Trade-off discovery for inter-basin water transfer in India: are donor basins always water surplus?

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Abstract

The spatio-temporal variability of water resources combined with growing demand for this limited resource has forced planners to look for alternative water management strategies, including, inter-basin transfer of water. Inter-basin water transfer has been implemented in several countries across the globe and accounts for nearly 14% of global water withdrawals in 2005 (540 billion cubic meters per year), which is likely to increase to 25% by 2025 [1]. However, transferring such large volumes of water poses two key challenges. First, there are known negative ecological consequences related to transfer of large volumes of water from one region to another. Second, there is no clarity on how to categorize a basin as water surplus or deficit in the face of uneven growth in demands for water and likely changes in climatic conditions in both the donor and recipient basins. We focus on this second issue in this analysis using a proposed water transfer scheme in southern India as a test case.

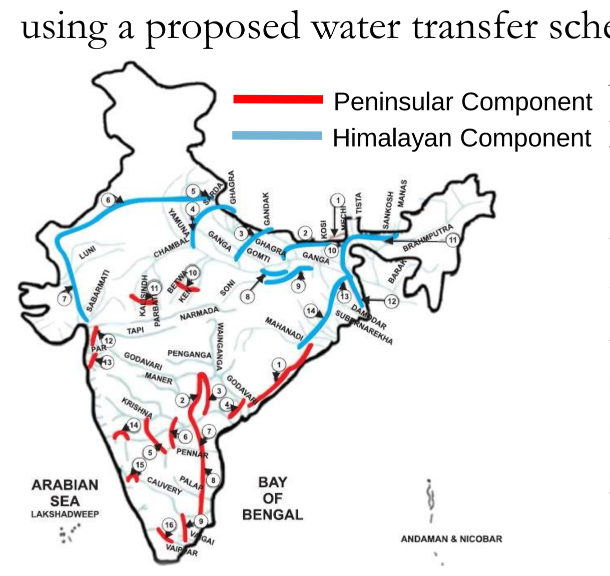

Figure 1. Schematic representation of the proposed river linking project [3].

A transfer scheme consisting of around 30 river-links is proposed to connect rivers from northern to southern India (Figure 1) [2,3]. We employ many objective robust decision making (MORDM) to assess whether historically defined *surplus* and *deficit* basins remain as such at finer temporal resolutions (monthly vs. annual), and under changing demands and climatic conditions. MORDM explores tradeoffs between the objectives of meeting demands and minimum environmental requirements in both *surplus* donor and *deficit* recipient basins. We show that the choice of problem formulation constrains the achievable reliability of demand satisfaction in the either basins, suggesting:

A flexible definition of *surplus* and *deficit*, allowing for seasonality and potential changes in drivers of water availability, enables identification of a broader suite of compromise strategies.

Methodology

We identify strategies for operating the Inchampalli-Nagarjuna Sagar river link, located in southern India (Figure 2). In order to simulate the available water supply in the two basins under various climatic scenarios, we employ a monthly water balance model that is calibrated for donor and recipient basin separately (Figure 3) [4]. The transfers from the donor to recipient basin are simulated while accounting for reservoir storage (Figure 4). The transfer strategy, or decision lever for the many objective problem constitutes of two components: volume and timing transferred water at monthly time steps. In addition, we also consider reservoir volumes as decision levers. Using, MORDM and various combinations of objectives (see: Results), we obtain the Pareto-optimal strategies after optimization using the BORG multi objective optimization algorithm [5]. For the present analysis, we simulate all variables for a representative year (1967) and apply changes to climatic conditions on monthly time series for the representative year.

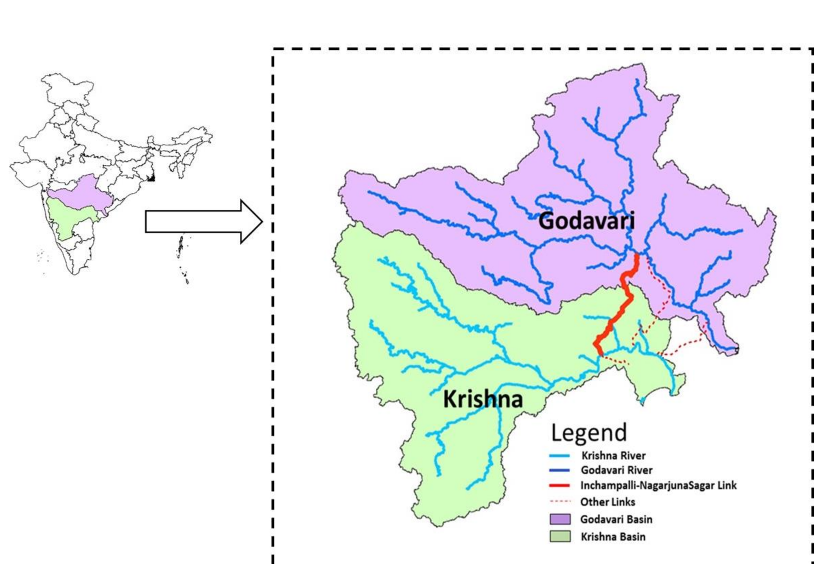

Figure 2. Three links are proposed between the Godavari and Krishna basins. The Inchampalli-Nagarjuna Sagar link is chosen for the study as currently it amounts for bulk of the proposed transfers between the two basins and is located upstream, thus can be analysed independent of downstream transfers. The water is transferred from Godavari basin (donor) to Krishna basin (recipient).

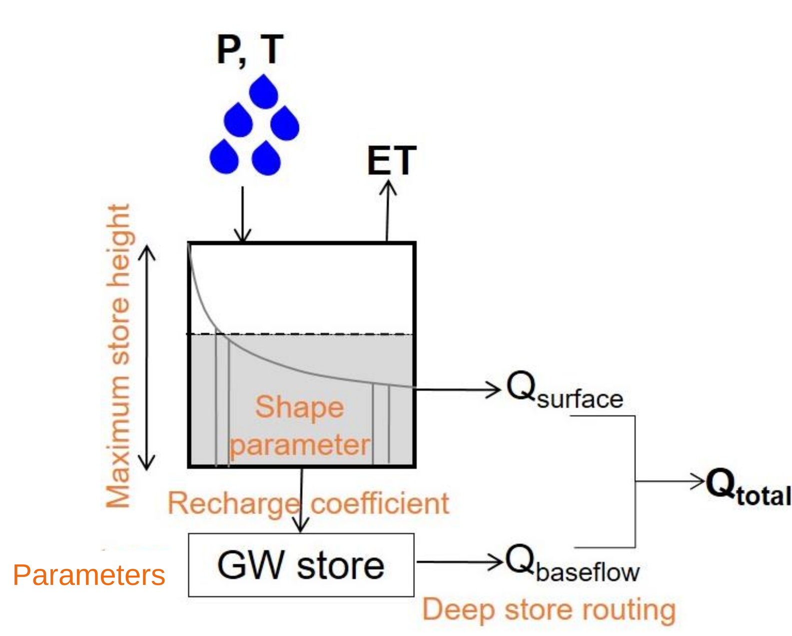

Figure 3. A lumped conceptual monthly water balance model with four parameters [5]. 10,000 random parameter sets are generated using Latin Hypercube Sampling and the set with the highest NSE (Nash Sutcliffe efficiency) is chosen for further analysis. Inchampalli (donor) and Nagarjuna (recipient) sites reported NSE values of 0.87 and 0.56, respectively, with percentage volumetric bias of 0.5% and -2.6%, respectively.

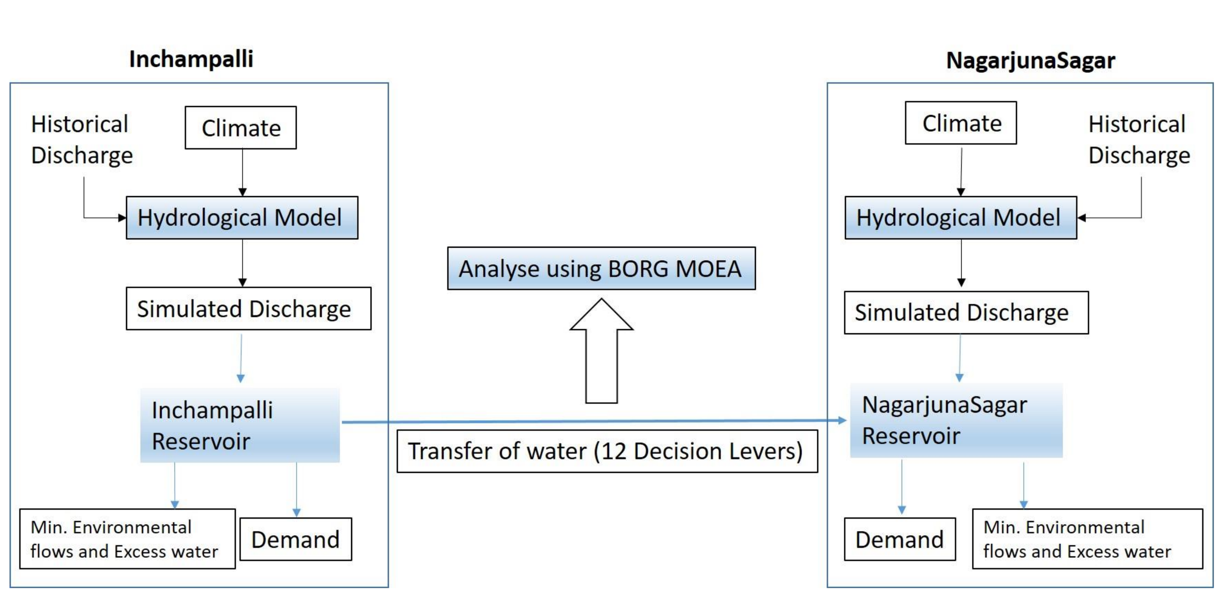

Figure 4. Methodology followed in the study. Observed discharge at the gauge stations on donor and recipient sites are used to calibrate the hydrologic model. The models provide water supply input to the reservoirs, which are coupled by the transfer link.

Minimum environmental flows are released downstream of site at 10% of monthly flow values prior to demand satisfaction [6]. Excess water beyond the storage capacity of reservoir is also released downstream. Demand is further divided into : agricultural, industrial, domestic and hydro-power demands.

Results: Trade-offs across formulations

Impact of problem formulations

In order to assess to what extent a transfer strategy can satisfy the demands in both donor and recipient basins, we design various problem formulations. Different problem formulations represent the diverse ways in which decision makers may chose to identify a transfer strategy. Previous work has shown that low objective formulations tend to be myopic, i.e., they represent a very small subset of possible trade-offs when projected in a higher dimensional objective space [7]. We design four problem formulations with increasing number of objectives and constraints (Table 1). The objectives are: demand deficit in donor and recipient basins, reliability of water supply in donor and recipient basins, and cost of reservoir construction.

Objectives→ Problem Formulations↓	Deficit (Donor)	Deficit (Recipient)	Reliability (Donor)	Reliability (Recipient)	Cost
P1	✓	✓	×	×	×
P2	✓	✓	✓	✓	×
P3	✓	✓	✓	✓	✓
P4	✓	✓	✓	✓	✓

Table 1. Problem formulations for the Krishna Godavari link considering a total of 5 objectives and 2 constraints. Constraints are placed on reliability values for both the donor and recipient basins and are only included in P4.

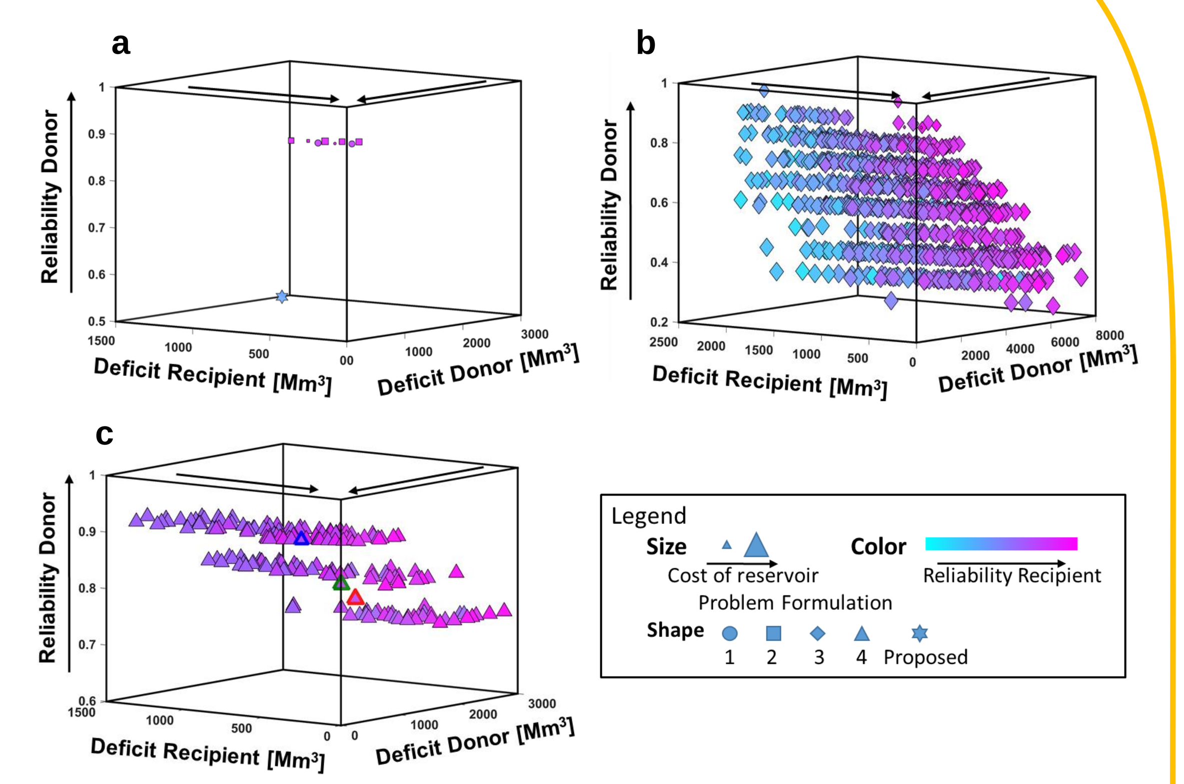

Figure 5. Trade off discovery by visualizing Pareto fronts across problem formulations (a) P1 and P2, (b) P3, and (c) P4, as defined in Table 1. Deficit of recipient basin, deficit of donor basin, and reliability of donor basin are plotted on x, y, z axis, respectively. Reliability of the recipient basin is shown through color of markers. Cost of reservoir construction is shown via size of marker. Arrows indicate the direction of preference for each objective function. The transfer scheme proposed by [2] is shown as a star in (a)

The range of annual transfer volumes across solutions in Figure 5(c) is 962-31653 Mm^3. The annual transfer volume proposed in [2] is 16426 Mm^3. Overall, we note that there are many possible transfer schemes that represents varying levels of compromises between the objectives of the donor and recipient basins. In particular, we note the poor performance of the scheme by [2] in maintaining reliability of water supply for the donor basin. Some selected solutions from Figure 5(c) are shown in Figure 6. In addition the transfer volumes proposed in the NCIWRD report [2] are also shown. The transfer volumes in [2] are based on fixed storage volumes of the reservoirs and are specified on a seasonal basis.

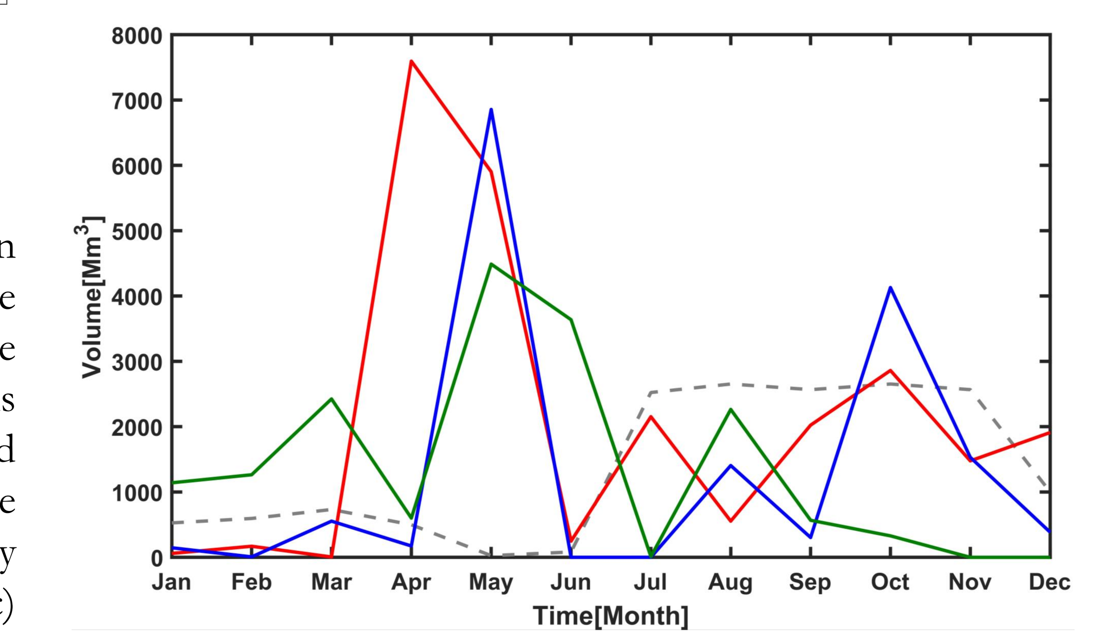

Figure 6. Transfer volumes for three solutions selected from P4 as highlighted in Figure 5(c). Blue (red) lines represent transfer strategies with the maximum (minimum) cost of construction. The three solutions also represent three different reliability values in the donor basin. The proposed transfer from [2] is shown as dashed gray lines.

Impact of changing demands and climate

In order to ascertain the impact of changing climate and demands on the performance of the transfer, we re-evaluate all solutions obtained from P1-P4 under 4 scenarios. Increase in demand account for the urbanisation and population growth. First, demand, mean annual temperature, and mean annual precipitation are changed independently, then all changes are simultaneously applied.

We find that the cost of construction remains similar across all change scenarios. This is likely due to the constraints on reliability basins (Figure 7). When change in both the climate and demand conditions occur simultaneously, the minimum reliability of recipient basin reduces from 0.75 to 0.42, indicating that the donor basin can be severely water deficit in the future.

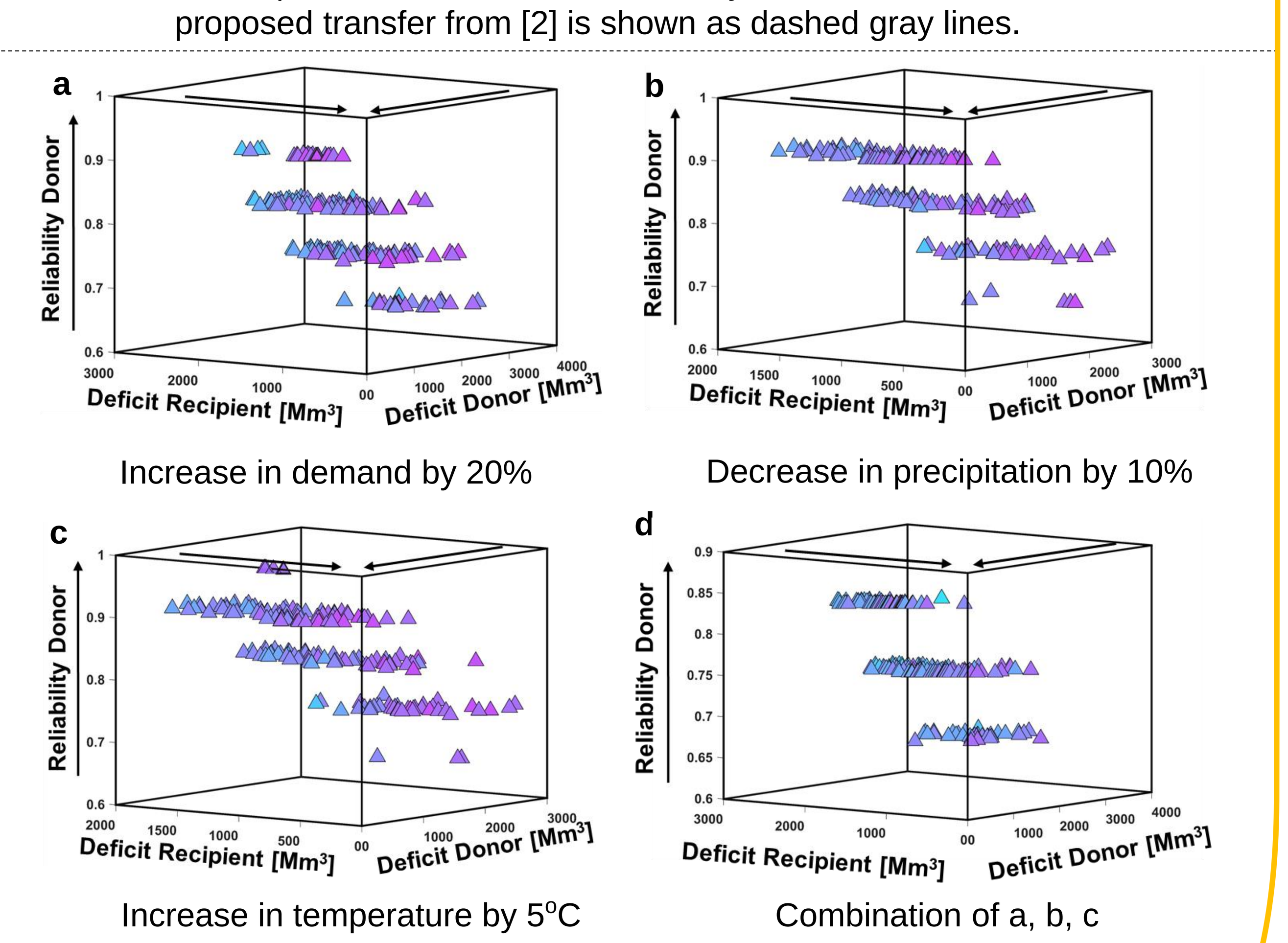

Figure 7. Re-evaluating solutions from Figure 5(c) under changing climatic and demand conditions. (a) demand is increased by 20%, (b) mean annual precipitation is reduced by 10%, (c) mean annual temperature is increased by 5°C, and (d) all changes are applied simultaneously. The objectives are plotted following the same scheme as Figure 5.

Conclusions and Next Steps

In this analysis, we show how the static definition of water *surplus* and *deficit* basin change even within historical period depending upon choice of transfer protocol and problem formulation. In addition, when relatively small changes are applied to historically assumed demands and climate, severe degradation in the water supply of the donor basin are noted.

We also show that flexibility in storage volumes allow for greater reliability of water supply in both the donor and recipient basins at a moderate cost. Thus, one can compromise on reliability or cost of reservoir construction. For now, it will be difficult to chose a single transfer strategy from among the various trade-off solutions. Further work aims to perform a robustness analysis to identify strategies that degrade minimally in the presence of applied changes.

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