Church, JA, Clark, PU, Cazenave, A, Gregory, JM, Jevrejeva, S, Levermann, A, Merrifield, MA, Milne, GA, Nerem, RS, Nunn, PD, Payne, AJ, Pfeffer, WT, Stammer, D and **Unnikrishnan, AS** 2013 Sea Level Change. In: Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, TF, Qin, D, Plattner, G-K, Tignor, M, Allen, SK, Boschung, J, Nauels, A, Xia, Y, Bex, V and Midgley, PM (eds.). Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Darby, SE, Dunn, FE, Nicholls, RJ, Rahman, M and **Riddy, L** 2015 A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges-Brahmaputra-Meghna delta. *Environ. Sci.: Processes Impacts* **17**. 1587–1600. DOI: https://doi.org/10.1039/C5EM00252D

Department of Water Resources (DWR) 2011 The California State Water Project at a Glance. *Report of the California Department of Water Resources (DWR),* 4.

Fischer, S, Pietron, J, Bring, A, Thorslund, J and **Jarsjö, J** 2016 Present to future sediment transport of the Brahmaputra River: reducing uncertainty in predictions and management. *Reg. Environ. Change*. DOI: https://doi.org/10.1007/s10113-016-1039-7

Global Runoff Data Centre (GRDC) 2017 *Koblenz, Federal Institute of Hydrology (BfG).* Vijayawada Station.

Goodbred Jr., SL and **Kuehl, SA** 1999 Holocene and modern sediment budgets for the Ganges-Brahmaputra river system: evidence for highstand dispersal to flood-plain, shelf, and deep-sea depocenters. *Geology* **27**(6): 559–562. DOI: https://doi.org/10.1130/0091-7613(1999)027<0559:HAMSBF>2.3.CO;2

Gourdji, S, Knowlton, C and **Platt, K** 2005 Indian Interlinking of Rivers: A preliminary evaluation. *Unpublished Master's Project.* University of Michigan, Ann Arbor, MI School, City, State, 162.

Gourdji, S, Knowlton, C, Platt, K and **Wiley, MJ** 2008 Chapter 7: Modeling the Interlinking of the Ganges River: Simulated Changes in Flow. In: Mizra, MMQ, Ahmed, AU and Ahmad, QK (eds.), *Interlinking of Rivers in India: Issues and Concerns*, 107–127. London, UK: Taylor and Francis. DOI: https://doi.org/10.1201/9780203894576.ch7

Grant, EH, Lynch, HJ, Muneepeerakul, R, Arunachalam, M, Rodriguez-Iturbe, I and **Fagan, WF** 2012 Interbasin water transfer, riverine connectivity, and spatial controls on fish biodiversity. *PLOS ONE* **7**(3): e34170. DOI: https://doi.org/10.1371/journal.pone.0034170

Gupta, H, Kao, S-J and **Dai, M** 2012 The role of mega dams in reducing sediment fluxes: a case study of large Asian rivers. *J. Hydrol.* **464–465**: 447–458. DOI: https://doi.org/10.1016/j.hydrol.2012.07.038

Hanjra, MA and **Qureshi, ME** 2010 Global water crisis and future food security in an era of climate change. *Food Policy* **35**(5): 365–377. DOI: https://doi.org/10.1016/j.foodpol.2010.05.006

Hasson, S, Lucarini, V and **Pascale, S** 2013 Hydrological cycle over South and Southeast Asian river basins as simulated by PCMDI/CMIP3 experiments. *Earth Syst. Dynam.* **4**: 199–217. DOI: https://doi.org/10.5194/esd-4-199-2013

Higgins, S 2015 Review: advances in delta-subsidence research using satellite methods. *Hydrogeol. J.* **23**(3): 587–600. DOI: https://doi.org/10.1007/s10040-015-1330-6

Immerzeel, WW, van Beek, LP and **Bierkens, MF** 2010 Climate change will affect the Asian water towers. *Science* **328**: 1382–1385. DOI: https://doi.org/10.1126/science.1183188

Institute of Water Modeling (IWM) 2010 Ganges river basin modelling: final report, Report number 103885. Washington. D.C.: World Bank Group, 201.

Islam, MR, Begum, SF, Yamaguchi, Y and **Ogawa, K** 1999 The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation. *Hydrol. Process.* **13**: 2907–2923. DOI: https://doi.org/10.1002/(SICI)1099-1085(19991215)13:17<2907::AID-HYP906>3.0.CO;2-E

Joshi, NM 2013 National River Linking Project of India. *HYDRO Nepal* **12**: 13–19. DOI: https://doi.org/10.3126/hn.v12i0.9026

Kumar, KR, Sahai, AK, Kumar, KK, Patwardhan, SK, Mishra, PK, Revadekar, JV, Kamala, K and **Pant, GC** 2006 High-resolution climate change scenarios for India for the 21st century. *Cur. Sci. India* **90**: 334–345.

Lakshminarayanan, S and **Jayalakshmy, R** 2015 Diarrheal diseases among children in India: current scenario and future perspectives. *J. Nat. Sci. Biol. Med.* **6**(1): 24–28. DOI: https://doi.org/10.4103/0976-9668.149073

Lemoalle, J, Bader, J-C, Leblanc, M and **Sedick, A** 2012 *Global Planet. Change* **80–81**: 2470254. DOI: https://doi.org/10.1016/j.gloplacha.2011.07.004

Liu, JP, Xue, Z, Ross, K, Wang, HJ, Yang, ZS, Li, AC and **Gao, S** 2009 Fate of sediments delivered to the sea by Asian large rivers: Long-distance transport and formation of remote alongshore clinotherms. *The Sedimentary Record* **7**(4): 4–9.

Lutz, AF, Immerzeel, WW, Shrestha, AB and **Bierkens, MFP** 2014 Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nat. Clim. Change* **4**: 587–592. DOI: https://doi.org/10.1038/nclimate2237

Mizra, MMQ, Ahmed, AU and **Ahmad, QK** 2008 Interlinking of Rivers in India: Issues and Concerns. London, UK: Taylor Francis, 289.

Montgomery, DC and **Runger, GC** 2011 *Applied Statistics and Probability for Engineers*, 5th Edition, 423. New York: Wiley.

National Sample Survey Office (NSSO) 2016 Swachhta Status Report. *Publication of the Ministry of Statistics and Programme Implementation, Government of India,* 90.

Panda, DK, Kumar, A, Ghosh, S and **Mohanty, RK** 2013 Streamflow trends in the Mahanadi River basin (India): Linkages to tropical climate variability. *J. Hydrol.* **495**: 135–149. DOI: https://doi.org/10.1016/j.jhydrol.2013.04.054

Pervez, MS and **Henebry, GM** 2014 Projections of the Ganges–Brahmaputra precipitation— Downscaled from GCM predictors. *J. Hydrol.* **517**: 120–134. DOI: https://doi.org/10.1016/j.jhydrol.2014.05.016

Rao, KN, Subraelu, P, Naga Kumar, KChV, Demudu, G, Malini, BH, Rajawat, A S and **Ajai, [no last name given]** 2010 Impacts of sediment retention by dams on delta shoreline recession: evidences from the Krishna and Godavari deltas. India. *Earth Surf. Proc Land.* **35**(7): 817–827. DOI: https://doi.org/10.1002/esp.1977

Rogers, KG, Goodbred Jr., SL and **Mondal, DR** 2013 Monsoon sedimentation on the 'abandoned' tide-influenced Ganges-Brahmaputra delta plain. *Estuarine, Coastal and Shelf Science* **131**: 297–309. DOI: https://doi.org/10.1016/j.ecss.2013.07.014

Sarker, MH 2004 Impact of upstream human interventions on the morphology of the Ganges-Gorai system. In: Mizra, MMQ (ed.), *The Ganges Water Diversion: Environmental Effects and Implications*, 49–80. Dordrecht, The Netherlands: Spring Science+Business Media. DOI: https://doi.org/10.1007/978-1-4020-2792-5

Syvitski, JPM, Kettner, AJ, Correggiari, A and **Nelson, BW** 2005 Distributary channels and their impact on sediment dispersal. *Mar. Geol.* **222–223**: 75–94. DOI: https://doi.org/10.1016/j.margeo.2005.06.030

Syvitski, JPM, Kettner, AJ, Overeem, I, Hutton, EWH, Hannon, MT, Brakenridge, GR, Day, J, Vörösmarty, CJ, Saito, Y, Giosan, L and **Nicholls, RJ** 2009 Sinking deltas due to human activities. *Nat. Geosci.* **2**: 681–686. DOI: https://doi.org/10.1038/ngeo629

Syvitski, JPM and **Milliman, JD** 2007 Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *J. Geology* **115**: 1–19. DOI: https://doi.org/10.1086/509246

Syvitski, JPM, Peckham, S, Hilberman, R and **Mulder, T** 2003 Prediction the terrestrial flux of sediment to the global ocean: a planetary perspective. *Sedimentary Geology* **162**: 5–24. DOI: https://doi.org/10.1016/S0037-0738(03)00232-X

Tessler, ZD, Vörösmarty, CJ, Grossberg, M, Gladkova, I, Aizenman, H, Syvitski, JPM and **Foufoula-Georgiou, E** 2015 Profiling risk and sustainability in coastal deltas of the world. *Science* **349**(6248): 638–643. DOI: https://doi.org/10.1126/science.aab3574

Verstraeten, G and **Poesen, J** 2000 Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield. *Progress in Physical Geography* **24**(2): 219–251. DOI: https://doi.org/10.1191/030913300676742153

Vörösmarty, CJ, Meybeck, M, Fekete, B, Sharma, K, Green, P and **Syvitski, JPM** 2003 Anthropogenic sediment retention: major global impact from registered river impoundments. *Global Planet. Change* **39**(1–2): 169–190. DOI: https://doi.org/10.1016/S0921-8181(03)00023-7

Wallace, JS 2000 Increasing agricultural water use efficience to meet future food production. *Agr. Ecosyst. Environ.* **82**(1–3): 105–119. DOI: https://doi.org/10.1016/S0167-8809(00)00220-6

Walling, DE 2008 The changing sediment load of the Mekong River. *AMBIO* **37**(3): 150–157. DOI: https://doi.org/10.1579/0044-7447(2008)37[150:TCSLOT]2.0.CO;2

Werner, AD, Bakker, M, Post, VEA, Vandenbohede, A, Lu, C, Ataie-Ashtiani, B, Simmons, CT and **Barry, DA** 2013 Seawater intrusion processes. investigation and management: recent advances and future challenges. *Ad. Water Resour.* **51**: 3–26. DOI: https://doi.org/10.1016/j.advwatres.2012.03.004

World Bank 1992 Karnali Preparation Project – Phase I, Project Completion Report – No. 11013, Energy and Infrastructure Operations Division. country Department I, South Asia Regional Office, World Bank, 34.

Zhang, Q 2009 The South-to-North Water Transfer Project of China: Environmental Implications and Monitoring Strategy. *J. Am. Water Resour. As.* **45**(5): 1238–1247. DOI: https://doi.org/10.1111/j.1752-1688.2009.00357.x

How to cite this article: Higgins, SA, Overeem, I, Rogers, KG and Kalina, EA 2018 River linking in India: Downstream impacts on water discharge and suspended sediment transport to deltas. *Elem Sci Anth,* 6: 20. DOI: https://doi.org/10.1525/elementa.269

Domain Editor-in-Chief: Oliver Chadwick, University of California, Santa Barbara, US

Guest Editor: Paola Passalacqua, University of Texas at Austin, US

Knowledge Domain: Earth and Environmental Science

Part of an *Elementa* Special Feature: Deltas in the Anthropocene

Submitted: 02 February 2017 **Accepted:** 05 December 2017 **Published:** 28 February 2018