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A new framework for integrated, holistic, and transparent evaluation of inter-basin water transfer schemes

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Abstract

Water shortages are forecast to affect 50% of the world’s population by 2030, impacting developing nations most acutely. To increase water security there has been a significant increase in Inter-basin Water Transfer (IBWT) schemes, engineering mega-projects that redistribute water from one basin to another. However, the implementation of these schemes is often contested, and evaluation of their complex impacts inadequate, or hidden from full public scrutiny. There is an urgent need to develop more integrated, holistic, and transparent ways of evaluating the multiple interlinking impacts of IBWT schemes of this scale. In this paper, we address this gap by outlining an experimental methodology to evaluate IBWT schemes using a multidisciplinary and transparent methodology which utilises publicly available data. We illustrate the method using a case study from the Inter-Linking Rivers Project in Northern India, comparing the results of the experimental approach against the official analysis of the proposed scheme produced by the State Government of Jharkhand. The results demonstrate that the proposed experimental method allows more detailed evaluation of spatial and temporal variability in water availability and demand, as well as holistic evaluation of the functioning of the proposed scheme under different future scenarios. Based on these results we propose a flexible framework for future evaluation of proposed water transfer schemes which embeds the principles of integrated assessment, transparency, and sound science which can be adapted to other IBWT projects across the world.

Keywords: Integrated water resources management; inter-basin water transfer; water resource modelling; water scarcity

Competing Interests: None

1 Introduction

Water security is one of the most pressing problems of the 21st Century (Srinivasan et al., 2017), with current estimations suggesting that water shortages are likely to affect 50% of the world's population by 2030 (Zhuang, 2016). In light of the seriousness of the issue, water security has been explicitly included in the 2015 United Nation's (UN) Sustainable Development Goals (Harmancioglu, 2017). In order to mitigate water shortages many countries have proposed the redistribution of water across natural drainage divides through so called 'Inter-basin Water Transfer' (IBWT) schemes (Bhaduri et al., 2008). In 2005, approximately 14% of the total water withdrawal from rivers globally was for IBWT, which is predicted to increase to 25% by 2025 (Gohari et al., 2013; ICID, 2005).

Such large schemes are complex and value laden, with a spread of impacts, problems, and perspectives (Batie, 2008; Pueppke et al., 2018). Proponents claim that IBWT is beneficial for socio-economic development (Shao et al., 2003) and the ecological recovery of water-stressed basins (Ghassemi and White, 2007). In contrast, critics of IBWT have raised concerns over governance (Amarasinghe, 2012; Moore, 2014; Smakhtin et al., 2007), the equitability of impacts and outcomes (Chopra, 2006; Howe and Easter, 1971), and more simply the practicality of implementing such large engineering interventions (Gupta and Zaag, 2008).

A key challenge is how to assess the implications of IBWT schemes effectively (de Andrade et al., 2011; Gupta and Zaag, 2008). Only a few large scale, multi-disciplinary studies have evaluated the impacts of schemes (Wilson et al., 2017), and pre-construction assessment methods and data are often hidden from public scrutiny (Pasi and Smardon, 2012) or contain large uncertainties (Wilson et al., 2017). Previous studies have evaluated schemes against the principles of Integrated Water Resources Management (IWRM) (Gupta and Zaag, 2008), however, few attempts have been made to translate these general approaches into a formalised, practically applicable framework. Given the number of potential schemes worldwide, there is an urgent need for such a framework. To addresses this need we propose a method for IBWT scheme evaluation which operationalises the principles of IWRM, delivering a holistic, transparent, and publicly accessible way of effectively evaluating the complex spatially and temporally variable impacts of an IBWT scheme which considers the needs of both the donor and recipient catchments. We test the method against part of the ongoing Interlinking Rivers Project (ILR), a mega-scale IBWT project which has been evaluated officially by the National Water Development Agency (NWDA) of India that has attracted significant criticism for how it has been developed and justified (Alley, 2004)

The research presented demonstrates that, by utilising publicly available environmental and socio-economic data, we can not only evaluate present day water demand and supply effectively in the context of proposed IBWT schemes, taking into account spatial and temporal variability, but also evaluate potential future water transfer scenarios post-construction. Application of this method to the ILR case study identifies a number of shortcomings in the original analysis prepared in support of the proposed case study scheme. In particular the original analysis fails to take account of spatial and temporal variability in the availability of, and demand for, water within both donor and recipient catchments. The new method has significant implications for the future assessment of IBWT schemes, offering opportunities to democratise debates around the planning and implementation of such schemes, aligning more closely with the Dublin Principles, which promote participation and equitability in water management (Savenije and Zaag, 2002).

2 Inter-basin Water Transfer (IBWT): background and assessment

IBWT is the "*purposeful rearrangement of natural hydrologic patterns via engineering works* […] *to move water across drainage divides to satisfy perceived human needs*" (Micklin, 1984, p. 37). IBWT schemes exist, or are planned, across all continents, with the exception of Antarctica, in both developed and developing countries (Gupta and Zaag, 2008; Shumilova et al., 2018). Shumilova et al. (2018) identified 76 'Mega' IBWT projects costing over US$1 billion, either under construction (25) or in the planning phase (51) which, if all are constructed, will transfer up to 1,910 $km^3\ a^{-1}$ of water, equivalent to 26 times the average annual flow of the River Rhine (Figure 1).

Fig 1 *– Major existing and proposed IBWT schemes globally (data collated from Ghassemi and White, 2007; Shumilova et al., 2018; UNESCO, 1999; Zhang et al., 2015).* **[FULL WIDTH]**

2.1 Critiques of IBWT

IBWT projects are principally driven by governing authorities who promote these projects as critical to alleviate water deficits and to ensure water security (Angelakis et al., 2012; Gupta and Deshpande, 2004; WWF, 2007). Proponents argue that they deliver socio-economic development (Gichuki and McCornick, 2008; Matete and Hassan, 2006) and enhanced water security (Das, 2006), and result in environmental benefits through the alleviation of environmental degradation in recipient basins suffering water shortages (Berkoff, 2003; Sun et al., 2017; Zhuang, 2016). IBWT schemes also sometimes offer potential reductions in flood risk (Zhuang, 2016).

Yet, IBWT schemes are often contested and controversial (Das, 2006), with frequent conflicts of interest and many overlapping questions regarding potential impacts (Rogers et al., 2019). Overarching concerns relate to the decision-making processes, especially the rationale used to justify these mega-scale projects. Existing projects have been challenged for using incorrect data inputs (Gichuki and McCornick, 2008; Micklin, 1984), or for relying on data at spatial (Gupta and Zaag, 2008) and temporal (Smakhtin et al., 2007) resolutions that do not map onto the scale of the project, which can lead to inaccurate assessment of water availability (Micklin, 1984) and demand (Liu and Ma, 1983). A lack of robust methods has been exacerbated by concerns that governance of schemes lacks transparency (Thakkar and Chaturvedi, 2006; UNESCO, 1999), and that there are large discrepancies in the power and influence that different water users have in scheme planning and design, and the allocation of water resources post-construction (Abed-Elmdoust and Kerachian, 2014).

Critics of IBWT have also highlighted that following construction, the socio-economic and ecological impacts of schemes can contradict the positive image presented during the planning phase. The construction of IBWT infrastructure often displaces "*large sections of people from their land, economy, resources and culture*" (Singh, 2002, p. 182) and resettles them (World Commission on Dams, 2000). These people tend to have low-incomes or be from indigenous communities (Das, 2006; Patekar and Parekh, 2006) and their emotional, cultural and livelihood losses, and loss of valued land, are routinely neglected by IBWT planners (McCully, 2001; Singh, 2002). Resettled communities tend not to benefit from IBWT projects, which instead favour large-scale projects such as irrigation (Micklin, 1984). Such irrigation projects often promote the development of overreliance on cash crops for export, with consequent limitations on the sustainability and resilience of agricultural economies (Howe, 1977; WWF, 2007, 2002). IBWT projects have also been critiqued for causing irreversible environmental impacts (Gichuki and McCornick, 2008; Howe and Easter, 1971) including changes to flow regimes (Erskine et al., 1999; Hirji, 1998; Kingsford, 2003), restricting minimum environmental flows (Smakhtin et al., 2007), altering morphology downstream (McCully, 2001), the drying up of wetlands (Richter et al., 2010), and delta retreat leading to sea-water incursion (Higgins et al., 2018).

The impacts of IBWT projects occur at a range of spatial and temporal scales. For instance, the proposed ‘Project Integration of the São Francisco River’ (PISF) in north-eastern Brazil is intended to transfer water from the São Francisco River basin to small basins in the arid regions. The São Francisco River basin has an area of approximately 641,000 km^2 (7.5% of the total area of Brazil), covers eight states and houses 15.5 million inhabitants. Concerns over the economic and social impacts of these water transfers exist at both a local (homeowner and community) and a national scale (de Andrade et al., 2011). Impacts can also be felt transnationally where river basins are not contained within individual states. For example, the Indian ILR project will directly transfer water between India and Nepal, and will indirectly impact Bangladesh rivers, even though no direct IBWT infrastructure crosses into Bangladesh itself (Amarasinghe and Sharma, 2008; Misra et al., 2007). Rogers et al. (2019) evaluated the potential impacts of China’s ongoing South–North Water Transfer Project (SNWTP) and concluded that continuous, long-term evaluation of socio-economic, environmental, and political impacts are necessary to truly understand the project’s implications.

2.2 Evaluating Inter-basin Water Transfer Schemes

Conflict over IBWT schemes reflects their lack of systematic evaluation; a direct result of their complexity, multiple stakeholders and their myriad of objectives (Wilson et al., 2017). Sscholars have proposed standardised approaches, based on specific criteria drawn from IWRM, by which schemes can be assessed (Gupta and Zaag, 2008) (Table 1).

Table 1 *– Criteria sets developed to evaluate IBWT schemes.*

Existing criteria sets share two main common requirements:

1. **The donor basin must have surplus Water Availability (WA)**, taking into account existing and future WD; and
2. **The recipient basin must have real Water Demand (WD)**, after considering all possibilities for WA within the basin.

Although the criteria sets generally contain references to multi-disciplinarity or holistic assessment, the use of sound science, and integrated approaches to social, environmental, and economic sustainability, there is no consistency in how this is incorporated, or the extent to which this is prioritised. Early criteria sets were founded on a relatively restrictive set of procedures for assessment and include specific statements on environmental impacts and social and cultural impacts (Cox, 1999). Gupta and van der Zaag's (2008) criteria are more flexible, recommending only that projects should be "*socially, environmentally and economically sustainable*" (p.32). In contrast, the most recent criteria, proposed by Kibiiy and Ndambuki (2015), contains no specifics on what should be assessed or how, relying instead on the addition of 'sub-branches' of assessment at different levels to consider different aspects.

This transition from mechanistic to flexible sets of criteria may reflect a changing understanding that no two IBWT schemes can be evaluated by the same criteria, and that the complexity of benefits and impacts changes over time. However, relying on a process which lacks specificity opens up the assessment process to potential criticism, given the highly contested and often technocratic nature of IBWT projects (Gupta and Zaag, 2008; Pasi and Smardon, 2012; Thakkar, 2012).

3 Methods

In this study we developed an experimental methodology for evaluating IBWT schemes, which integrates the principles of IWRM (Section 2) to provide a solution for the evaluation of IBWT schemes which are often presented by expert government agencies on the basis of calculations which are hidden from full public scrutiny. We combined a flexible approach similar to that adopted by Kibiiy and Ndambuki (2015), but incorporated specific areas highlighted in the other approaches. We adopted the following as essential criteria:

1. The donor basin must have surplus WA after fulfilling all its present and future WD.
2. The recipient basin must have a water deficit after tapping all possibilities of WA within the basin.
3. The completed project must be supported by an integrated, multi-disciplinary assessment of potential impacts and benefits, intended to minimise adverse impacts and maximise benefits, and demonstrate equitable distribution among donor and recipient basins.

In response to criticisms of a lack of transparency and unequal power dynamics in previous schemes, we propose including a fourth criterion:

4. Analysis must use, where possible, data which is freely available within the public domain, and which should be made available for scrutiny.

We developed and tested the method against a case study from part of the Indian Interlinking Rivers (ILR) Project, a scheme which proposes to transfer water from a donor basin to a recipient basin through two river links.

First we present the case study and the calculations used to justify the scheme, before outlining the experimental method. Further details of calculations are included within the supplementary materials.

3.1 The case study

The IBWT scheme used for this study is part of the proposed ILR Scheme, an ambitious IBWT project proposed by the Government of India (GOI), consisting of approximately 30 inter-state and 35 intra-state inter-basin transfer links (Higgins et al., 2018). Our study examined two of the proposed intra-state links: the Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr), proposed by the State Government of Jharkhand (GOJ) (Figure 2). We considered these as one project referred to as the S-SK-Sr link.

Fig 2 *– Overview of the study area showing the locations of HOCs, and the catchments identified by the NWDA assessment and those considered in this study; (a) the study area in relation to the proposed inter-state Inter-Linking Rivers links, (b) the study area in relation to the Brahmani-Baitarini and Subarnekha Rivers Basins.* **[FULL WIDTH]**

The S-SK-Sr link is planned to withdraw a total of 1,887 million cubic metres of water per annum (M m^3 a^{-1}) from two donor rivers, the Sankh and South Koel (referred to as the donor basin), and transfer it to the Subarnarekha River basin (referred to as the recipient basin) through the Kharkai River. The transferred water is primarily intended to provide irrigation for agriculture in the recipient basins (Deogharia, 2016).

3.2 Evaluation of the proposed Sankh-South Koel - South Koel-Subarnarekha Link by the National Water Development Agency

Analysis in support of the proposed water-transfer link was provided by feasibility reports published by the National Water Development Agency (NWDA) (2009a, 2009b). These calculations represent the baseline against which to test the effectiveness of the experiment method.

The NWDA calculated WA and WD only for upstream donor catchments (Figure 2, inset b). WA was calculated based on annual natural water yields at 75% dependability[1] at the Jenapur HOC (Hydrological Observation Centre), (downstream of the proposed ILR link), using observed flow data from 1964-65 to 1997-98. The calculated natural flow was used to calculate annual WA for the whole basin upstream of the Jenapur HOC, including future imports, but not including groundwater availability (NWDA, 2009a). WA for each link of the scheme was calculated per km^2 according to the size of the donor catchment.

WD was calculated from the sum of domestic, irrigation, and industrial water demand, and a share of committed water utilisation from the Rengali Dam (based on a proportionate area approach). Domestic WD was calculated based on 2050 population projections calculated according to United Nations estimates (United Nations Population Division, 1995), with the share of urban and rural populations (66% urban and 44% rural) also calculated using these estimates. Domestic WD was based on usage rates of 135.00 (urban) and 53.15 (rural) litres per capita per day (NWDA, 2009a). 100% of urban and 50% of rural WD was assumed to be satisfied from surface water, whilst 80% of the calculated domestic WD was assumed to be regenerated flow. Industrial WD was assumed equal to domestic WD due to a lack of evidence of industrial usage rates. Irrigation use was calculated based upon total current and future irrigation schemes. Regenerated flow was assumed to be 10% of net irrigation water demand, less 20% of total irrigational water in evaporation-loss.

Water surplus/deficit was then calculated by:

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[1] 75% dependability denotes the amount of flow which is projected to be available in the river for 75 years out of 100 years (Reddy 2005)

Eq 1.

$$Water\ surplus\ or\ deficit = (WA_{nat} - WD_{tot}) + R_{dom} + R_{ind} + R_{irrig}$$

where WA_{nat} is the natural water availability; WD_{tot} is the total water demand; and R_{dom}, R_{ind}, and R_{irrig} are regenerated flows from domestic, industrial, and irrigation respectively. All values are in M m^3 a^{-1}.

Annual WA was then compared against proposed water transfer through the scheme to determine scheme viability.

3.3 The experimental Method

Our experimental method for evaluating IBWT schemes is composed of two main components (Figure 3), which are intended to readily address the criteria for evaluation of IBWT set out at the beginning of this section: the first evaluates Water Availability (WA) and Water Demand (WD) across proposed donor and recipient areas (Criteria 1 and 2); the second models potential scheme impacts using a commonly available numerical model (Criteria 3).

Fig 3 *– Overview of the experimental method; (a) is the assessment of overall water surplus or deficit across the donor and recipient catchments, and (b) is a holistic analysis of potential impacts of the scheme under different future scenarios.* **[1.5 Width]**

3.3.1 Data for the experimental method

To address Criteria 4 the method was developed using only publicly available data. Data were collected from government sources, either from the GOJ or from the Central GOI. They were supplemented, where necessary, from international organisations, such as the UN.

Where possible the data collected was at catchment scale, however, in some cases this was augmented by other datasets where catchment-level data were unavailable (Table 2).

***Table 2** – overview of principal data sources and their use within the experimental method.*

3.3.2 Characterising the donor and recipient basins

The study area was divided between the donor and recipient basins (Figure 2) on the basis of their hydrology, levels of urbanisation, and by the percentage area under irrigation[2]. The donor basin has an area of 21,806 km^2, whilst the recipient basin is smaller at 14,148 km^2. Both basins have elevations between 65-1100 m asl, with diverse lithologies, dominated by poor quality soils which store little water. Hydrologically, the entire study area shows inter-annual variability in rainfall and river flows relating to its monsoonal climate. The donor basin receives greater rainfall than the recipient during monsoon periods, but this is reversed during the non-monsoon season. Flows in donor basins are significantly higher than recipient basins during monsoons, but only marginally higher during non-monsoon season. Both basins also showed short-term patterns of wet-dry variability likely to be related to El Niño.

The population distribution between rural and urban areas and landcover, in particular percentage area of cropping, show relatively small differences between the two basins. However, the recipient basin has higher levels of urbanization (2.2% by area in comparison to less than 1%), as well as greater industrial activity, including mining, metal founding, automotive, and chemicals production. 33% of the recipient basin is under irrigation, in comparison to 13% for the donor basin.

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[2] Further details of both catchments can be found within the supplementary materials.

3.3.3 Assessing Water Availability

WA was calculated at a monthly temporal resolution at 75% dependability for all six HOCs within the area of interest in order to effectively represent the seasonal variability resulting from the monsoon climate (Smakhtin et al., 2007; Smakhtin and Eriyagama, 2008). Mean monthly natural flows for the period 1980-2013 were used (Equation 2a), and then annual WA was calculated for each catchment (Equation 2b) following Galkate et al. (2015).

(Eq 2a)

$$MMQ_{x\%dep} * Days\ per\ month = WA_{month\ x\%dep}$$

where $MMQ_{x\%dep}$ is the Monthly mean natural flow of each month at x% flow dependability and $WA_{month\ x\%dep}$ is the Monthly water availability of each month at x% flow dependability.

(Eq 2b)

$$Annual\ WA\ at\ x\%\ dependability = \sum_{n=1}^{12} (MMQ_{x\%dep} * \text{Days per month})$$

3.3.4 Assessing Water Demand

WD within each catchment was calculated based on WD allocated to different demand categories, in this case domestic, irrigation, industrial, livestock, and environmental uses. Evaluation of these factors considered temporal variability drawing upon examples within the literature. Estimates of livestock (after Singh 2006) and a more detailed calculation of industrial and irrigation WD were included to characterise their impact on WD and its seasonal variability (after Zawawi et al. 2010). Environmental flows, which can have significant impact on WA for other users depending on their magnitude, were set according to the method proposed by Smakhtin and Anputhas (2006), following guidance from the

Indian Institute of Technology (Indian Institute of Technology, 2011). Additional details of these calculations can be found in the supplementary material.

To determine overall WD within each basin, direct summation of catchment WD was possible for the Tilga, Jaraikela and Adityapur catchments. For Gomlai, Jamshedpur and Ghatshila catchments, which receive flows from other catchments, total WD was calculated within the contributing catchment area to the scheme measured at their outflow points.

3.3.5 Assessment of potential water surplus or deficit

Water surplus or deficit was calculated at 75% dependability for each donor and recipient catchment. WA and WD were first integrated by calculating return flow at both annual and monthly levels. Water surplus/deficit was calculated as:

(Eq 3)

$$Water\ Surplus/Deficit = (WA_{tot} - WD_{tot}) + TWR$$

Where WA_{tot} is the total water available at 75% dependability[3], WD_{tot} is total water demand, and TWR is total regenerated flow.

3.3.6 Evaluation of scheme performance

Simulation of potential scheme performance was undertaken using numerical modelling with the Water Evaluation and Planning (WEAP) modelling package (Yates et al., 2005). WEAP has been used previously for the analysis of IBWT schemes, for example Bharati et al. (2008), and Mousavi et al. (2017). It has also been applied to the planning and management of other water resource projects, for example water allocation in different climatic conditions (Lévite et al., 2003) and under climate change (Rosenzweig et al., 2004), impact

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[3] Note that WA_{tot} in this case is not equal to WA_{nat} and will always be a smaller value.

assessment of water policy change (Varela-Ortega et al., 2011) and projections of WA and WD (Dimova et al., 2014). To represent the proposed case study scheme, a WEAP model was configured to represent the main rivers and significant tributaries, proposed transmission links, return flows, and water diversions, as well as demand nodes representing domestic, livestock, irrigation, and industrial demand; a model schematic can be found in the supplementary materials.

WA was adapted for the case study to include observed flow and storage in reservoirs above 1M m^3 (Equation 4):

(Eq 4)

$$Naturalised\ Flow = Flow_{Obsv} + (WD_{tot} - TWR) + Change\ in\ Reservoir\ Storage$$

where $Flow_{obsv}$ is daily observed flow at HOCs, WD_{tot} is total water demand, and TWR is total regenerated flow.

Naturalised flow for the Tilga, Jaraikela and Adityapur catchments was calculated on the basis of their area-ratio with their respective catchments. These natural flows were used as a water supply node in each of the catchments or sub-catchments. For WD, each demand node (domestic including urban and rural, livestock, irrigation and industry) was assigned data on annual activity, water-use rates, consumption percentage and monthly variation. WEAP objects for minimum flow requirements (representing environmental WD) were also added, as well as streamflow gauges for model validation. Highest joint priority within the model was given to domestic WD and minimum flow requirements (environmental WD), followed by livestock, irrigation, and then industry, on the basis of socio-economic patterns observed within the basins, and the priorities used by the NWDA. All WD in the upstream catchments were prioritised over WD in downstream catchments. Validation of the model outputs was carried out using streamflow gauges at the two final outflow points; Gomlai HOC for the donor basin and Ghatshila HOC for the recipient basin. Nash-Sutcliffe efficiency (*E*) (Nash and Sutcliffe, 1970) was used to validate the results obtained against observed flows.

3.3.7 Model Scenarios

Five scenarios were explored using the model (Table 3) to explore the impact of water allocation priority on post-construction WA (Scenarios 2 and 3) and to investigate drivers of socio-economic demand and their potential impact on WA in the donor and recipient catchments (Scenarios 4 and 5). Two extremes of water allocation priority were considered for this study: priority given to ILR transfers, where proposed transfers of water were undertaken before water was allocated to other WD areas; and priority given to donor catchment WD, where all donor catchment WDs were met first, with any net water allocated to the ILR transfer. In all cases donor basin WD is prioritised over recipient WD.

***Table 3** – Overview of scenarios simulated using the WEAP model.*

ILR scheme performance in each scenario was assessed against the reliability index (Equation 5) following Hashimoto (1982):

(Eq 5)

$$Reliability\ (\%) = \frac{Number\ of\ time\ periods\ WD\ was\ fulfilled}{Total\ number\ of\ time\ periods\ considered} * 100\%$$

The reliability index shows the probability (%) of WD being met completely by the available water resources (Gohari et al., 2013). The annual reliability of ILR links was estimated using WEAP, whilst monthly reliability was calculated using monthly unmet WD for each month (Hashimoto et al., 1982). We further calculate and report ‘risk’ using:

(Eq 6)

$$Risk\ (\%) = 100 - Reliability$$

Risk represents the probability (%) of WD not being met by the available water resources. It is a useful metric for evaluating the performance of IBWT schemes since it represents a potential shortfall in WA. These indices were used to evaluate of the ILR scheme's performance in terms of; (i) meeting the WD of all catchments, referred to as the risk posed to catchments, and (ii) the ability of the ILR to meet its proposed flow regime, referred to as the risk posed to the ILR scheme.

4 Results

4.1 Results of the NWDA evaluation of ILR scheme feasibility

The results of the NWDA evaluation (Table 4) show that on an annual basis, both links report a water surplus, +788.06 M m^3 a^{-1} in the case of the S-SK ILR Link, and +2097.51 M m^3 a^{-1} for the SK-Sr ILR link. It was proposed that 498 M m^3 a^{-1} be transferred through the S-SK ILR link, providing 55 M m^3 a^{-1} and 30 M m^3 a^{-1} of water to irrigational and domestic use, with an estimated loss of approximately 10 M m^3 to transmission. The SK-Sr link was proposed to transfer 1792 M m^3 a^{-1}, providing 38 M m^3 a^{-1} and 30 M m^3 a^{-1} of water en route to irrigational and domestic use respectively, with approximately 40 M m^3 a^{-1} of transmission losses. Based on the NWDA analysis, a total of 1684 M m^3 a^{-1} water will therefore be transferred through the scheme to the water-deficit Subarnarekha River. Both of the proposed links are intended to operate throughout the year, but the proposed supply is not uniform across the year, with peak transfers in February-March and July-August (Table 4b).

Table 4 *– (a) Results of the NWDA analysis of water surplus for the proposed ILR link, and (b) the proposed monthly transfer schedule of water along the proposed link* (NWDA, 2009b, 2009a).

4.2 Results from the experimental method

4.2.1 Assessment of Water Availability

Figure 4 presents the calculation of WA for each catchment. WA for all catchments is highest during the monsoon (June-September) and declines significantly during September and October. At a catchment level, Gomlai has the highest WA of all catchments, closely followed by Jamshedpur and Ghatshila.

Fig 4 *- Monthly WA per km^2 at 75% flow dependability (1980-2013) by catchment.* **[SINGLE WIDTH]**

4.2.2 Assessment of Water Demand

The WD of domestic, livestock, irrigation, industry and environmental needs were projected for each catchment for the year 2050 (Table 5).

Table 5 *–WD for each catchment by sector using the experimental method.*

Jamshedpur has the highest domestic and urban WD. Rural domestic WD is highest in Jaraikela, which also shows high WD for livestock and irrigation. Industrial WD is highest in Ghatshila, although these results include the WD for the Adityapur Industrial Development Area (AIDA). No data are available on the distribution of cross-boundary WD for this area so in this case it was allocated to the WD calculation for Ghatshila. Although this does not appear to significantly impact on the calculations, further sensitivity testing could be undertaken to evaluate this.

Gomlai and Ghatshila represent environmental as well as total WD for both donor and recipient basins respectively. Domestic, livestock, and industrial WD are divided equally across all months, whilst environmental and irrigation WD are distributed seasonally (Figure 5).

Fig 5 *– Variability in WD across the year by catchment showing (a) variability in predicted irrigation WD, (b) variation in environmental WD.* **[SINGLE WIDTH]**

Monthly WD in non-monsoon months is influenced by irrigation and was high in February. Environmental WD is highest during the monsoon, with peak WD in August. Gomlai, which is representative of the donor basin, shows the highest WD among all catchments during monsoon months, followed by Ghatshila, which is representative of the recipient catchments. In non-monsoon months Ghatshila has the highest WD, due to its high industrial WD, followed by Gomlai.

4.2.3 Determination of water surplus or deficit

Table 6 shows the calculation of water surplus or deficit on an annual basis for the six catchments under consideration. All catchments show annual surplus water at 75% dependability.

Table 6 *– Water surplus at 75% dependability by catchment using the experimental method.*

The donor basin shows less surplus water than the recipient basin, due to high environmental WD. Adityapur, the main recipient catchment, has less surplus water than the main donor catchment Jaraikela. Ghatshila, which is located downstream of Jamshedpur, showed lower water surplus than Jamshedpur. This pattern is likely to be attributed to the high industrial WD in Ghatshila due to AIDA, which includes some industrial WD for the remaining two recipient catchments.

In contrast, the monthly calculation of water surplus highlights the temporal variability in the calculation of water surplus/demand resulting from the impact of the monsoon climate. Figure 6 shows surplus/deficit results for the monsoon (June-September) and non-monsoon season (October – May).

Fig 6 *- Monthly water surplus or deficit at 75% dependability by catchment in (a) monsoon and (b) non-monsoon seasons.* **[SINGLE WIDTH]**

The results demonstrate that all catchments report a water surplus during the monsoon season, with Jamshedpur recording the highest surplus. However, in the non-monsoon season, particularly from December to May, all catchments either break even, or in the case of the donor catchments (Tilga, Jarakeila, and Gomlai), report water deficits up to 100 Mm^3/month.

4.3 Results of the evaluation of ILR scheme performance using the WEAP model

4.3.1 Validation of the WEAP model

The results of model validation show that for Gomlai, *E* was 0.97, while for Ghatshila *E* was 0.86. No investigators that have used the WEAP model have undertaken any validation of model outputs using gauged stream flows (for example Bharati et al., 2008; Dimova et al., 2014; Jamshid Mousavi et al., 2017; Lévite et al., 2003; Varela-Ortega et al., 2011), so it is difficult to compare this result to other directly equivalent studies. However, these results compare extremely favourably with other river modelling studies which have used Nash-Sutcliffe model efficiency for validation against streamflow data, where N values exceeding 0.79 are considered acceptable (Moriasi et al., 2007; Rollason et al., 2018).

4.3.1.1 Assessment of risk in fulfilling catchment Water Demand

Results presented in Table 7 indicate that even in the current-day, pre-ILR scenario (Scenario 1), some donor catchments are unlikely to be able to fulfil the proposed irrigation and industrial water demands. In the case of Tilga, risk of not meeting supply is low, however, in the upstream parts of Jarakeila, upstream of the proposed ILR, risk is high, especially during non-monsoon months. The remaining catchments and sub-catchments in the donor basin showed negligible or no risk in meeting their WD. Similarly, catchments in the recipient basins show little or no risk in meeting their WD.

***Table 7** – Results of the modelling undertaken with WEAP showing annual and monthly risks to fulfilling catchment water requirements.*

The results of other scenarios show similar patterns, but the extent of risks is predominantly dictated by the prioritisation of water use. In donor-catchment WD prioritised scenarios (Scenarios 2 and 4) there is little change in risk noted in donor catchments during current scenarios, however, risk increases in the future scenario. A marginal improvement in the risks is seen in Adityapur during current scenarios, however, a negligible risk in future scenarios remains. Note that in this scenario, the WD of the recipient catchments are fully satisfied. In contrast, when water transfer is prioritised (Scenarios 3 and 5), donor catchments show sharp increases in risk in meeting their WD in both current and future scenarios. In Scenario 3 annual risks in the Tilga increase to moderate or high, and in Jarakeila risk is high across all demand types, extending into the mid-part of the catchment. Examined monthly, risk across Tilga and Jarakeila in non-monsoon months is very high, and even during the monsoon season is moderate. In upstream areas of Jarakeila 100% risk is seen during the February-May period. Similar patterns are seen in scenario Scenario 5, with upstream Tilga showing a sharp increase in the risks for all WD, increasing them from moderate to significant risk levels. The monthly risk pattern also increases considerably, showing almost 100% risk during December-May. All parts of Jaraikela show heightened risks across all WD types. These risks were high or very high in the upstream and middle parts of the catchment. Similar to Tilga, they displayed a higher monthly risk pattern with 100% risk in all WD during February-May. The remaining catchments and sub-catchments in donor and recipient basins showed no risk in meeting their WD.

4.3.1.2 Assessment of risk in fulfilling ILR water transfers

The results for the present day scenarios show a risk of 47% for the S-SK link and a risk of 51% for the SK-Sr link at the annual timescale in meeting the flow requirements of the proposed ILR Scheme. Both links show higher risk in donor-catchment prioritised scenarios (see supplementary materials for full results).

The monthly risk pattern suggests a strong seasonality, with both links showing very high risk during the non-monsoon period (December – May), switching immediately to low risk in the early monsoon season (June). The S-SK link demonstrates negligible risk during the monsoon season, however, the SK-Sr link shows moderate to high risk during October and November, particularly under a catchment prioritised flows scenario. Similar patterns are seen in the future scenarios, with small increases in annual risk identified across both links in both catchment and transfer-prioritised scenarios. At a monthly timescale there is little change in risk for the S-SK link, with the same level of seasonality present, with a slightly increased risk in November if water transfer is prioritised. However, the SK-Sr link shows significantly increased risk in the non-monsoon season, with high risk identified in both October and November.

4.3.1.3 Assessment of risk in meeting catchment environmental flow requirements

The results of the modelling indicate that in present day scenarios there was limited risk in fulfilling catchment environmental flows, even under water transfer prioritisation scenarios assuming the ILR link was built today. Only Jaraikela showed minor, but negligible risks during the Business as Usual scenario (Scenario 1) in June and August, but risks were reduced under the catchment-prioritised scenario (Scenario 2) in June. Risk increased considerably under link-prioritised scenario (Scenario 3) covering months from June-January, but only at low to moderate levels. Under the future scenario (Scenario 5), similar patterns were shown, with marginal or negligible change in risk seen.

5 Discussion

This paper has developed and presented a method for the evaluation of IBWT schemes in response to long-standing criticisms of the existing methods used to justify these mega-scale engineering projects. The method adopts the principles of IWRM, demonstrating a transparent approach to assessment using publicly available data, aiming to increase the transparency of assessment of proposed schemes and ensure that the potential impacts of water transfers are evaluated effectively.

5.1 Evaluating the NWDA assessment against IBWT assessment criteria

The feasibility assessments undertaken by the NWDA justify the proposed S-SK-Sr link on the basis of a simplistic assessment of WA and WD which fails to adequately assess real WA and WD both spatially and temporally. As such the assessments fail to fully satisfy the criteria sets laid out in Sections 2 and 3. By using averages across hydrological years, the significance of inter-seasonal variations in WA resulting from the monsoon climate is not accounted for. This issues has been highlighted by Smakhtin et al. (2007) in relation to other Indian IBWT projects. This means that the assessment is unable to accurately judge the degree of WA in donor catchments, making the satisfaction of Criterion 1 difficult, if not impossible. In addition, the NWDA analysis fails to account for temporal variability present in WD, also noted by Liu and Ma (1983) in relation to IBWT projects in China. This is exacerbated by the assessment of WA and WD considering only donor catchments. The NWDA analysis therefore fails to identify whether the recipient catchment has a real water deficit, making achievement of Criterion 2 difficult to evaluate.

In addition, the NWDA assessment makes only limited attempts to evaluate potential future impacts, considering 2050 population growth estimates but not evaluating the impacts of the scheme as it is likely to function. Additionally, the calculations are not complete, with some components requiring reconstruction and considerable interpretation, not satisfying the requirement that the assessment should be transparent and open to external critique.

5.2 Evaluating the performance of the experimental method against the NWDA analysis

In contrast to the analysis by the NWDA, the experimental method demonstrated in this study embeds the principles of IWRM and provides a more holistic assessment capable of satisfying the requirements of the criteria set out in Sections 2 and 3. Our experimental method adopted a spatially and temporally distributed approach to assessing WA and WD across both donor and recipient catchments. The results indicate a much lower WA in the donor catchments of the Sk-Sr link (Figure 7a) than that calculated by the NWDA. Similarly, WD is estimated to be much higher in the donor catchments of the S-SK link (Figure 7b) than

NWDA estimates. Based on this evaluation upstream catchments are at significant risk of being unable to fulfil their water requirements following IBWT scheme implementation; hence, they do not have surplus WA after fulfilling their existing and present WD (criterion 1). Additionally, the results of this study indicate that recipient catchments lack a real water deficit to justify the proposed link, showing almost no risk in meeting water demands, even under a current ‘business as usual’ scenario (Criterion 2). The proposed water transfers (Figure 7c and d) do not reflect these temporal patterns and if progressed would exacerbate water stress across catchments which already show risk in meeting basic water needs (Criterion 3).

Fig 7 - *(a) Comparison of annual water availability with 75% dependability in the catchment area contributing to the two ILR links. (b) Projected annual water demand in 2050 in the upstream donor catchments of the two ILR links. (c) Proposed monthly water transfer of Sankh-South Koel (S-SK) and (d) South Koel-Subarnarekha (SK-Sr) ILR links* (NWDA, 2009b, 2009a) *along with the projected monthly surplus water with 75% dependability in 2050 at the upstream donor catchments.* **[FULL WIDTH]**

The new experimental method is therefore able to demonstrate that the proposed S-SK-Sr scheme as proposed does not satisfy the criteria laid out in Sections 2 and 3, avoiding the ambiguity involved in the NWDA calculations.

These calculations have been undertaken using data which is freely available and has been made available for scrutiny (Criterion 4). This latter aspect is particularly welcome as this study has clearly communicated the approach and methods adopted, which influence the calculations of WA and WD. Several components of the experimental method demonstrated here would warrant further research be undertaken to evaluate the impact of adopting different approaches, for example consideration of Environmental WD, something which the experimental method allows and encourages.

5.3 Implications for the S-Sk-Sr Project

Sternberg (2016) argues that

> "*water projects create winners – residents and regions who gain access to water, receive economic advantage and improve quality of life – and losers – who benefit little if at all from* [water transfer] *megaprojects, pay more for an essential good, and lose land and livelihoods*" (p. 316).

Jharkhand, which hosts the proposed S-Sk-Sr link, is one of the most under-developed states in India (Mukherjee and Chakraborty, 2012). The proposed donor catchments used in our study have a combined population of 4,875,330 (2011 census), of which 80% are involved in agricultural activities. In contrast, the recipient catchments contain larger urban areas, and greater concentrations of modern industry. Evidence suggests that water transfer into basins which lack real water deficit, as is the case in the recipient catchments in this study, encourages unsustainable economic development, consequently increasing water usage (Gohari et al., 2013). In the case of the S-Sk-Sr link this will be at the expense of less developed donor catchments, which are already experiencing a degree of water stress which is likely to increase into the future; our results thus demonstrate that if the proposed ILR link goes ahead, there will be clear winners and losers, a situation not considered by the NWDA assessment used to justify the proposed water transfers.

5.4 Implications for the global inter-basin water transfer projects

The implications of the new method presented are not limited only to India or to the ILR scheme. Shumilova et al. (2018) documented the number of large-scale IBWT projects which are proposed globally, many in areas of water stress or scarcity, or in locations with extreme temporal and spatial variability in precipitation, such as arid/dryland areas or monsoonal precipitation regimes *(Gassert et al., 2015; Jacques et al., 2013; Kottek et al., 2006; Shumilova et al., 2018)*. Whilst climatic factors make the equitable distribution of water in these areas a key factor in promoting development, many proposed schemes are located in countries with unstable governance (e.g. Turkey, South Africa, Jordan, Sudan) (Bogardi et al., 2012; Economist Intelligence Unit, 2019), which in turn might compound issues with a lack of transparency in evaluation of potential impacts. Prior examples of IBWT schemes in such locations have seen politically driven schemes proposed (Gupta and Zaag, 2008), the use of questionable science (Bandyopadhyay, 2012), and the coercion of affected populations (Moore, 2014). Failure to effectively evaluate potential impacts, both upstream and downstream, at suitable temporal and spatial resolution, may have disastrous consequences for the environment (Moore, 2014) and may create many millions of losers in the global distribution of water (Sternberg, 2016).

5.5 A new framework for guiding the assessment of Inter-Basin Water Transfer Projects

The results of this study have underlined how governments and their agencies can justify large-scale alterations to a regions hydrology without effective evaluation of real WA and WD in the areas which will be impacted. A framework to guide future evaluations of IBWT schemes is therefore needed. Such a framework must be comprehensive, integrated, and adaptable to different scales and contexts, able to be applied to the wide variety of proposed IBWT schemes around the world. It must also be freely available, transparent and open to external scrutiny to allow the data, assumptions, and calculations to be tested and validated. In so being it could be applied by any organisation involved in IBWT: governments keen to effectively plan proposed IBWT schemes, bodies interested in the scrutiny of governmental proposals, opposition political parties, the World Bank, or the International Monetary Fund. We propose that the experimental method demonstrated in this study could be such a framework (Figure 9). The proposed framework is intended to both encourage critical analysis of, and dialogue around, proposed IBWT schemes, but also strengthen the justification for proposed projects where this exists.

Fig 9 *– Proposed framework for the evaluation of future IBWT schemes.* **[1.5 WIDTH]**

The new model framework is comprised of three main components:

1. **Catchment assessment**

   The proposed framework embeds the criteria set outlined in Section 3, requiring an integrated assessment of the characteristics of the catchments affected by any proposed IBWT scheme. It addresses the complex and integrated nature of water scarcity issues and their proposed solutions. The model proposes landscape characteristics (Biggs et al., 2007; Colby, 2003); hydrological behaviour (Bracken et al., 2008; Burt and Weerasinghe, 2014; Ceballos and Schnabel, 1998; Morán-Tejeda et al., 2012); and socio-economic trends and conditions (Global Water Partnership (GWP), 2009; Iglesias et al., 2007; Rosenzweig et al., 2004) as the principal catchment characterisations. However, flexibility may be necessary in some cases and the framework should be applied as required.

2. **Integrated assessment of Water Availability and Demand**

   The framework estimates WA and WD at the catchment level as a complex problem (after Asiliev 1977), involving multiple objectives and stakeholders with conflicting perspectives and requirements (Zhang et al., 2012). The proposed approach presents an integrated and transparent approach founded on the use of freely available data to present calculations in a clear and logical manner. Decisions on how WD should be calculated and why, and the appropriate temporal resolution for calculation of WA, should be undertaken based on the detailed understanding of catchment processes developed in 1.

3. **Scenario modelling and scheme assessment**

   Assessments should be based on sound science (Gupta and Zaag, 2008), communicated in a transparent manner (Lund, 2012). Doing so allows the assessment of how adverse impacts on donor basins have been minimised and the benefits to recipient catchment maximised in an equitable fashion (Cox, 1999; Kibiiy and Ndambuki, 2015), enabling others to interrogate the data and results. The identification of appropriate scenarios should be informed by the understanding of the study area and the proposed scheme.

The proposed framework also enables the sensitivity of risks to be evaluated against different futures to identify the impact of areas of uncertainty or knowledge gaps. It could, for example, be used to explore longer term variability in WA resulting from the impacts of El Niño on rainfall patterns (Annamalai and Sperber, 2016), long term reductions in rainfall resulting from climate change (Zhang et al., 2018), or to explore the potential feedbacks associated with increased water availability, which have been identified but not explored fully within this research.

By adopting the proposed framework we can develop more rigorous, integrated, but transparent assessments of the viability of proposed IBWT schemes, giving a voice to those who are affected by potential water transfers. The approach will also help to increase the legitimacy of effectively justified schemes, ensuring that they are practical and sustainable solutions to the complex problem of water scarcity.

6 Conclusions

IBWT is championed as a bold solution to the unequal distribution of water across the world. Large-scale engineering projects have been undertaken, or are planned, across the world to encourage development and increase prosperity in areas affected by water scarcity. However, the scale of these projects mean they have massive socio-economic and environmental impacts which are difficult to assess and even harder to forecast. Many are accused of being justified on the basis of biased or inadequate calculations hidden from public scrutiny.

This research has demonstrated an experimental method for evaluating the viability and impacts of IBWT schemes, which embeds the principles of IWRM, using freely accessible data. Testing the method against the proposed S-Sk-Sr IBWT link, part of the Indian ILR scheme, has demonstrated the limitations of the NWDA justification of the scheme, and proven the ability of the experimental method in helping understand spatial and temporal heterogeneity in WA and WD, and the impact of potential future water usage scenarios.

The findings of the research have significant implications for IBWT schemes globally. Many future schemes are proposed in areas of existing water stress, or in countries lacking robust democratic governance structures. Inadequate justifications for major water transfers have the potential to devastate affected catchments, creating or enhancing existing water stress and negatively impacting the lives of millions of people. The assessment framework developed through this research will provide a valuable tool in opening up and democratising the analysis of proposed IBWT schemes worldwide.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 1 – Criteria sets developed to evaluate IBWT schemes

Criteria Set	Details
International Commission of Irrigation and Drainage, 1978 (Rahman, 1999)	1. The donor basin must have surplus water after fulfilling all its needs, and its current and future water requirements must be secured before implementing IBWT. 2. The recipient basin must have a water deficit after deducting water available: a. Through all possible alternative sources which are cheaper than IBWT, and b. By saving available water through effective management without affecting the productivity. 3. Adverse impacts of the water transfer are minimised.
(Cox, 1999)	1. The recipient basin must encounter substantial water deficit in present or in future after deducting its: a. Natural Water Availability, and b. Possible Water Availability through Water Demand management. 1. The donor basin must not encounter water deficit in the present or in the future due to the water transfer and IBWT project must not significantly hinder its future economic development. However, the donor basin can consider transferring water in the case of obtaining compensation in lieu of its productivity loss. 2. A thorough EIA must be carried out for donor and recipient basins to ensure that the project will not adversely affect the environment. However, a project can be considered if it is ready to compensate for the environmental damage. 3. A detailed evaluation of social and cultural influence is required to guarantee that the project will not cause any significant interruption. However, projects can be considered if they are ready to compensate for any potential loss. 2. The net benefits from the water transfer must be shared impartially between donor and recipient basins.
Gupta and Zaag (2008)	1. The donor basin should have real surplus water while the recipient basin should have a real water deficit after efficient water use is available there. 2. The IBWT project should be socially, environmentally and economically sustainable and should be adaptive to natural and social stress. 3. The IBWT project should be planned under good governance practice.

	4. The project should balance the existing rights of territory of the project with the needs of the project. 5. The IBWT project should be based on sound science including hydrological, ecological and socio-economic analyses which should identify associated risks, uncertainties and any knowledge gaps. All alternatives should be considered.
Kibiiy and Ndambuki (2015)	1. Justification of the need for water transfer 2. Demonstration of minimising the anticipated negative impacts 3. Demonstration of maximising the anticipated positive impacts

Table 2 – overview of principal data sources and their use within the experimental method

Data	**Source**	**Usage**
Daily discharge data for 6 HOCs within study area	Water Resource Information System (WRIS)	Calculation of Water Availability
Average water usage rates (urban, rural, livestock)	NWDA (2016)	Calculation of Water Demand
District level agricultural usage data (livestock population and cropped area)	Technical note on the 19th Livestock census by Ministry of Agriculture (2012); Open Government Data platform.	
Irrigation projects and their command area	Prefeasibility reports of S-SK-ILR link and SK-Sr ILR link (NWDA, 2009b, 2009a); Report by Regional Remote Sensing Service Centre (Sharma et al., 2007)	
Industrial demand information	Water Resource Department, Government of Jharkhand (2012); Ministry of Micro Small & Medium Enterprises (2016)	

Table 3 – Overview of scenarios simulated using the WEAP model

	Scenario	Description	Scenario Code
1	Baseline (2012)	With no ILR to represent the present day, 'business as usual' scenario	2012
2	Baseline (2012) with priority given to donor-catchment WD	Depicting the current conditions assuming ILR links are constructed and priority given to donor-catchment WD.	2012-WL-PC
3	Baseline (2012) with priority given to water transfer	Depicting the current conditions with ILR links constructed and priority given to proposed water transfer.	2012-WL-PL
4	Future (2050) with priority given to donor-catchment WD	Depicting change in demand drivers (socio-economic) in projected future with ILR links constructed and priority given to donor-catchment WD.	2050-WD-WL-PC
5	Future (2050) with priority given to water transfer	Depicting change in demand drivers (socio-economic) in projected future with ILR links constructed and priority given to proposed water transfer.	2050-WD-WL-PL

Table 4 – (a) Results of the NWDA analysis of water surplus for the proposed ILR link, and (b) the proposed monthly transfer schedule of water along the proposed link (NWDA, 2009b, 2009a).

(a) Calculation of water surplus	**S-SK ILR Link**	**SK-Sr ILR link**
Water Demand (WD)	**Water Usage ($M\ m^3\ a^{-1}$)**	**Water Usage ($M\ m^3\ a^{-1}$)**
Domestic	10.33	95.16
Industrial	11.52	106.08
Irrigational	94.28	939.05
Downstream commitment to Rengali Dam	139.33	475.86
Livestock	*Not considered*	
Total WD (WD_{TOT})	**255.47**	**1616.15**
Water Availability	**($M\ m^3\ a^{-1}$)**	**($M\ m^3\ a^{-1}$)**
Natural Water Availability (WA_{nat})	1018.5	3487.07
Regenerated Flows Domestic (R_{dom})	8.26	76.13
Regenerated Flows Industrial (R_{ind})	9.22	84.86
Regenerated Flows Irrigational (R_{irrig})	7.54	65.60
Water Surplus or Deficit (after Equation 1)	**+788.06**	**+2097.51**
(b) Proposed month-wise water transfer plan		

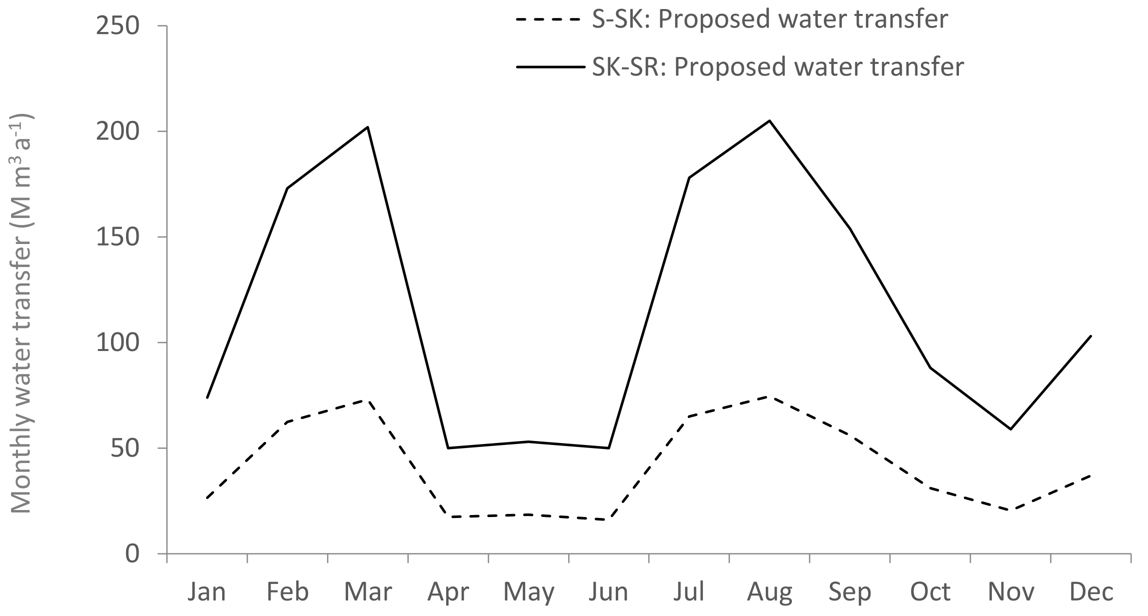

S-SK: Proposed water transfer
SK-SR: Proposed water transfer
Monthly water transfer (M m³ a⁻¹)
250
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

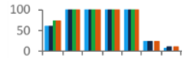
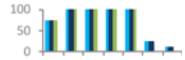
Table 5 –WD for each catchment by sector using the experimental method

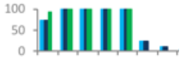
	Water Demand (M m^3 a^{-1})						
	Domestic			Livestock	Irrigation	Industry	Environmental
	Total	*Urban*	*Rural*				
Tilga	21	*10.7*	*10.5*	5.9	86	0.4	664
Jaraikela	197	*135*	*62*	25	607	16	991
Gomlai	89	*61*	*28*	18	141	64	2942
Adityapur	95	*58*	*37*	15	362	1.3	424
Jamshedpur	247	*200*	*47*	19	421	14.0	976
Ghatshila	75	*64*	*11*	4.6	14	1170	1273
Donor	**308**	***207***	***101***	**48**	**834**	**81**	**2942**
Recipient	**417**	***322***	***96***	**39**	**797**	**1185**	**1273**

Table 6 – Water surplus at 75% dependability by catchment using the experimental method

Basin	Catchment	Annual water surplus (M m^3 a^{-1}) at 75% dependability
Donor	Tilga	506
	Jaraikela	1,082
	Gomlai	3,128
Recipient	Adityapur	893
	Jamshedpur	4,538
	Ghatshila	3,991

Table 7 – Results of the modelling undertaken with WEAP showing annual and monthly risks to fulfilling catchment water requirements.

Scenario		Baseline (pre-ILR)					Scenario 2					Scenario 3				
		Annual Risk				Monthly Risk	Annual Risk				Monthly Risk	Annual Risk				Monthly Risk
Catchment	Zone	Domestic	Livestock	Irrigation	Industry	🟦 Domestic ■ Live 🟩 Irrigation 🟧 Indu Jan Feb Mar April May Jun Jul Aug Sept	Domestic	Livestock	Irrigation	Industry	🟦 Domestic ■ Live 🟩 Irrigation 🟧 Indu Jan Feb Mar April May Jun Jul Aug Sept	Domestic	Livestock	Irrigation	Industry	🟦 Domestic ■ Lives 🟩 Irrigation 🟧 Indu Jan Feb Mar April May Jun Jul Aug Sept
Tilga	U/S	0.0	0.0	5.8	5.8		0.2	0.2	5.8	6.0		45.6	47.2	47.0	47.9	
	D/S	0.0	0.0	-	-		0.2	0.2	-	-		1.4	1.4	-	-	
Jaraikela	U/S	0.5	0.5	32.9	33.3		0.2	0.2	32.9	33.1		47.9	50.7	52.5	56.9	
	Mid	0.7	0.7	0.2	-		0.2	0.2	0.0	-		56.0	56.0	51.9	-	
	D/S	0.9	0.9	-	0.9		0.2	0.2	-	0.2		16.2	16.4	-	16.4	
Gomlai		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	
Adityapur	U/S	0.5	0.5	0.0	0.5		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	
	D/S	0.5	0.5	1.4	*-		0.0	0.0	0.0	*-		0.0	0.0	0.0	*-	
Jamshedpur		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	
Ghatshila		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	

Scenario		Scenario 4					Scenario 5				
		Annual Risk				Monthly Risk	Annual Risk				Monthly Risk
Catchment	Zone	Domestic	Livestock	Irrigation	Industry	🟦 Domestic ■ Livestock 🟩 Irrigation 🟧 Industry Jan Feb Mar April May Jun Jul Aug Sept Oct Nov Dec	Domestic	Livestock	Irrigation	Industry	🟦 Domestic ■ Livestock 🟩 Irrigation 🟧 Industry Jan Feb Mar April May Jun Jul Aug Sept Oct Nov Dec
Tilga	U/S	0.2	0.2	24.8	25.0		47	47.5	49.5	50.5	
	D/S	0.2	0.2	-	-		1.4	1.4	-	-	
Jaraikela	U/S	6.0	9.5	41.0	41.2		50.5	50.9	52.8	57.2	
	Mid	0.2	0.2	40.3	-		56	56	59	-	
	D/S	2.1	2.1	-	2.3		16.7	16.7	-	17.4	

Notes				
Risk (%):	0 – 25	25 - 50	50 - 75	75 - 10
Significance:	Low	Moderate	High	Very High
U/S	Above ILR link inflow (donor catchments) or outflow (recipient catchments)			
Mid	Between ILR link outflow and inflow			

Gomlai		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		Below Below ILR link inflow (donor catchments) or outflow (recipient catchments) - No water demand *- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.
Adityapur	U/S	0.0	0.0	0.7	0.7		0.0	0.0	0.7	0.7		
	D/S	0.0	0.0	0.9	*-		0.0	0.0	0.9	*-		
Jamshedpur		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		
Ghatshila		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		

Highlights:

- Growth in Interbasin Water Transfer has large scale socio-ecological implications
- Scheme impact assessments are often highly contentious and lack public scrutiny
- An interdisciplinary approach for evaluating IBWT using open data is developed
- The approach is demonstrated using a case study from India
- A new framework for assessing IBWT scheme impacts is proposed

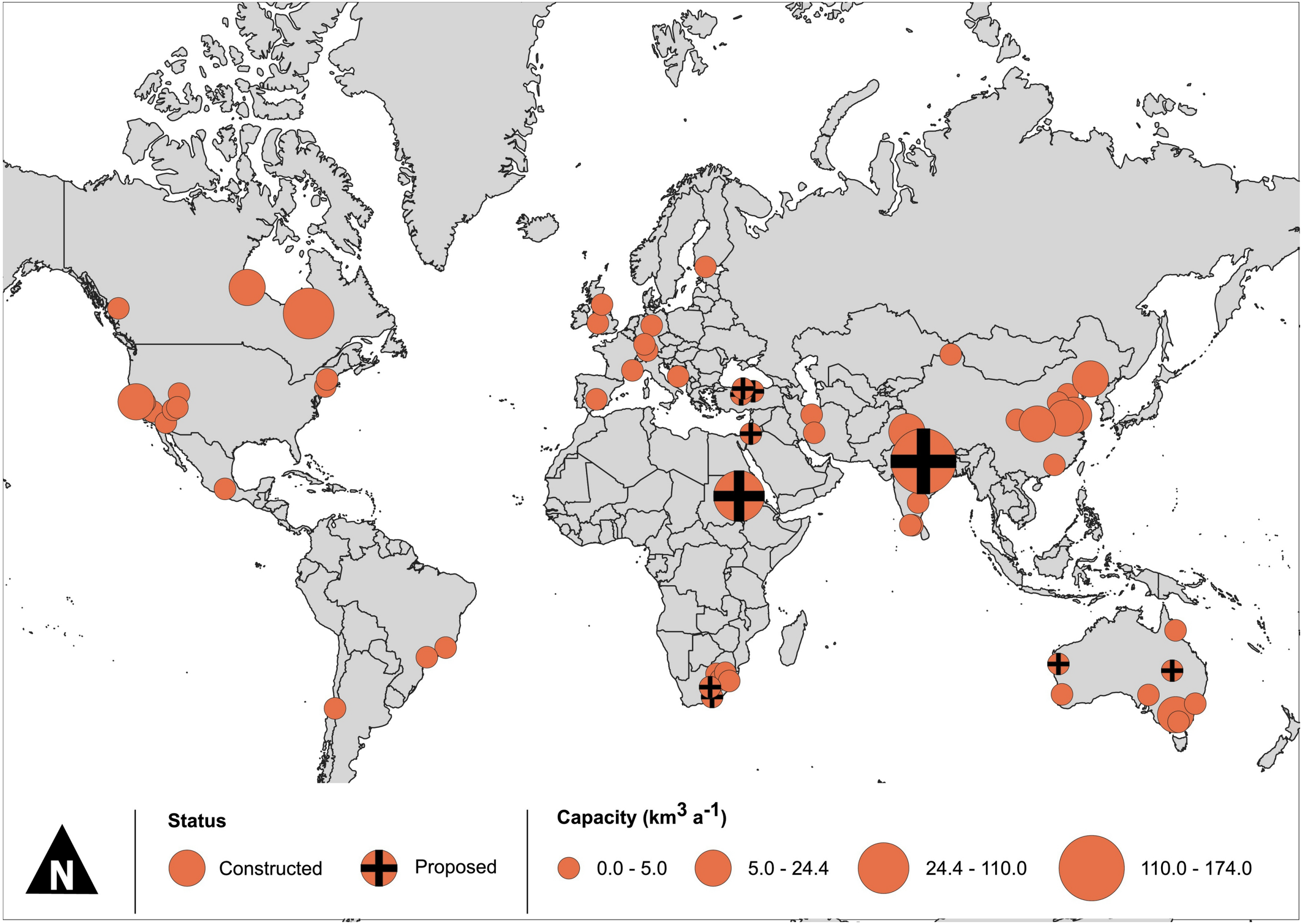

N
Status
Constructed
Proposed
Capacity (km3 a-1)
0.0 - 5.0
5.0 - 24.4
24.4 - 110.0
110.0 - 174.0

Figure 1

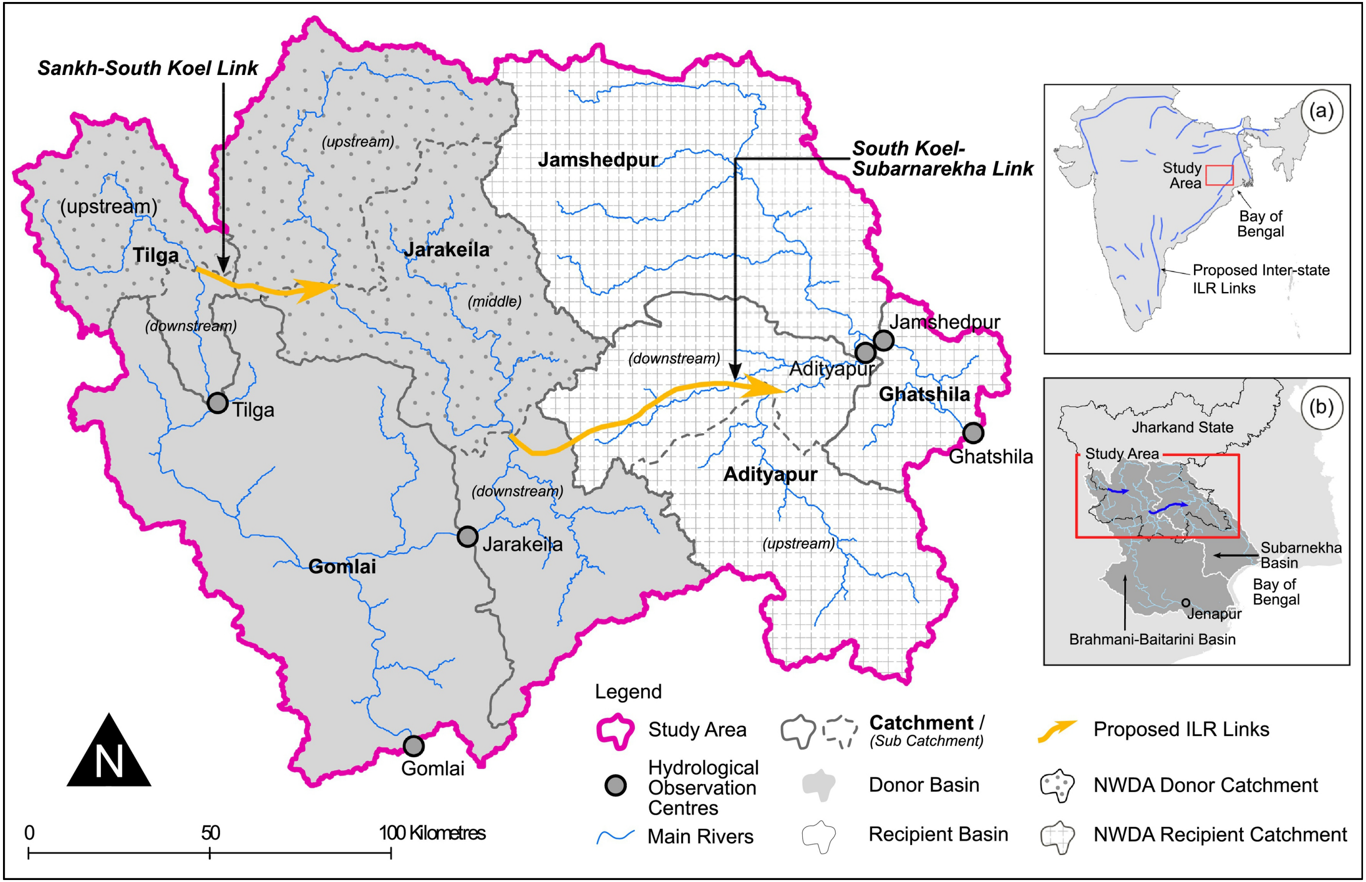

Sankh-South Koel Link
South Koel-Subarnarekha Link
(upstream)
Tilga
(downstream)
Tilga
(upstream)
Jarakeila
(middle)
(downstream)
Jarakeila
Gomlai
Gomlai
Jamshedpur
Jamshedpur
(downstream)
Adityapur
Adityapur
(upstream)
Ghatshila
Ghatshila
N
0
50
100 Kilometres
Legend
Study Area
Hydrological Observation Centres
Main Rivers
Catchment / (Sub Catchment)
Donor Basin
Recipient Basin
Proposed ILR Links
NWDA Donor Catchment
NWDA Recipient Catchment
(a)
Study Area
Bay of Bengal
Proposed Inter-state ILR Links
(b)
Jharkand State
Study Area
Subarnekha Basin
Bay of Bengal
Jenapur
Brahmani-Baitarini Basin

Figure 2

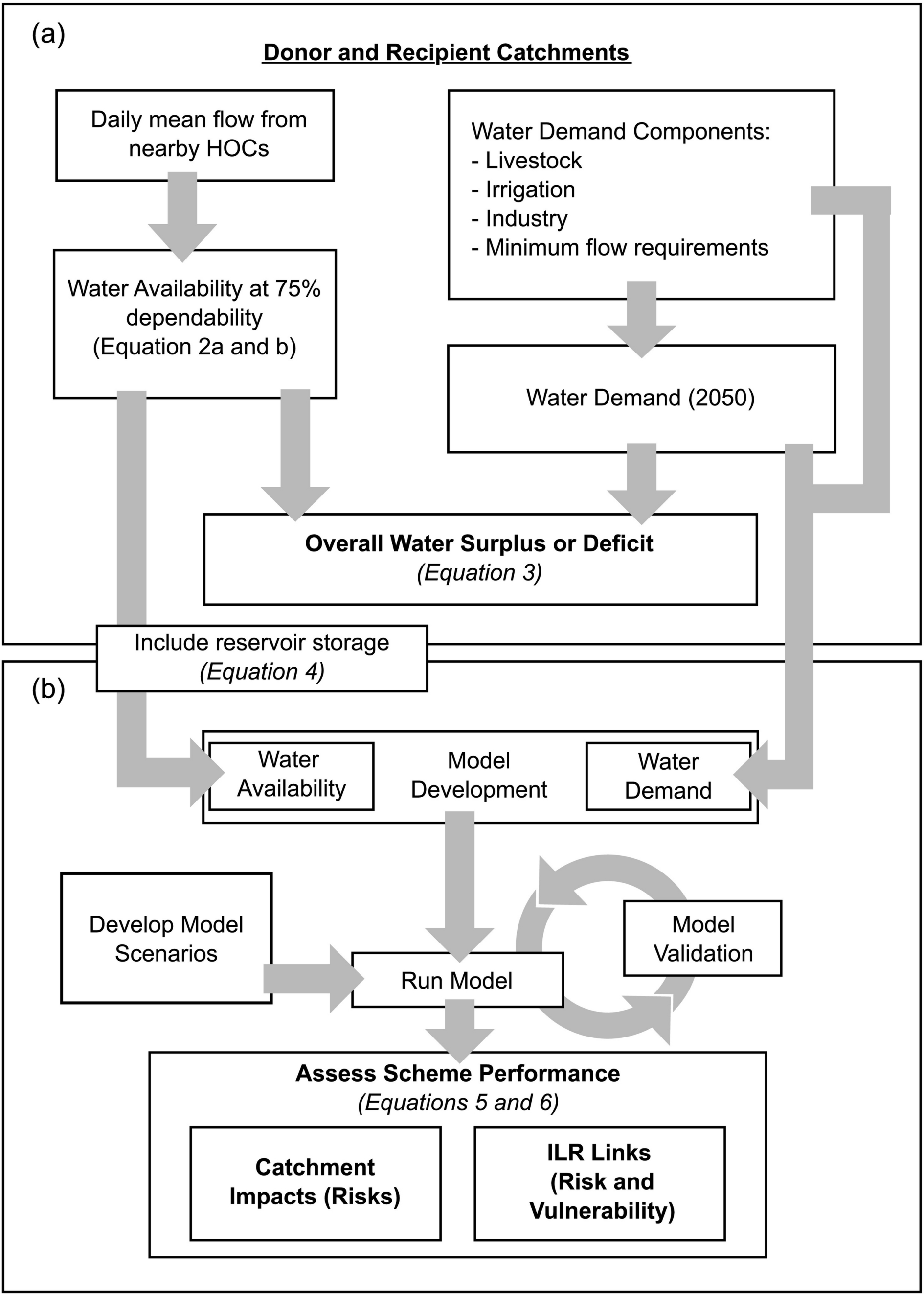

(a)
Donor and Recipient Catchments
Daily mean flow from nearby HOCs
Water Availability at 75% dependability (Equation 2a and b)
Water Demand Components:
- Livestock
- Irrigation
- Industry
- Minimum flow requirements
Water Demand (2050)
Overall Water Surplus or Deficit
(Equation 3)
Include reservoir storage
(Equation 4)
(b)
Water Availability
Model Development
Water Demand
Develop Model Scenarios
Run Model
Model Validation
Assess Scheme Performance
(Equations 5 and 6)
Catchment Impacts (Risks)
ILR Links (Risk and Vulnerability)

Figure 3

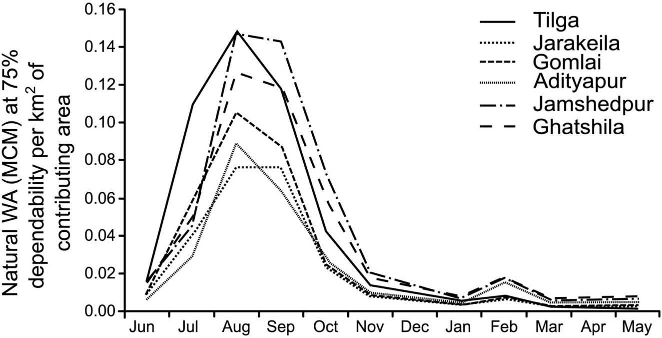

Natural WA (MCM) at 75% dependability per km² of contributing area
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Tilga
Jarakeila
Gomlai
Adityapur
Jamshedpur
Ghatshila

Figure 4

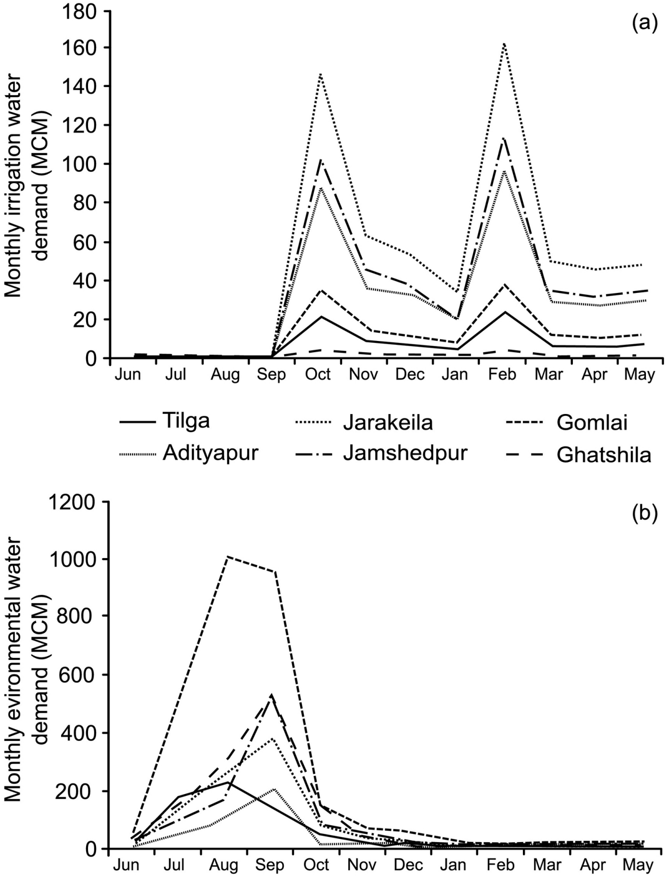

(a)
Monthly irrigation water demand (MCM)
180
160
140
120
100
80
60
40
20
0
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Tilga
Adityapur
Jarakeila
Jamshedpur
Gomlai
Ghatshila
(b)
Monthly evironmental water demand (MCM)
1200
1000
800
600
400
200
0
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May

Figure 5

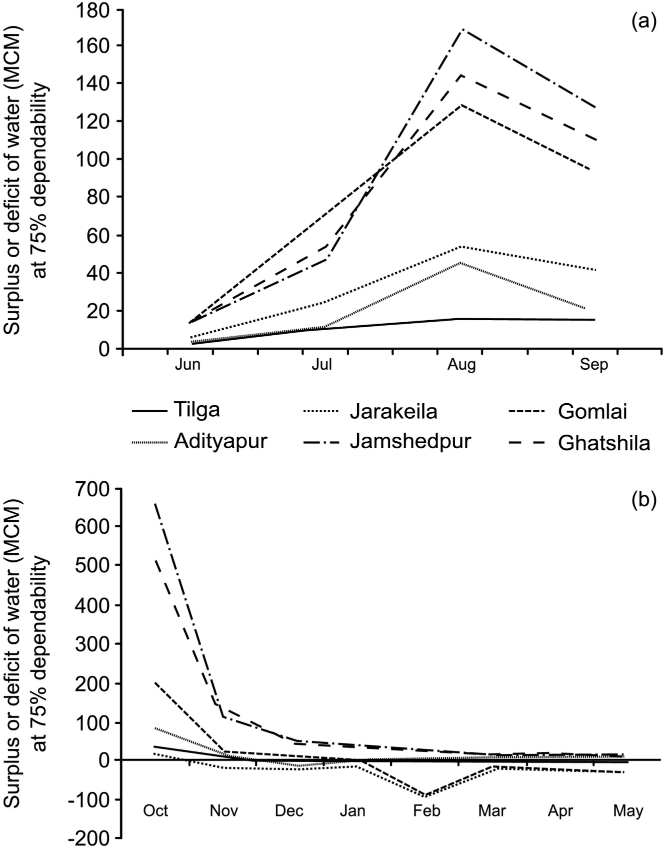

(a)
Surplus or deficit of water (MCM) at 75% dependability
180
160
140
120
100
80
60
40
20
0
Jun
Jul
Aug
Sep
Tilga
Jarakeila
Gomlai
Adityapur
Jamshedpur
Ghatshila
(b)
Surplus or deficit of water (MCM) at 75% dependability
700
600
500
400
300
200
100
0
-100
-200
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May

Figure 6

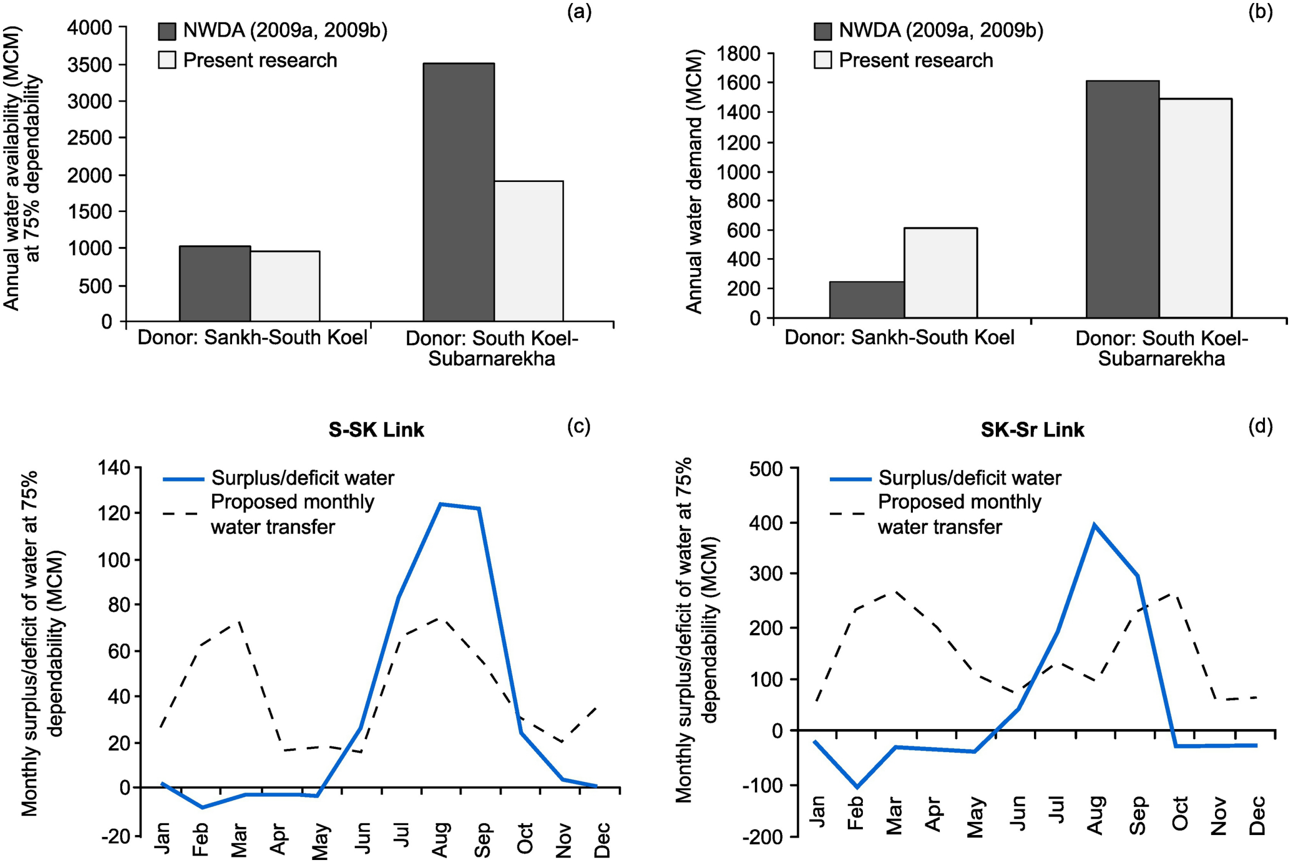

(a)
Annual water availability (MCM) at 75% dependability
0
500
1000
1500
2000
2500
3000
3500
4000
NWDA (2009a, 2009b)
Present research
Donor: Sankh-South Koel
Donor: South Koel-Subarnarekha
(b)
Annual water demand (MCM)
0
200
400
600
800
1000
1200
1400
1600
1800
NWDA (2009a, 2009b)
Present research
Donor: Sankh-South Koel
Donor: South Koel-Subarnarekha
S-SK Link
(c)
Monthly surplus/deficit of water at 75% dependability (MCM)
-20
0
20
40
60
80
100
120
140
Surplus/deficit water
Proposed monthly water transfer
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
SK-Sr Link
(d)
Monthly surplus/deficit of water at 75% dependability (MCM)
-200
-100
0
100
200
300
400
500
Surplus/deficit water
Proposed monthly water transfer
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 7

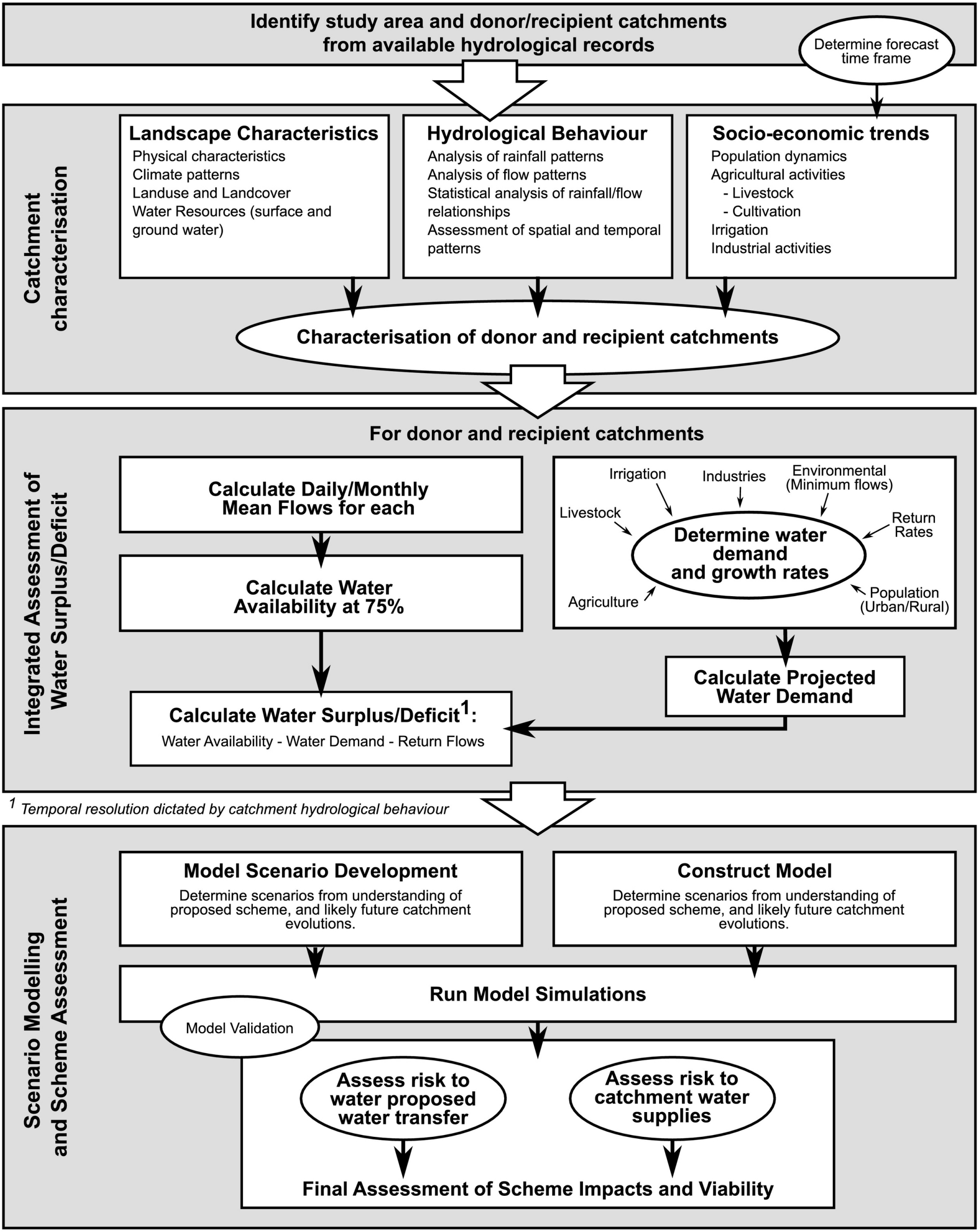

Identify study area and donor/recipient catchments from available hydrological records
Determine forecast time frame
Catchment characterisation
Landscape Characteristics
Physical characteristics
Climate patterns
Landuse and Landcover
Water Resources (surface and ground water)
Hydrological Behaviour
Analysis of rainfall patterns
Analysis of flow patterns
Statistical analysis of rainfall/flow relationships
Assessment of spatial and temporal patterns
Socio-economic trends
Population dynamics
Agricultural activities
- Livestock
- Cultivation
Irrigation
Industrial activities
Characterisation of donor and recipient catchments
Integrated Assessment of Water Surplus/Deficit
For donor and recipient catchments
Calculate Daily/Monthly Mean Flows for each
Calculate Water Availability at 75%
Calculate Water Surplus/Deficit1:
Water Availability - Water Demand - Return Flows
Irrigation
Industries
Environmental (Minimum flows)
Livestock
Return Rates
Determine water demand and growth rates
Agriculture
Population (Urban/Rural)
Calculate Projected Water Demand
1 Temporal resolution dictated by catchment hydrological behaviour
Scenario Modelling and Scheme Assessment
Model Scenario Development
Determine scenarios from understanding of proposed scheme, and likely future catchment evolutions.
Construct Model
Determine scenarios from understanding of proposed scheme, and likely future catchment evolutions.
Run Model Simulations
Model Validation
Assess risk to water proposed water transfer
Assess risk to catchment water supplies
Final Assessment of Scheme Impacts and Viability

Figure 8

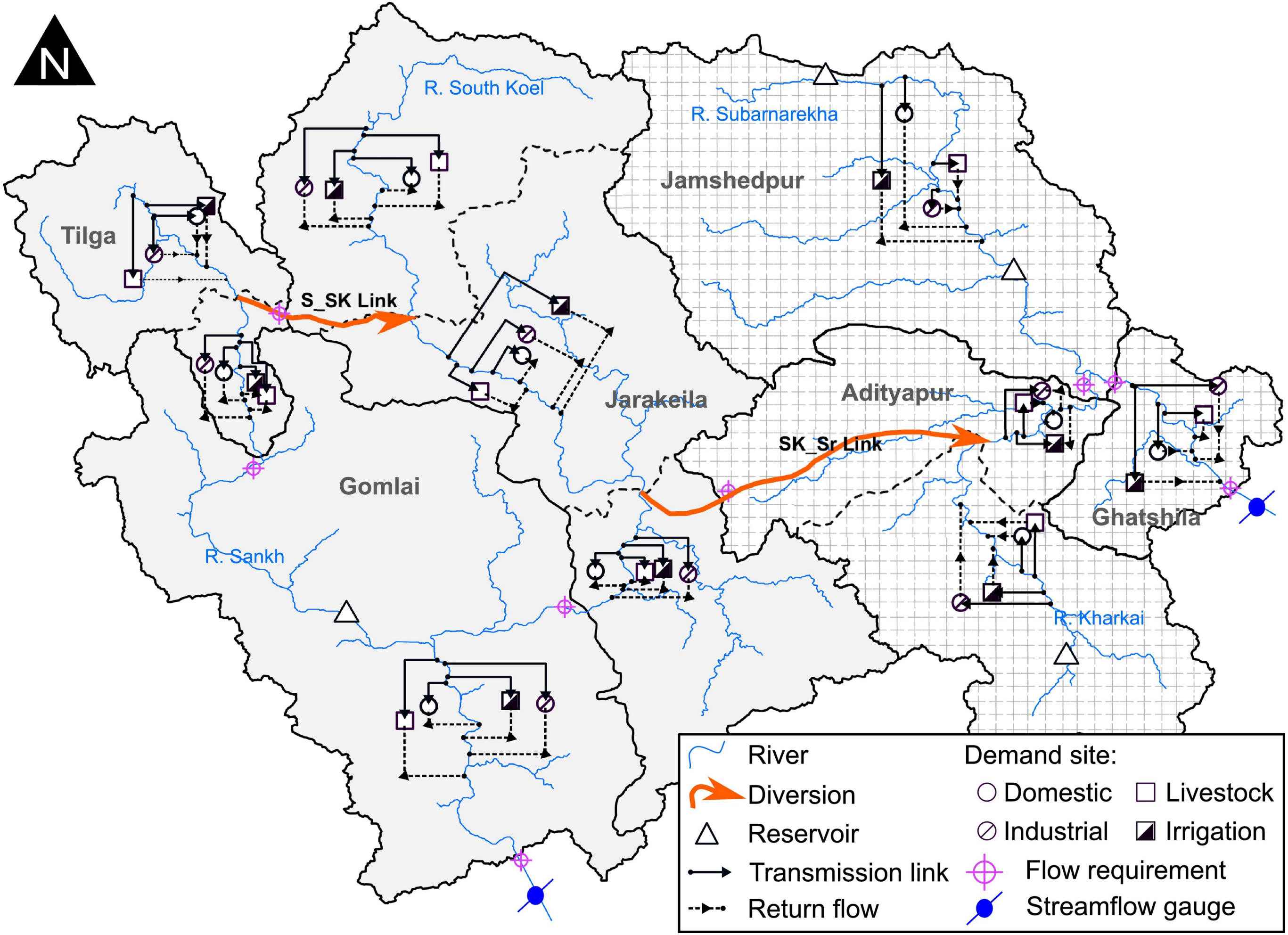

N
R. South Koel
R. Subarnarekha
Jamshedpur
Tilga
S_SK Link
Jarakeila
Adityapur
SK_Sr Link
Gomlai
Ghatshila
R. Sankh
R. Kharkai
River
Diversion
Reservoir
Transmission link
Return flow
Demand site:
Domestic
Livestock
Industrial
Irrigation
Flow requirement
Streamflow gauge

Figure 9