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An Integrated water balance model for assessing water scarcity in a data-sparse interfluve in Eastern India

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Abstract:

The objective of this study is to measure the balance of water demand versus water resource availability in an interfluve of West Bengal, India to support water resource planning, particularly of inter-basin transfers. Surface water availability was modelled using the Soil Conservation Service Curve Number (SCS-CN) model, whilst groundwater availability was modelled based on water level fluctuations and the rainfall infiltration method. Water use was modelled separately for the agricultural, industrial, and domestic sectors using a predominantly normative approach and water use to availability ratios calculated for different administrative areas within the interfluve. Overall, the approach suggested that the interfluve receives $327 \times 10^6 m^3 year^{-1}$ of excess water after satisfying these sectoral demands, but that the eastern part of the study area is in deficit. However, a sensitivity analysis carried on the approach to several assumptions in the model suggested changed circumstances would produce surplus/deficit ranging from $-215 \times 10^6 m^3 year^{-1}$ to $435 \times 10^6 m^3 year^{-1}$. The approach could have potential for localised water balance modelling in other Indian catchments.

Keywords: water scarcity, surface runoff, groundwater, SCS-CN method, rainfall infiltration, water level fluctuation, water requirement, water budget

INTRODUCTION

Almost one third of the global population lives under water scarce conditions (Alcamo et al., 2003, Arnell, 2004). Global climate change and rapid population growth coupled with rapidly increasing water demand exacerbate this problem and if present trends continue, by 2025 water scarcity will affect more than half of the world's population (UNESCO, 2007). To address water scarcity, metrics are required that demarcate the areas under water stress and several methods have been developed for this purpose locally, nationally and globally (Kummu et al., 2010). Examples at global and national level include *Falkenmark's index*, a measure of per capita water resources (Falkenmark et al., 1989), the *water vulnerability index,* which measures total annual withdrawals as a percentage of available water resources (Raskin et al., 1997), an availability index based on a normalized ratio of water demand to availability (Meigh et al., 1999) and the WATER GAP model (Alcamo et al., 2003, UNWWDR (United Nations World Water Development Report), 2003).

Such global assessments may not adequately portray local patterns of water scarcity, since they do not capture small scale spatial heterogeneity or take advantage of locally available data. Whilst water scarcity is a global concern, it can be addressed through micro scale planning (Falkenmark et al., 1989). Validation of water scarcity measures also becomes more feasible at more local levels. Despite this, particularly in lower middle and low income countries, water resource modeling is constrained by limited data availability, especially where catchments are ungauged or sparsely gauged (Xu and Singh, 2004). Under these circumstances, parameterisation and validation of models is challenging (Hrachowitz et al., 2013), making local-scale water resource assessment difficult (Xu and Singh, 2004).

Global assessments suggest that many states within India are considered water stressed (Kumar et al., 2005). Dakshinamurthy (1973) estimated water resources in India in relation to agricultural utilisation, whilst the National Institute of Hydrology quantified national Indian water resources in 1996 (Kumar et al., 1996). Climate-water resource interactions in India have also been investigated at national level for 2000 (Ramesh and Yadava, 2005). Despite this extensive literature on water availability in India, water demand relative to availability remains under-studied. All these studies show there is considerable local variation in water resource availability and use.

An overall water budget at the micro scale can help identify whether water scarcity is caused by limited water resources or by inappropriate use (Rijsberman, 2006), with demand management being an appropriate intervention in the latter case. Aside from demand management, local water budgets can be used to plan resource transfers from water-abundant catchments to water-scarce ones. In an Indian context, a programme of inter-basin transfers has been developed as a strategic planning initiative through the National Water Policy, enacted in 1997 and revised in 2002 (Thatte, 2007). Since under- or over-prediction in water budgets will affect planning of inter-basin transfers, this underscores the importance of local assessment of both water availability and requirements. Some earlier studies have examined this issue. For example, Bharati et al. (2009) described water supply and demand scenarios for the Krishna and Godavari basins, modeling transfers between these two basins. However, this study was designed to support water resource management, rather than quantify water demand in relation to available water resources.

The present study is a local level assessment of the water budget of the Lower Kasai-Keleghai interfluve in West Bengal, India, an area where inter-basin transfers are planned. The extent to which the interfluve is water stressed is contested. On the one hand, the West Bengal Government has developed inter-basin water transfer schemes to alleviate an apparent water resource deficit (Mukhopadhyay, 1987). Two inter-basin transfer projects, namely the Ganga-Damodar-Subarnarekha and Farakka-Sundarban schemes, are currently under construction by the National Water Development Authority of India to ensure uninterrupted water supply in a vast area that includes this interfluve (National Water Development Agency - Government of India, 2010). However, several previous studies suggested that monsoon precipitation (State Inter Agency Group-West Bengal, 2009) should result in considerable groundwater recharge or surface runoff. This study attempts to clarify this debate. The work presented here combines the SCS-CN model, previously used to model water resources in Indian catchments (e.g. by Mishra and Singh, 2004), with a water demand to availability ratio, broadly following the approach of Meigh et al (1999) at continental scale. In so doing, it combines a model that is widely used on the Indian sub-continent with an international approach to assessing water scarcity. The approach in our paper is intended to be one that could be implemented at a more local level in regions of low and middle income countries where water availability and demand data are scarce, but water resources are managed locally.

METHODS

Study Area:

The study area comprises an area of 2,585km^2 between the lower Kasai (Kangshabati or Cossaye) and Keleghai rivers (Figure 1) in West Bengal, India. This area is covered by 16 partial or entire administrative blocks within Purba and Paschim Medinipur district. A block is a geographic unit used in local government planning, with a typical population of 60000 to 70000 spread over 380 to 440 sq.km (Shetty and Ross, 1987).The Kasai River originates from the Jabourban hills (642 m altitude) of Purulia District and flows eastward through an undulating plateau before entering the study area.

Agriculture, a rapidly growing domestic sector, a relatively small industrial sector in the Medinipur-Kharagpur belt, and other activities like pisciculture all compete for water within this interfluve. The lower Kasai-Keleghai interfluve has a hot tropical monsoon climate, with a mean annual temperature over the past 60 years of 26.5°C and mean annual precipitation of 1275mm (Indian Meterological Department, 2010). Precipitation is concentrated in the monsoon season from mid-June to early October, averaging 1054mm.Over this period and post-monsoon seasons, temperatures range from 32°C to 47°C.The average monthly potential evapo-transpiration rate is 210mm.

Model overview

As shown in Figure 2, the water budget modeling comprises two main components, namely water resource availability, sub-divided into surface and groundwater resources, and requirements for major socio-economic sectors.

Given a reported decline in precipitation across India since 1998 (Koshy, 2009), data were acquired for the period 1998-2008 to characterize each of these components (Table 1).
The following sections describe the subsequent processing of these data sets within each model component.

Surface Water Resources

Surface runoff was estimated using the Soil Conservation Service Curve Number (SCS-CN) model (SCS national engineering handbook, 1956,1964,1971,1985,1993). We chose to use the SCS-CN model because it is well understood and has previously been applied to sub-humid areas of India (Subramanya, 2008), corresponding well with gauge data (Kulkarni et al., 2004, Mishra and Singh, 2004, Dadhwal et al., 2010, Sahu et al., 2012). It can thus produce satisfactory outputs for relatively sparsely gauged stations (Kulkarni et al., 2004).This approach includes as parameters soil texture, landuse/landcover, antecedent moisture condition, slope and rainfall to estimate surface runoff depth. The model was run separately for three catchments (Kapaleshwari, Churnia, and Bagui) demarcated from 1:50,000topographic maps and then results were summarised by administrative block. Daily precipitation data for six meteorological stations from1998 to 2008 were retrieved from the Indian Meteorological Department and interpolated to a regular grid using Inverse Distance Weighting.

The SCS-CN method is based on the water balance equation for precipitation over a known interval of time (Subramanya, 2008):

$$Q = \left(\frac{P - Ia}{P - Ia + S}\right) = \left(\frac{(P - \lambda S)^2}{\{P + (1-\lambda)S\}}\right) \text{for } P>\lambda S \text{ and } P>Ia. \qquad \text{.............Eqn 1}$$

Where P=Total Precipitation in mm/day, Ia = Initial Abstraction including evaporation and depression loss in mm/day, F = Cumulative Infiltration excluding Iain mm/day Q = Direct Surface Run-off in mm/day .λ S= area-specific fraction of Ia in mm/day

If P<Ia, then Q becomes zero.

Extensive measurements for small-sized catchments in India suggest λ should be between 0.1 and 0.3 depending on soil type. Based on this evidence, a value of 0.3 was used for the interfluve (Subramanya, 2008). The parameter S (potential maximum soil moisture retention) is a result of the complex interaction between soil, vegetation, landuse/landcover and Antecedent Moisture Condition (AMC) immediately prior to precipitation over the spatial unit. S (in mm) is expressed in terms of a dimensionless Curve Number (CN) as follows:

$$S = \left(\frac{25400}{CN}\right) - 254 \cdots\cdots \text{Eqn.2}$$

The constant 254 is used to express S in mm.

CN and AMC, expressing soil moisture conditions, are used interchangeably in SCS-CN modelling, which further distinguishes CN-I or AMC-I referring to dry conditions, CN-II or AMC-II to average conditions, and CN-III or AMC-III to wet conditions. Average moisture condition (CN-II) values were retrieved from a published CN table (Chow et al., 1988), based on land use / land cover and hydrologic soil group (Table 2). From these, CN-I and CN-III values were estimated using equations 3&4.

$$CN - I = \left(\frac{CN_{II}}{2.281 - 0.01281\,CN_{II}}\right) \cdots\cdots \text{Eqn.3}$$

$$CN - III = \left(\frac{CN_{II}}{0.427 + 0.00573\,CN_{II}}\right) \cdots\cdots \text{Eqn.4}$$

All CN numbers were then modified to account for slope (calculated from a DEM prepared by interpolating the spot height values from the Survey of India Toposheets (1:25000)) using the following equation (Kulkarni et al. 2004):

$$ModifiedCN - II = \left(\frac{1}{3}\right) \times \left(CN - III - CN - II\right) \times \left(1 - 2 \times EXP\left(-13.86 \times Slope\right) + CN - II\right) \cdots\cdots \text{Eqn.5}$$

These CN values were used to obtain runoff depth, which was multiplied by area to obtain runoff volume. For the entire procedure, the ArcCN-Runoff tool was used within the ARCGIS desktop environment (Zhan and Huang, 2004).

Groundwater resources:

Recharge from rainfall

Although the SCS-CN model can be used to estimate groundwater recharge, it was not used for this purpose here because the model's performance in predicting infiltration has been criticized (Chung et al., 2010).In particular, the model gives estimates for potential recharge (Thomas et al., 2000) instead of actual recharge. Following recent recommendations (Central Ground Water Board, 2009), we adopted two alternative approaches recommended for India (Ground Water Estimation Committee (GEC), 1997), namely the *Water Level Fluctuation* (WLF) method and the *Rainfall-Infiltration* (RI) method.

Groundwater recharge from rainfall in the monsoon season (June to October) was estimated by a combination of both WLF and RI methods. To estimate recharge by the WLF method, fluctuations in depth to groundwater pre- and post-monsoon were interpolated from state Surface Water Investigation Department (SWID) data for 105 measurement sites for 1998 to 2008. To calculate yield for different textural soil groups, recommended values from the SWID were applied to a soil group map published by the Indian National Atlas and Thematic Mapping Organisation (NATMO). These values were 0.4 for laterite, 1.2 for new alluvial soils and 0.2 for old alluvial soils. To account for inter-annual rainfall variation, the resultant recharge estimate for each year was normalized by the ratio of average rainfall over 1998 to 2008 to annual yearly rainfall per block, following GEC97 recommended practice:

$$R^{n}rfw = \frac{NR \times Wf \times Sy \times A}{AR} \text{........Eqn.6}$$

R^{n}_{rfw} = normalized runoff volume in $10^6 m^3$; NR = Normal or average monsoon rainfall in mm, AR= Actual monsoonal rainfall in mm for a given year; W_f = Monsoonal water level fluctuation in m;S_y = specific yield for different soil conditions; A = Area under each unit (m^2)

The RI method calculated annual groundwater recharge using the following expression:

$$R_{rf} = NMR \times Area \times RIF \text{..........Eqn.7}$$

WhereR_{rf} = Recharge after applying rainfall infiltration method NMR= Normal Monsoon Rainfall, RIF = Rainfall Infiltration Factor.

In our study, SWID-prescribed RIF values of 0.22 for alluvial soil and 0.06 for laterite soils were used.

For the final monsoonal groundwater recharge estimate from rainfall, WLF and RI method outputs were combined following GEC97 guidelines, which are based on empirical experience in India. The difference between the RI-based estimate and the WLF-based estimate is expressed as a percentage of the RI-based estimate (Chatterjee and Purohit, 2009). Where the two methods gave results that differed by less than 20%, the WLF estimate was used. Where the RI estimate exceeded the WLF estimate by more than 20%, the RI estimated was used but adjusted downwards by multiplying by 0.8.Where the WIF exceeded the RI estimate by more than 20%,the RI estimate is adjusted upwards by multiplying it by 1.2.Outside the monsoon season, the RI procedure only was used.

Recharge from other sources:
Groundwater recharge from sources other than rainfall (including return flows from irrigation, canal seepage, recharge from tanks and ponds, etc.) was estimated using annual block-level data provided by the state Surface Water Investigation Directorate (SWID).

Total recharge per CD block, net of natural discharge, was calculated by summing the groundwater recharge from rainfall and other sources for both monsoon and non-monsoon seasons. Natural discharge from groundwater was calculated as 10% of the non-monsoon total recharge for each block, again following guidance from GEC 1997 based on empirical experience in India. To avoid double-accounting, the natural discharge estimate derived via the GEC 1997 procedure was not used subsequently to adjust the SCS-CN run-off estimate.

Water Demand

Following many other previous water balance studies (Alcamo et al., 2003), water requirements from industry, agriculture and the domestic sector were estimated separately as follows:

Agriculture: As shown in Table 3, we used a normative model of agricultural water requirements, drawing on published annual irrigational water requirements for various crops (Rudra, 2006). Water requirement values were then multiplied with the net cultivated area per crop in each block, published by the state Bureau of Applied Economics and Statistics.

Industry: There is no consumption or geographic distribution data for the widespread small-scale industrial sector. Therefore, following (Van Rooijen, et al.2009), per capita industrial water demand was estimated from district-level statistics (Central Pollution Control Board (CPCB) Govt. of India, 1989, Van Rooijen et al., 2009) as 20 litres per capita per day. Since larger scale industry is concentrated exclusively in the Medinipur-Kharagpur industrial belt, which covers the Kharagpur-I, II, and Medinipur blocks, a total published water demand estimate of $14.24\times10^6 m^3 year^{-1}$ in this belt (Department of Environment- Govt. of West Bengal, 2011)was therefore divided equally between these three blocks.

Domestic demand: Water requirement norms were used to estimate domestic water demand for livestock and human consumption. The state government proposes a minimum daily domestic water requirement of 40 litres per person (Public Health and Engineering: Ministry of Water Resources (Govt. of India), 2007). We applied this requirement to population data at block level from the 2001 census of India (Govt. of India), projected over the period 1998-2008 using annual growth rate statistics. For livestock, a water requirement of 30 litres per day per cattle unit was applied to annual livestock numbers for each block, drawn from the state Department of Fishery and Animal Husbandry. This requirement was divided pro rata for livestock other than cattle, with one buffalo equivalent to two cattle units and two sheep equaling one cattle unit following a published livestock unit system (Kumar et al., 1996).

Water balance:

Water resources assessment is typically carried out using catchments as planning units, but sometimes also administrative boundaries (Alcamo et al., 2003, Arnell, 2004). Here, we used Community Development (CD) Block boundaries, since blocks are the main planning units in West Bengal and since much of the data used (e.g. groundwater discharge, population, agricultural area, etc) were available aggregated by CD Block. To calculate block level estimates of water balance, the catchment-based outputs for runoff were transformed to block level units through areal interpolation. We estimated water demand, renewable groundwater and surface water resources for each year over the period 1998-2008, as well as annual averages for this period.

Validation and Sensitivity Analysis

SCS-CN-derived estimates of run-off were validated against monthly discharge data for 1998-2008 for the single gauge station situated in the interfluve (shown in Figure 1), provided by the Irrigation and Waterways Department, Govt. of West Bengal. Current policy does not allow access to daily discharge data for research use. SCS-CN model performance was evaluated using two measures, namely Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970, Biggs and Atkinson, 2011).

We examined the sensitivity of water balance estimates to the choice of method for estimating groundwater recharge and to assumptions about natural groundwater discharge in non monsoon and water demand. We calculated water balance based on three different estimates of groundwater recharge, derived via the water level fluctuation method, the rainfall-infiltration method, and the GEC approach based on a combination of these two methods. We also evaluated sensitivity of model output to varying assumptions on natural groundwater discharge. Apart from the 10% assumption used in our model based on GEC 97, we also used published discharge estimates for similar Indian catchments. These estimates were no discharge (Maréchal et al., 2006), 1% (Umar, 2004), and 6% natural discharge (Massuel et al., 2007). We also explored the impact of varying assumptions about water demand based on the plausible range for the water required by different sectors. Irrigation requirement was changed based on the assumption modified for Aman paddy cultivation. Aman paddy being the most dominant crop in this region, was selected for the sensitivity analysis and irrigation requirements for the Aman crop were set to the upper limit of 600mm per year based on its range of irrigational water demand (table 3). Assumptions for urban domestic water requirement were changed following the methodology of Amarsinghe et al (2005). Under this alternative set of assumptions, domestic urban water consumption was assumed to be 135 litres per capita per day, but rural demand remained unchanged as after methodology given by Amarsinghe et al (2005) rural water consumption is also assumed to be 40 litre per capita per day. . In total, the combination of three different methods for estimating groundwater recharge and two sets of water demand assumptions gave six sets of estimates of the water resource availability to demand ratio.

RESULTS

Water resource availability:

Surface water availability

The spatial distribution of annual precipitation and average monthly variation in precipitation and potential evapo-transpiration (PET) are shown in Figure 3. Precipitation exceeds PET only in the monsoon period (Figure 3a), whilst precipitation varies comparatively little, but is lowest in the central eastern part of the study area (Figure 3b).

Figure 4 shows the depth of the surface water resources in each Community Development Block, which averages 358 mm per year across the interfluve. There is substantial variation in runoff between blocks. Generally, runoff is higher in the western area of the interfluve, showing correspondence with annual rainfall distribution (Figure 4.), whilst Pingla and Sabong blocks experience the lowest runoff. Annual runoff was greatest in 2001 (523mm) and lowest in 2005 (198mm).

Validation of runoff via the SCS-CN model against monthly gauge data produced an RMSE of 29.91mm, a Nash-Sutcliffe Efficiency of 0.67, and an $r^2$of 0.73 ($p<0.05$), suggesting an acceptable level of agreement between model output and monthly discharge.

Groundwater availability:

Figure 5 shows the estimated depth of groundwater recharge per CD Block, which varied by block from 16.52 mm per year to 64.23mm per year with a mean value of 41.97 mm per year over the interfluve.

Table 4 shows the annual variation in groundwater recharge, expressed as recharge coefficients relative to precipitation. Mean annual recharge depth is moderately correlated over space with the precipitation distribution ($r=0.59$; $p=.025$), but much more strongly correlated with precipitation over time ($r=0.92$, $p=0.002$), with recharge coefficients varying from 0.037 to 0.064.

Figure 6 shows the total estimated renewable water resources available by CD Block. Narayangarh and Bhagwanpur-I show the highest and lowest availability of water resources respectively.

Water resource requirements:

Table 5 shows the estimated water demand across the interfluve by CD Block. There is high irrigational water demand in the lower Kasai-Keleghai interfluve because of summer and winter rice cultivation there, alongside cultivation of potatoes, jute, and wheat etc. However, rice paddy cultivation dominates demand, accounting for almost 97.64% of the total irrigational water requirement of the interfluve. Overall water demand for irrigation dominates other forms of demand within the interfluve. Demand changed little from year to year, reflecting the use of constant normative water requirements and only gradual annual changes in cropping patterns, livestock, and projected population estimates.

Water Budget*:*

Figure 7 shows the average annual ratio of renewable water resource availability to requirements by administrative block for 1998-2008. The 8 blocks in the central and western parts of the interfluve, particularly Narayangarh, Kharagpur-I & II and Nandakumar are in water surplus, with the remainder in water deficit. Despite greater water resource availability per block in eastern areas, water demand is greater there creating a deficit overall. For example, Sabong block has the highest water resource availability if the blocks situated at the eastern part of the interfluve is concerned, yet has a water deficit of $116.47\times10^6 m^3 year^{-1}$. Water demand was however correlated with supply ($r=0.68$; $p=0.091$).

Overall, the study shows that the interfluve has substantial spatial variation in its water resources and their requirements. Although 50% of the blocks in the interfluve are in water deficit, the interfluve has on average an overall water surplus of $327.05\times10^6 m^3 year^{-1}$ for 1998-2008. However, within this period, there were two deficit years, 2002 and 2005, when the interfluve's water deficit was $-84.9\times10^6 m^3 year^{-1}$ and $-175.7\times10^6 m^3 year^{-1}$ respectively. The peak surplus ($940.7\times10^6 m^3 year^{-1}$) was experienced in 2001.

Sensitivity Analysis

Evaluation of model sensitivity (Table 6) generated estimates of the interfluve's overall water budget that varied from $-215.63\times10^6 m^3 year^{-1}$ to $483.13\times10^6 m^3 year^{-1}$ in response to different assumptions about water demand, varying assumptions about natural groundwater discharge and different methods for calculating groundwater recharge. Reducing the rate of natural groundwater discharge on the basis of published estimates increased the surplus water balance overall. The groundwater recharge estimate derived via the RIF method generated an estimated overall water deficit for the interfluve relative to some demand scenarios. Thus, the analysis indicates that the interfluve's overall water budget was less sensitive to the assumptions made about water demand than to the method of groundwater recharge calculation.

DISCUSSION

India is considered to be water scarce (Arnell, 2004)with an expanding and increasingly affluent population and agro-industrial expansion adding to demands on water resources affected by uncertain monsoonal rainfall. West Bengal is also considered water scarce (Centre for sustainable production and consumption (C-SPAC), 2005). Inter-catchment water transfers are planned in West Bengal to meet demand in water scarce areas using resources from water abundant ones. To meet development and economic goals, uninterrupted water supplies remain a target even in remote places. However, relatively little attention is paid to over-exploitation of this precious resource. In a water balance study, Rudra (2006) found agriculture to be the major source of water demand in West Bengal and if this was controlled, the state could still achieve self-reliance over water resources. Thatte et al (2007) noted that for India nationally, agriculture accounted for 83% of water requirements with just 4% each required for domestic purposes and industry. The present study supports these earlier findings for a small spatial unit, with agriculture dominating water requirements, followed by the domestic and industrial sectors.

Limited data availability regarding water resources hinders planners from linking availability estimates with requirements and therefore longer-term strategic planning. This is specifically the case in ungauged or sparsely gauged basins in West Bengal, where there are little or no observations of spatially variable hydrological parameters. Since implementation and maintenance of water management systems are expensive, in a setting like West Bengal, where public funds are limited, management decisions must be made after careful analysis of the existing resources and demand trends. All these factors together mean research to quantify water resources is a priority. The overall water balance sheet for the interfluve shows that it has $327.05\times10^6 m^3 year^{-1}$ of water in surplus. In theory given this surplus, an internal redistribution of the total water resources of the interfluve according to block-level water demand would alleviate water scarcity. However, sometimes even a demand to resource availability greater than 20% is considered an indication of water scarcity (Meigh et al., 1999)and according to such a threshold almost all the interfluve would be considered water scarce. Given also that this water resource may not be sufficient to ensure the future sustainability of the region (Public Health and Engineering: Ministry of Water Resources (Govt. of India), 2007), the current focus on inter-basin transfer through the National Water Policy seems justified in this area, if coupled with agricultural demand management. The government is encouraging expansion of water holding capacity in the form of ponds and reservoirs (Ministry of Environment and Forest-Government of India, 2012). Given that two water deficit years were experienced from 1998-2008, this strategy for carrying forward stored water from wet years into subsequent dry years seems justified.

In India, several studies have assessed the availability or demand for water resources (Kumar et al., 1996, Rudra, 2006), but few have considered the balance of the two at local level. For example, some previous studies have quantified surface runoff or groundwater recharge, but not demand (Chatterjee and Purohit, 2009).Conversely, studies of water demand in India have usually focussed on actual quantities of water abstracted by the different sectors(Kumar et al., 1996, Reddy, 2009), rather than normative estimates for domestic and agricultural demand as used in the assessment here. These studies are useful to understand the present nature of water resource exploitation, but they do not take into account the *need* for water as opposed to current *use* patterns. Unlike normative demand estimates, current abstraction patterns may reflect over-exploitation of water and thereby mask a need for water demand management.

Limited validation of SCS-CN output against monthly discharge data from a single gauge station suggested the model's performance was acceptable. This confirms the findings of previous studies in India, which found the model's performance to be acceptable. A sensitivity analysis suggested that the water balance model is less sensitive to the demand and natural groundwater discharge assumptions than to the method for estimating groundwater recharge. A previous sensitivity analysis of a coarse spatial resolution Indian water balance model (Singh and Patwardhan, 2010) suggested that the choice of input meteorological data gave the most pronounced variation in water balance, implying that future work on the approach described here may examine the model's sensitivity to choice of input data subject to data availability.

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There are several weaknesses to this study of the water balance of the interfluve, which would affect its uptake elsewhere. Firstly, the SCS-CN model used to estimate run-off has several recognized weaknesses, namely its inability to account for rainfall intensity, with different storm events in a given catchment generating different runoff patterns even under similar antecedent moisture conditions (Ponce and Hawkins, 1996, Michel et al., 2005). There has also been concern that it does not capture the scale-dependent nature of precipitation-runoff relationships, which may differ between equivalent secondary and tertiary catchments, for example (Soulis and Valiantzas, 2012). The potentially arbitrary basis for setting parameters such as Initial Abstraction Ratio and AMC, and poor performance in predicting groundwater recharge have also been criticised (Ponce and Hawkins, 1996). As such, this study only examines annual and not seasonal variation in water scarcity. Given this latter issue, we used the GEC 1997 procedure to estimate groundwater recharge rather than the SCS-CN model. However, whilst the GEC 1997 approach is presumed to be based on empirical experience, the published report (Central Ground Water Board, 2009) does not present data to justify the approach to reconciling recharge estimates and estimating natural discharge.

In some cases, particularly concerning groundwater fluctuations, we relied on historic, cross-sectional data, which may not reflect the current status of groundwater replenishment and more generally, it was difficult to identify available data from a consistent time period to measure all components of the water balance model. Agricultural and domestic water demand was assessed based on normative water requirements rather than actual withdrawals and the actual pressure on water resources may differ from this. In the absence of more detailed data, we assumed that small-scale industrial water demand was distributed according to population across the study area and ignored intra-block variation in water demand, which may not portray the actual situation. Aside from industrial, domestic and agricultural demand, recently there have been attempts to measure environmental water requirements - in other words, the water resource needed to protect an ecosystem and its possible restoration if required (Smakhtin et al., 2004). Our study ignores such environmental water requirements, given the considerable data availability challenges in estimating demand for the other three sectors.

In extending the work presented here, the sensitivity analysis could be expanded to assess the impact on water balance estimates of choice of elevation or precipitation data sets, and to assess the impact of SCS-CN model parameterisation. Apart from an enhanced sensitivity analysis, the transferability of the methodology could be assessed through the study of other Indian catchments where inter-basin transfers are being considered. The approach could also be extended to predict the future water balance for the study area, based on predicted land use, population, and climate changes for example.

CONCLUSION

This study assessed the potential of an interfluve to be self-sustaining in terms of water resources. In a context of limited data availability, three practical, widely used models of runoff and groundwater recharge were combined with a largely normative approach to estimating water requirements and used to analyse the water budget at a local level. The assessment revealed that though the interfluve is in water surplus, this may not be sufficient to attain sustainability in the region as many parts of the interfluve are in deficit. This confirms the necessity to import external water resources into the interfluve in the future. The outputs are expected to help planners identify the underlying potential of a region to be self-sustaining in its water resource use and conserve an over-exploited water resource to achieve sustainability for future use. The methodology could be implemented in other similar catchments across India.

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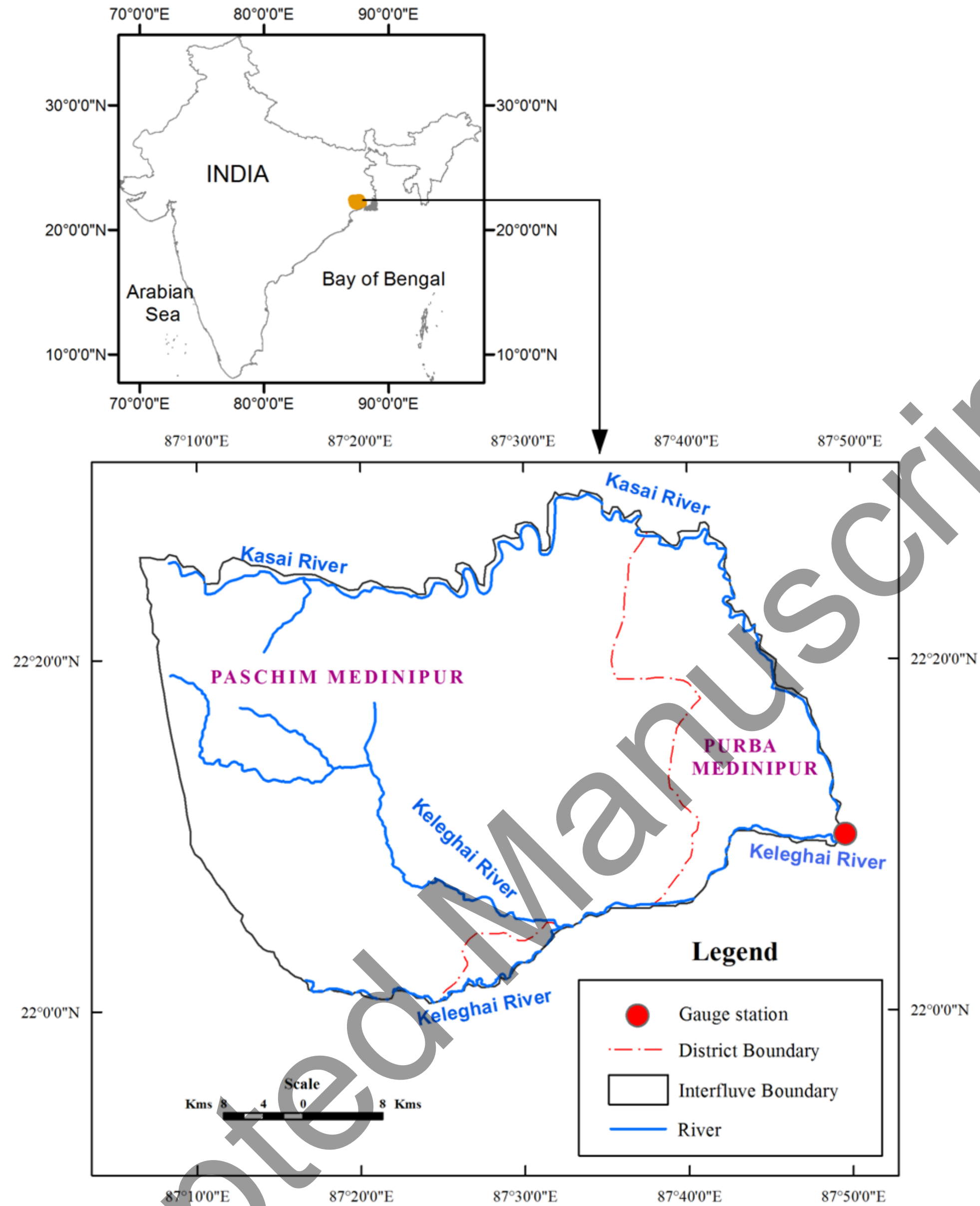


Figure 1. Administrative map of the lower Kasai-Keleghai Interfluve and its location within India

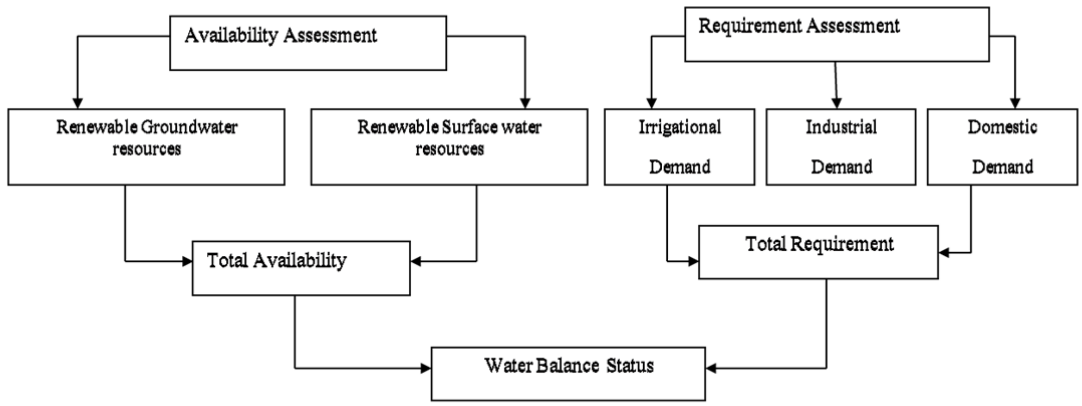
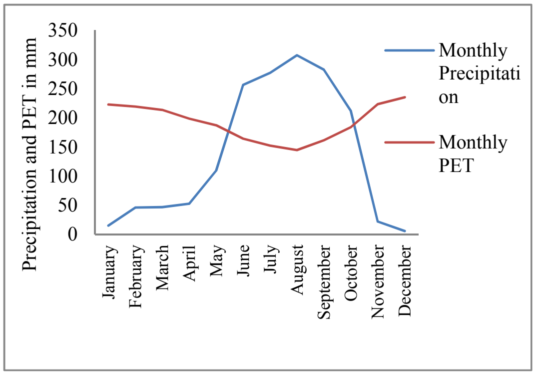


Figure 2. Overview of methodology for estimating catchment water balance



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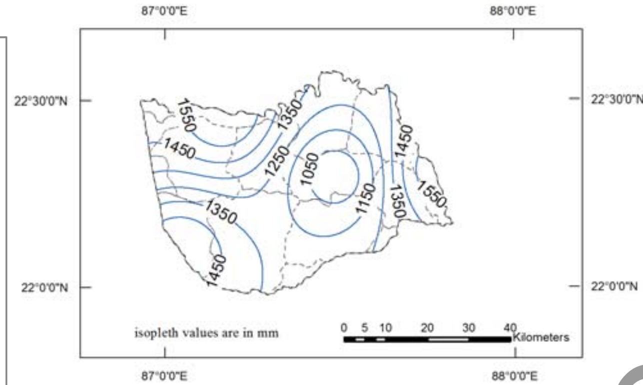

b.

Figure 3.a.long-term monthly precipitation and potential-evapotranspiration (PET) for the study area **b.** Spatial distribution of long-term annual precipitation

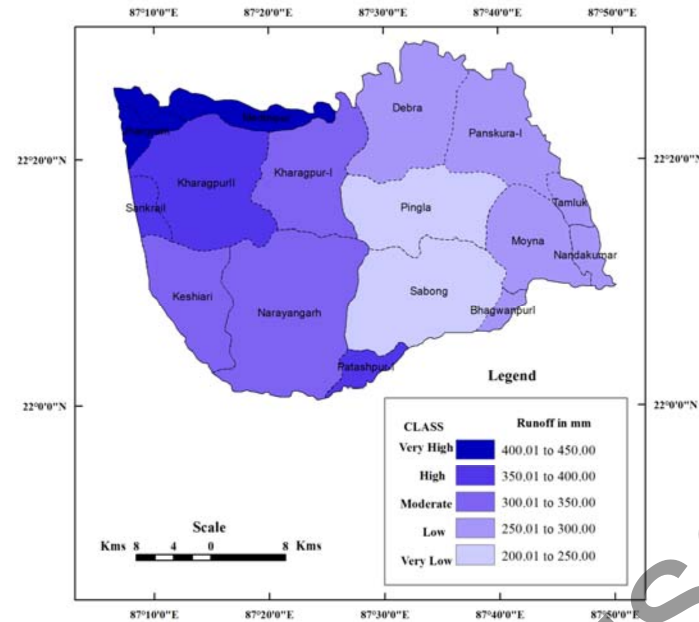

Figure4. Mean annual renewable surface water resources by block for 1998-2008

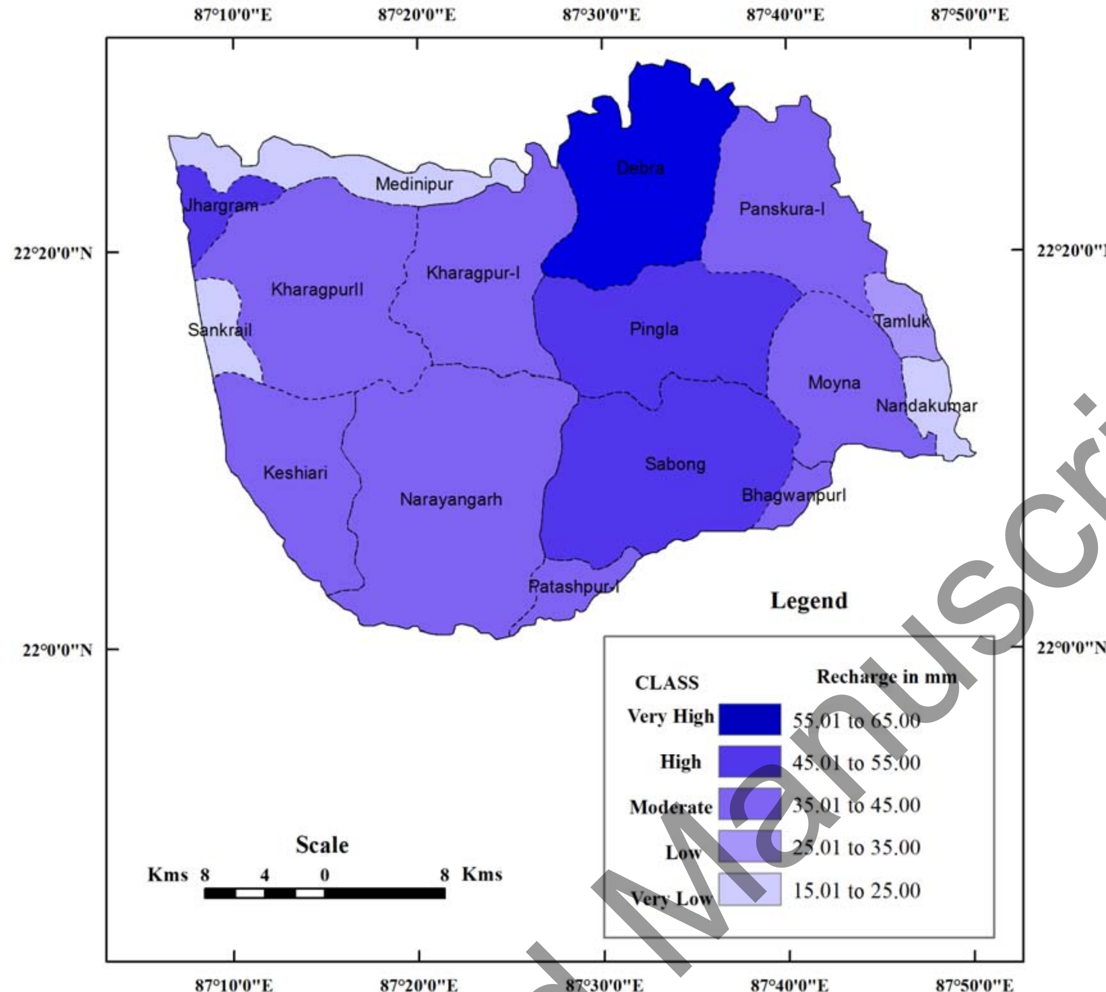

Figure 5. Mean Annual Depth of groundwater recharge (mm/year)by block for 1998-2008

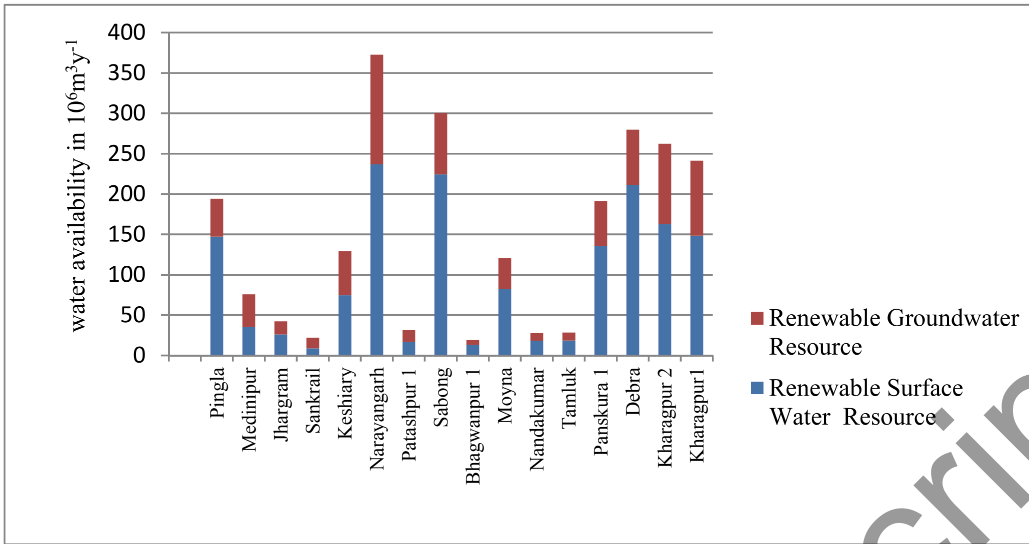

Figure 6. Block level distribution of mean annual total water resources for 1998-2008

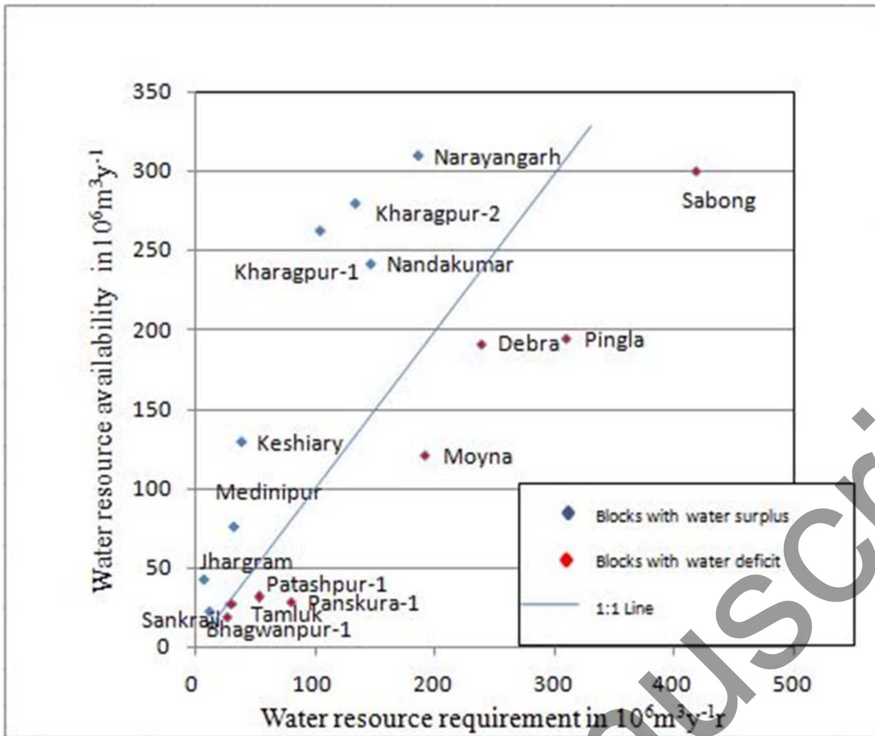

Figure7. Average annual balance between water requirements and availability per block, showing water surplus and deficit for 1998-2008

Table 1. Data sources used to characterize the interfluve's water balance

Types of data	Years of information	Source	Model component
topographical sheet	1974	Survey of India	Surface water assessment
Monthly discharge for 1 gauge station	1998-2008	Irrigation and Water ways Department	Surface water assessment/validation
Soil Textural Data	N/A	NATMO, Govt. Of India	Surface water assessment
Daily Climatic data	1998 to 2008	Indian Meteorological Department and Agro-Meteorological Department, Govt. Of India	Surface water assessment & Dynamic Groundwater assessment
Monthly climatic average data	1950-2010	Indian Meteorological Department and Agro-Meteorological Department, Govt. Of India	PET estimation and rainfall map generation
Geological Information	N/A	Geological Survey of India	Dynamic Groundwater assessment
Groundwater structure	2007	Irrigation and Water ways Department	Dynamic Groundwater assessment
Annual fluctuations in depth to groundwater	1998 -2008	Surface Water Investigation Directorate	Dynamic Groundwater assessment
Geo-lithological Information	2009	Central Groundwater Board	Dynamic Groundwater assessment
Crop Water Requirement	N/A	Irrigation and Water ways Department	Irrigation requirement assessment
Cropped area	1998-2008	State Bureau of Applied Economics and Statistics	Irrigation requirement assessment
Livestock Data	1998-2008	Animal Husbandry	Domestic requirement assessment
Population data	2001	Census of West Bengal	Domestic and industrial requirement assessment

Table 2.CN values used for the study (Adapted from (Chow et al., 1988))

Description of Land Use	Hydrologic Soil Group			
	A	**B**	**C**	**D**
Cultivated (Agricultural Crop) Land*:				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Woods and Forests:				
Poor (small trees/brush destroyed by over-grazing or burning)	45	66	77	83
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77
Open Spaces :				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84

Table 3. Irrigational Water Requirement for Crops (source: Department of Irrigation and Waterways, Govt. of West Bengal, 1987)

Crop	Aus	Aman	Boro	Wheat	Potato	Jute	Pulses	Oil seed
Water-Requirement excluding utilisable rainfall (in $10^{-3}mKm^{-2}y^{-1}$)).	300-450	300-600	1400-1600	400-450	400-450	200	250	250-300

Table 4. Temporal response pattern of groundwater recharge to precipitation

Years	Annual Precipitation in mm	Annual Recharge in mm	Recharge Coefficient
1998	1311.00	84.73	0.06
1999	1265.39	55.09	0.04
2000	1338.77	80.79	0.06
2001	1584.52	102.26	0.06
2002	879.94	33.15	0.04
2003	1192.00	68.11	0.06
2004	1390.46	86.87	0.06
2005	799.28	44.76	0.06
2006	923.80	56.42	0.06
2007	1423.00	86.58	0.06
2008	1227.06	71.74	0.06

Table 5. Blockwise mean water resource requirements in $10^6 m^3 year^{-1}$ in the interfluve for 1998-2008

Name of the blocks	Irrigational Water requirements	Human water requirements	Livestock water requirements	Industrial Water Requirements	Total water requirement
Pingla	303.39	3.45	1.34	1.73	309.91
Medinipur	23.79	2.15	0.55	5.81	32.30
Jhargram	6.90	0.33	0.12	0.17	7.52
Sankrail	11.70	0.28	0.16	0.14	12.28
Keshiary	35.61	1.73	0.67	0.86	38.87
Narayangarh	176.92	4.92	1.78	2.46	186.07
Patashpur 1	53.15	0.69	0.22	0.34	54.40
Sabong	408.18	4.86	1.69	2.43	417.15
Bhagwanpur 1	25.84	0.50	0.12	0.25	26.71
Moyna	185.43	3.52	0.83	1.76	191.54
Nandakumar	29.42	1.02	0.21	0.51	146.63
Tamluk	79.24	1.25	0.16	0.62	31.16
Panskura 1	229.23	5.22	1.35	2.61	81.27
Debra	126.53	3.84	1.43	1.92	238.42
Kharagpur 2	92.81	3.53	1.55	6.51	133.73
Kharagpur1	126.46	9.85	0.65	9.67	104.40

Table 6: Sensitivity of annual water balance estimates in response to different assumptions about water demand and methods of groundwater recharge estimation (all values in $10^6 m^3 year^{-1}$)

Groundwater recharge model	Demand assumptions	Availability	Requirement	Surplus/Deficit	Maximum Demand per block	Maximum Availability per block	Minimum Demand per block	Minimum Availability per block
GEC 1997 (*)	Normative requirements (*)	2339.41	2012.36	327.05	417.15	372.68	7.52	19.16
GEC 1997	Changed requirements	2339.41	2219.75	119.66	426.32	372.68	11.56	19.16
Water level fluctuation method	Normative requirements	2447.78	2012.69	435.09	417.15	389.97	7.52	37.34
Rainfall infiltration method	Normative requirements	2004.12	2012.36	-8.24	417.15	321.69	7.52	16.12
Water level fluctuation method	Changed requirements	2447.78	2219.75	228.03	426.32	389.97	11.56	37.34
Rainfall infiltration method	Changed requirements	2004.12	2219.75	-215.63	426.32	321.69	11.56	16.12
GEC 1997 with Natural Discharge=0%	Normative requirements (*)	2495.49	2012.36	483.13	417.15	396.44	7.52	20.48
GEC 1997 with Natural Discharge =0%	Changed requirements	2495.49	2219.75	275.74	426.32	396.44	11.56	20.48
GEC 1997 with Natural Discharge =1%	Normative requirements (*)	2478.33	2012.36	465.97	417.15	393.83	7.52	20.33
GEC 1997 with Natural Discharge =1%	Changed requirements	2478.33	2219.75	258.58	426.32	393.83	11.56	20.33
GEC 1997 with Natural Discharge =6%	Normative requirements (*)	2392.49	2012.36	380.13	417.15	380.82	7.52	19.60
GEC 1997 with Natural Discharge=6%	Changed requirements	2392.49	2219.75	172.74	426.32	380.82	11.56	19.60

(*) indicates the default method and assumptions used