A quantitative framework for estimating water resources in India

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While issues related to water attract considerable attention in all spheres of life in India, very little quantitative information is available on the water budget of the country. There are primarily two reasons for this lacuna: first, the dearth of information on the variables associated with hydrology, and second, the absence of an easily accessible quantitative framework to put these variables in perspective. In this article, we discuss a framework that has been assembled to address both these issues. At the core of the framework is a hydrological routing model (HYDRA)[1,2] that has been used to study the water balance of basins on various scales, ranging from a few square kilometres to continents. The basic data needed for implementing the framework are a suitable digital elevation model (DEM) and data on precipitation and evapotranspiration. Available discharge data can be used to validate the performance of the model.

We demonstrate the viability of the framework by applying it to the hydrology of the Mandovi river on the western slopes of the Sahyadris; it is typical of the rivers along the Indian west coast. Most of the catchment area of the river is in Goa, but parts of the river also flow through Karnataka and Maharashtra. We use a 30″-resolution (~ 1 km) DEM (GLOBE)[3] and HYDRA to show that the model output mimics the observed discharge well, providing indirect validation for the surface run-off and sub-surface drainage values on which no data are available.

FROM ancient times, rivers have been the cradles of civilization. Most civilizations have sprung up in fertile river valleys, which provided freshwater, an essential requisite for the growth of settlements. The freshwater in rivers has its source in precipitation and in the seasonal melting of snow; therefore, rivers are subject to the vagaries of weather and climate. Though periodic scarcity of water and its impact on life due to changes in weather and climate has been felt several times in recorded history[4,5], the problem of water resources is much more acute today owing to the manifold increase in our need for water over the last few centuries, beginning with the Industrial Revolution; the Green Revolution in the 1960s led to another major increase in the use of water for growing the new hybrid crops. Coupled with the exponential growth in population, this has put available water resources under severe stress. Evidence from palaeoclimatology and archaeological and historical records shows that man responds to scarcity of water in a variety of ways[4,5], which include strategies for water conservation, rainwater harvesting, and when inevitable, migration.

India, as one of the countries affected by both population explosion and the Green Revolution, hardly sees a day without some problem related to water figuring in the news. The problems are twofold[5–9]. First, there is the problem of scarcity, resulting in drought or famine; second, there is the problem of surplus (mostly during the summer monsoon, when most of India receives almost 80% of the annual precipitation), resulting in floods. It is also evident that certain regions of the country, especially in the south and northwest, are more prone to drought, while other regions, especially in the east and northeast, are more prone to floods. With each disaster comes the clamour for some long-term solution. One solution that has been proposed is the transfer of water, through the medium of a network of canals, from river basins with a surplus (mostly the rivers in the north and northeast) to river basins with a deficiency[6,10] (mostly in the south and northwest). This idea received a major boost last year following one of the worst droughts of the century[11].

The financial implications of networking rivers over an area of the size of India (Figure 1) are enormous: a tentative estimate for this project is Rs 5,60,000 crores[10]. Commissioning a project of such magnitude and then executing it successfully will require a vast database on hydrology and a framework that can use the data to quantify the water budget for each river basin. This apart, given the pressure that exists on the resources of freshwater, there is an urgent need to evolve better, sustainable strategies for managing the country’s water resources. This, in turn, requires hard data on the basis of which decisions can be made: we need quantitative estimates of water budgets for the river basins at a resolution small enough for evolving strategies for, say, an average Indian district, yet large enough to make possible an estimate of water resources on the scale of the Indian subcontinent.

The estimates of water resources available in India today are often on too small a scale, like a small watershed, or are on too large a scale, like gross statistics based on the average precipitation over the entire country and the measurements made at a few stream-flow gauges on major

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rivers and in the neighbourhood of some dams[6,9,12–16]. For individual river basins, the tendency has been to adopt an empirical systems approach[6,17] to facilitate the generation of information critical for planning in agriculture[18–20] or for managing large dams like the Bhakra[15]. What is lacking is an overview that provides a reliable quantitative estimate of the water resources of the country. There are two reasons for the absence of such estimates. First, there is a dearth of information on the basic hydrological variables of interest – groundwater recharge rates, stream-flow, evapotranspiration, etc. Only precipitation data have been collected systematically over a long period; evapotranspiration data are scanty[21]; stream-flow data are confined to a few rivers, and are often not easily accessible[10,22]. Second, a quantitative framework that can put these variables in perspective is often missing. Though several hydrological software packages are available, Indian academic institutions are reluctant to invest in them because these packages are usually expensive and are geared to handle situations in developed countries where the hydrological databases are much more advanced. These packages are oriented toward understanding the hydrology of small systems: catchment area of a small river, hydrology of a city, etc. They also rely too often on commercial GIS (Geographical Information Systems) packages, which are expensive for Indian academic institutions. Hence, in view of the present state of continental-scale hydrology of the subcontinent, it seems that what is needed today is a quantitative framework that satisfies the following conditions.

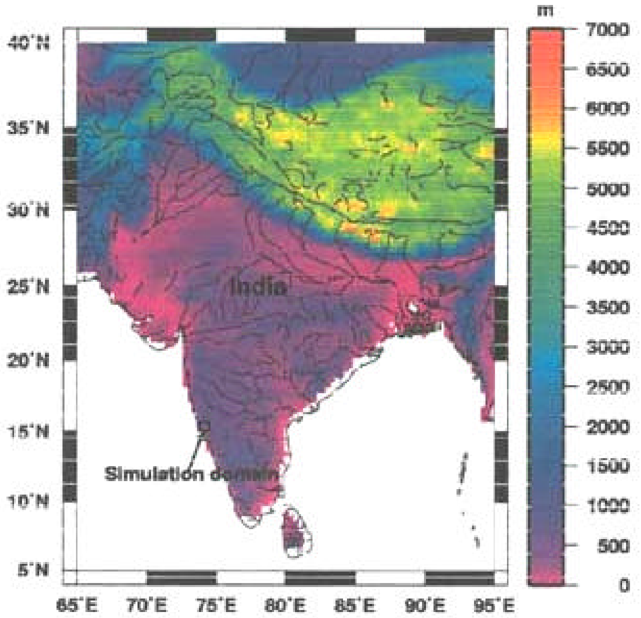

Figure 1. Relief of the Indian subcontinent (in metres above mean sea level) based on the 20′ (~ 33 km) ETOPO20 data. The tiny square on the west coast is the domain for which the simulations in this article are reported.

(i) The framework should include a simple hydrological model that can provide a reliable water balance of a river system.
(ii) Demands on the database required by the model should be consistent with the realities in the country.
(iii) The packages that incorporate the model should be able to handle a range of spatial scales, from small rivers to continental scales, to enable many groups working independently on different river basins to dovetail their analyses into a coherent picture on the larger scale.
(iv) The models and their ancillary software should be freely accessible.

In this article, we assemble tools to meet the above requirements. This has become possible because of recent advances in climate modeling and remote sensing, and the availability of high-speed processors on a desktop computer, all the work reported here was done on a desktop PC. At the core of this framework is a hydrological routing algorithm (HYDRA)[1,2] that, given the distribution of local precipitation and evapotranspiration, can route the run-off to its destination, the sea or an inland lake. HYDRA is highly scalable: it has been used to model the water balance of basins on various scales, ranging from a few square kilometres (Michael Coe, pers commun, 2003) to continents[1,2]. The basic data required by the model are a digital elevation model (DEM) that maps the topography on the required scale, and data on precipitation and evapotranspiration. DEMs on a range of scales, from 1° latitude and longitude (ETOPO60) to ~ 1 km (GLOBE)[3], are now available through satellite remote sensing. Data on evapotranspiration are available from climate models and atmospheric general circulation models (AGCMs); an example is the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Reanalyses[23] dataset. These models also provide continuous (in both space and time) precipitation data, permitting an estimate of local run-off even in regions without direct precipitation measurements; the hydrological models, in turn, serve as a stringent test to evaluate the performance of these AGCMs[1]. For analysing the model results, a powerful tool is a GIS, because the variables associated with hydrology are inherently geographical. We choose the GRASS (Geographical Resource Analysis Support System) GIS[24], preferring it to other available GISs because it meets the requirements listed above. It is freely available, contains several software modules for hydrology, which can be modified to suit our needs (because the source is available), and has been used as the GIS for the GLOBE DEM.

We first describe this framework and then demonstrate its viability by applying it to a river basin. Our choice for testing the framework is the Mandovi river (also called Mahadayi and Mhadei over some stretches), which has its

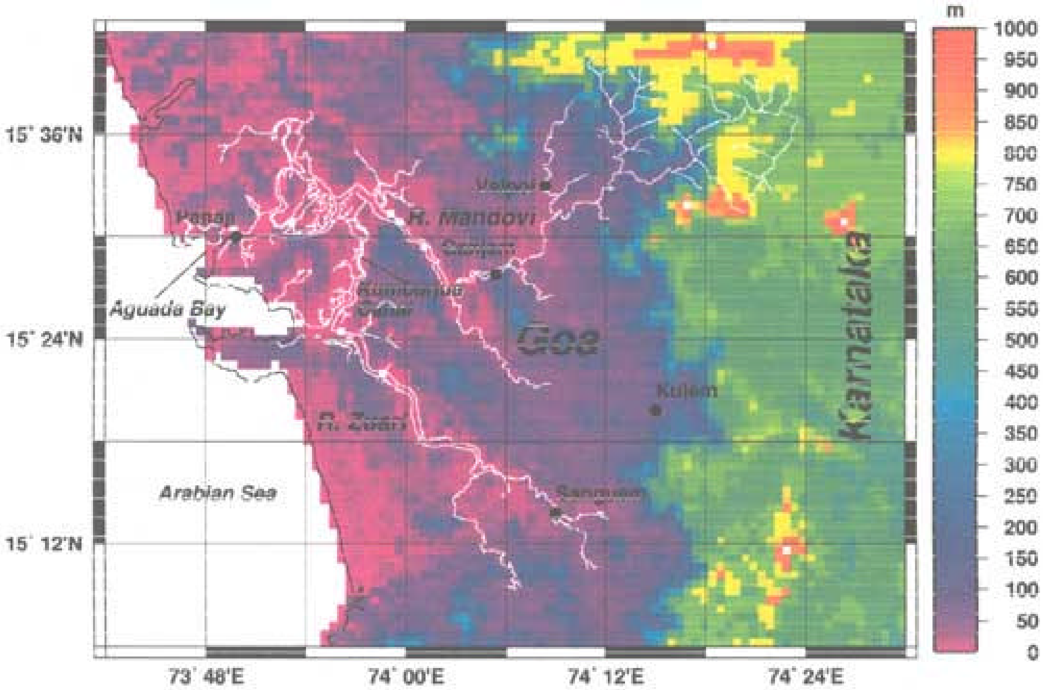

Figure 2. Topography of the region, as seen in GLOBE data (after editing the DEM). Superimposed rivers were digitized from the maps of the Survey of India. The domain of the simulations described here lies mostly in Goa. The Mandovi and the Zuari are two main rivers of Goa. The Mandovi flows into the Aguada Bay near Panaji, the capital of Goa and the location of its main meteorological observatory. A stream-flow gauge is located on the Mandovi at Ganjem; Valpoi has the easternmost rain gauge in Goa, but data for 1959 from Kulem, farther east, are available for 1959 (ref. 31).

source in the Sahyadri range and flows into the eastern Arabian Sea (Figure 2). Its catchment area is mostly in Goa, but also extends into the neighbouring states of Karnataka and Maharashtra. This choice is dictated by the following considerations. First, being one of the two rivers that flow past Panaji, the capital of Goa and the location of the National Institute of Oceanography, it is one of the best-studied estuarine stretches in India, and is typical of the rivers along the west coast of India. Second, it is a small river, with a channel width less than 1 km over much of its 105 km length, thus providing a rigorous test of the DEM's accuracy: a DEM that works in this region should also work elsewhere in India. Third, discharge data are available for the Mandovi at one point, about 50 km from the mouth, making it possible to validate the framework. We conclude the article by discussing the potential of this quantitative framework for quantifying the water resources of India.

Description of the quantitative framework

The hydrological routing algorithm we use is called HYDRA[1]; it was developed at the Center for Sustainability and the Global Environment (SAGE: http://www.sage.wisc.edu/), University of Wisconsin. HYDRA uses a linear reservoir model to transport local surface run-off and sub-surface drainage (or baseflow) through a river network to its destination, the sea or an inland lake. The linear reservoir model simulates water transport in terms of local flow directions derived from the local topography, residence times within a grid cell, and effective flow velocities.

A potential river drainage basin is defined as the sum of the area of all grid cells potentially draining through a common outlet to the ocean. HYDRA uses the DEM to compute local flow directions for each grid cell. It uses the elevation and local flow directions in an iterative procedure to do this; the procedure also identifies the lakes and wetlands that form a part of the watershed[1,2].

The total water entering the hydrologic network at each grid cell is the sum of the land surface run-off (R_s), subsurface drainage (R_d), precipitation (P_w) and evaporation (E_w) over surface waters, and the flux of water from upstream grid cells[1] ($\sum F_{in}$). The water transport is represented by the time-dependent change of three water reservoirs. The first is the river water reservoir (W_r), which contains the sum of upstream and local water in excess of that required to fill a local surface water depression; the second is the surface run-off pool (W_s), which contains water that has run-off the surface locally and is flowing towards a river; and the third is the sub-surface drainage pool (W_d), which contains water that has drained through the local soil column and is flowing towards a river. All three reservoirs are represented in m^3 and the run-offs and precipitation and evaporation in $m^3 s^{-1}$. The flow is governed by the following ordinary differential equations:

$$\frac{dW_s}{dt} = R_s - \frac{W_s}{T_s}$$

$$\frac{dW_d}{dt} = R_d - \frac{W_d}{T_d}$$

$$\frac{dW_r}{dt} = \left(\frac{W_s}{T_s} + \frac{W_d}{T_d}\right) \times (1 - A_w) + (P_w - E_w) \times A_w - \frac{W_r}{T_r} + \sum F_{in}.$$

Here A_w is the fractional water area in a grid cell: from 1 (lake, wetland, or reservoir covering the entire cell) to 0 (no water present). T_s, T_d, and T_r are the residence times of water in each of the three reservoirs. The first two are set to constant values for simplicity. The stream flow residence time, T_r, is defined as the ratio of the distance between the centres of the local and downstream grid cells (a function of the DEM resolution) and the effective velocity of water; the effective velocity is parameterized differently for grid cells with and without wetlands or standing water (see Coe[1] for more details). The model equations are integrated forward in time using an explicit differencing scheme. HYDRA requires the following inputs: a DEM to map the topography, surface run-off and sub-surface drainage for each grid cell, and precipitation and evaporation over and from water bodies like lakes or wetlands (if present).

Coe[1,2] used a DEM that gives the relief of the earth's surface on a 5′ (~9 km length scale) and used the run-off from the NCEP/NCAR Reanalyses[23], which partition the local run-off (local precipitation minus evapotranspiration) into surface run-off (30%) and sub-surface drainage (70%). The simulations of Coe[1] were global: all major rivers were modelled. A comparison of the results with observed discharges proved that HYDRA is a powerful tool for simulating terrestrial hydrology.

Application to the Mandovi river in Goa

The Mandovi is one of the two major rivers located in Goa, the other being the Zuari (Figure 2). The two rivers are connected by a narrow channel, the Kumbarjua Canal[25]; many tributaries also feed into the two rivers. The Mandovi, the Zuari, the Kumbarjua Canal, and the tributaries form a network. The cross-sectional area of both rivers decreases rapidly upstream[25]. Tidal influence is felt in the Mandovi just a little downstream of Ganjem (Figure 2), approximately 50 km inland, during the dry season[25]. The estuarine stretches (where at least some salinity intrusion occurs during the dry season) receive freshwater primarily from rivers that originate in the Sahyadris (or Western Ghats), but there is additional inflow at several points along the main channels. A stream-flow gauge is located on the Mandovi at Ganjem, just upstream of the limit of tidal and salt incursion.

The Indian west coast is one of the two regions of precipitation maxima in the north Indian Ocean (Figure 3). Most of the precipitation in this region is during the summer monsoon (June–September), which peaks in July. The run-off in the rivers flowing down from the Sahyadris follows the same pattern (Figure 4): the rivers are flushed by a run-off that is over 25 times the basin volume during June–September, and the run-off during December–May is two orders of magnitude smaller.

The small scale of the Mandovi, which is much less than 1 km wide over much of its course, makes the ETOPO relief data unsuitable for our purpose. Hence, we use a new DEM that has become freely available and has a much finer resolution: GLOBE[3] (Global Land One-kilometer Base Elevation; see the GLOBE website http://www.ngdc.noaa.gov/seg/topo/globe.shtml for more

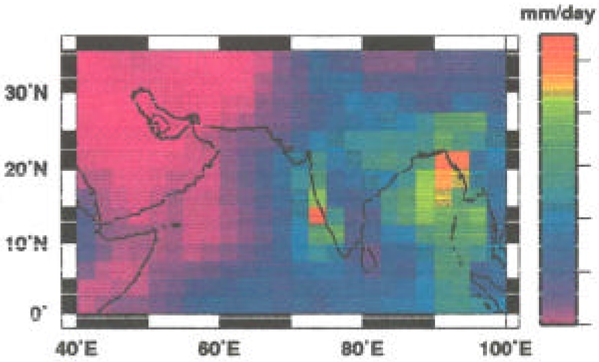

Figure 3. Climatology of precipitation over the north Indian Ocean in July[40]. Climatology is defined over 1979–98. One of the two precipitation maxima lies along the Indian west coast and the adjoining eastern Arabian Sea.

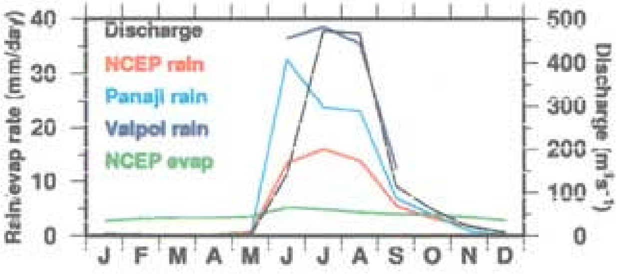

Figure 4. Climatology of observed precipitation and evapotranspiration (mm/day) and discharge ($m^3 s^{-1}$) in the Mandovi basin. Climatologies are defined over 1980–87. Precipitation data are from the NCEP/NCAR Reanalyses[23] and from the rain gauges at Panaji and Valpoi. Evapotranspiration data are from the NCEP/NCAR Reanalyses. Discharge was measured at Ganjem.

information) has a 30″ (~1 km) resolution. The topography of the region, as seen in the GLOBE data, is shown in Figure 2; the superimposed rivers were digitized from Survey of India maps and the good match shows that the GLOBE DEM is able to capture the watershed geometry well. The elevation data are used to determine the local flow directions for each grid cell. Once the basin geometry is defined, HYDRA can be forced by prescribing the surface run-off and sub-surface drainage at each grid cell and integrating forward in time. For the GLOBE DEM used here, the model time step is 5 min.

We force the model with the precipitation and evapotranspiration data from the NCEP/NCAR Reanalyses[23] (Case 1; see Table 1 for a brief description of the simulation cases). Since the NCEP/NCAR model resolution is 2.5°, a single NCEP/NCAR grid cell encompasses the entire basin, yielding a spatially uniform forcing field; its temporal variation is shown in Figure 4. The run-off required to force the model is the difference between precipitation and evapotranspiration (run-off is zero when the latter is greater), and the partition between surface run-off and sub-surface drainage is assumed to be the same as in Coe[1]: 30% surface run-off and 70% sub-surface drainage. The result is shown in Figure 5: there is almost no discharge into the sea, most of the local run-off tending to accumulate in lakes 30–50 m deep! Since no such 'potential water areas' (PWAs: regions where water can pile up, such as lakes or wetlands, and slow the flow through the river) are observed in the Mandovi basin upstream of Ganjem, this is due to the failure of the DEM to channel the run-off into and through the river.

Coe[1,2] faced the same problem in certain regions in his global simulation. A DEM is unlikely to resolve all the rivers accurately, and it may be necessary to edit it. Coe[2] used two objective procedures to eliminate spurious PWAs. The spurious PWAs that were left after these objective analyses were those due to the inability of the DEM to resolve narrow river valleys; these were edited subjectively by visually identifying them in a HYDRA simulation and correcting either or both the DEM elevation and the local flow direction.

Since our problem is due to the inability of the DEM to resolve the narrow river valleys accurately, we had to edit the DEM visually. We developed a set of tools based on the GRASS GIS to edit the GLOBE DEM. Once the DEM was edited by changing either or both elevation and local flow directions, the spurious PWAs in the Mandovi basin disappeared and the local run-off was routed by HYDRA to the sea. A comparison between the predicted and observed discharge at Ganjem (Figure 6) shows that the NCEP/NCAR run-off is able to capture the seasonal cycle, but considerably underestimates the magnitude. The difference between the simulated and observed discharges is much greater than the estimated error of 10–15% in the measurements[1,26,27]. The evapotranspiration during the summer monsoon in the Mandovi basin is negligible in comparison to precipitation (Figure 4), and the NCEP/NCAR evapotranspiration estimates compare favourably with those estimated by the India Meteorological Department[13]. Hence, the large difference between the simulated and observed discharge must be because of errors in the NCEP/NCAR precipitation.

That the NCEP/NCAR Reanalyses considerably underestimate the precipitation over Goa is confirmed by a comparison with the monthly climatology of precipitation at Panaji[28] (Figure 4). Forcing the model with the Panaji precipitation and NCEP/NCAR evapotranspiration (Case 2; note that the forcing is still uniform in space, i.e. the Panaji precipitation is used to compute the run-offs for all grid cells) gives much better results (Figure 6). The simulated discharge now matches that observed during June; it

Table 1. Observed and simulated annual discharge (10^6 m^3) at Ganjem. In Case 1, the precipitation forcing is based on the NCEP/NCAR Reanalyses[23]; in Case 2, the forcing is based on rain gauge data for Panaji[28]; in Case 3, the forcing is a combination of rain gauge data for Valpoi (June–September) and Panaji (other months); and in Case 4, the forcing is as in Case 3, except that the Valpoi precipitation for July and August is increased by 30%. The precipitation and evapotranspiration forcing in all four cases is uniform in space. The annual discharge simulated by Case 4 compares well with that observed at Ganjem, providing a posteriori justification for the assumption that precipitation on the foothills of the Sahyadris, which form a large fraction of the catchment area of the Mandovi at Ganjem, exceeds that at Valpoi during July–August

Case	Discharge
Observed	3425
Case 1	842
Case 2	1861
Case 3	2866
Case 4	3476

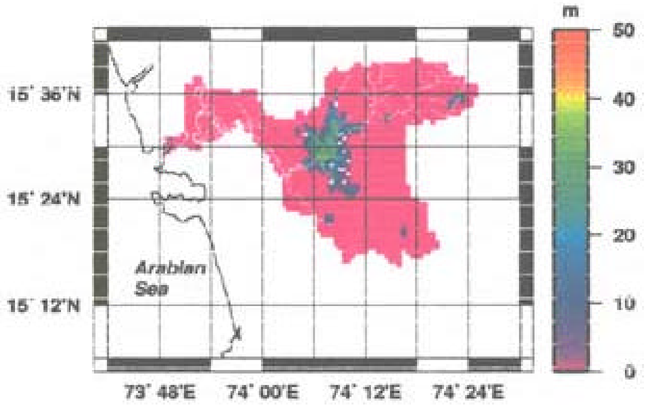

Figure 5. Using the GLOBE DEM and HYDRA to estimate the discharge in the Mandovi, whose catchment area (compare with Figure 2) is shown in colour, it can be seen that most of the local run-off piles up in 30–50 m deep pools, none of which exist in reality. The water level (metres) is also shown. This is due to the inability of the DEM to resolve the river valley, which is much less than 1 km wide over much of its length. The large 'lake' seen in the centre of the basin is just upstream of the stream-flow gauging station at Ganjem.

is, however, still much lower than that observed during the peak of the monsoon during July–August and in the months following it, leading to a much lower estimate of annual discharge (Table 1).

A least-squares fit to station gauge data shows that precipitation increases inland over Goa during the peak of the summer monsoon. The climatology of precipitation at Valpoi, about 32 km inland and located within the catchment of the Mandovi at Ganjem (Figure 2), was available to us (Sulochana Gadgil, pers commun, 2002) for the four months that comprise the summer monsoon, i.e. June–September. The precipitation at Valpoi is comparable to that at Panaji during June and September, but is much greater during July and August (Table 2, Figure 4). Hence, we construct another climatology of precipitation using the data for Valpoi during June–September and the data for Panaji during the rest of the year. Forcing the model with this climatology (Case 3; note that the forcing is spatially uniform) improves the results considerably, especially in the months following the summer monsoon (Figure 6). The discharge during July and August (Table 3), and therefore the annual discharge (Table 1), however, are still much less than that observed.

The reason for this lies again in an underestimate of precipitation in the catchment of the Mandovi at Ganjem. Much of this catchment area lies at altitudes much greater than at Valpoi, which is just 30 m amsl (Figures 2 and 7), and the heavy precipitation over the Indian west coast is known to be due primarily to the influence of orography[29,30]. There are no rain gauges available today at stations to the east of Valpoi, but data for 1959 (ref. 31) show that the trend of increasing precipitation away from the sea holds even farther eastward than Valpoi (Table 4, Figure 2). Kulem, the easternmost station for which precipitation information (only for 1959) is available, lies just 100 m msl; there are no stations on the slopes of the Sahyadris which rises steeply just a few kilometres to the east of Valpoi and Kulem (Figure 7). Hence since the precipitation at Valpoi differs from that at Panaji mostly during July and August, we assume that this is true farther east also. Therefore, the forcing for Case 4 is as in Case 3, but with the Valpoi precipitation for July and August increased by 30%. (Algorithms that extrapolate precipitation data from lowlands into mountain settings are available, but we have not used them here.) The temporal variation of the simulated discharge is shown in Figure 6 and its spatial variation in July is shown in Figure 8. The annual discharge now matches the observations (Table 1).

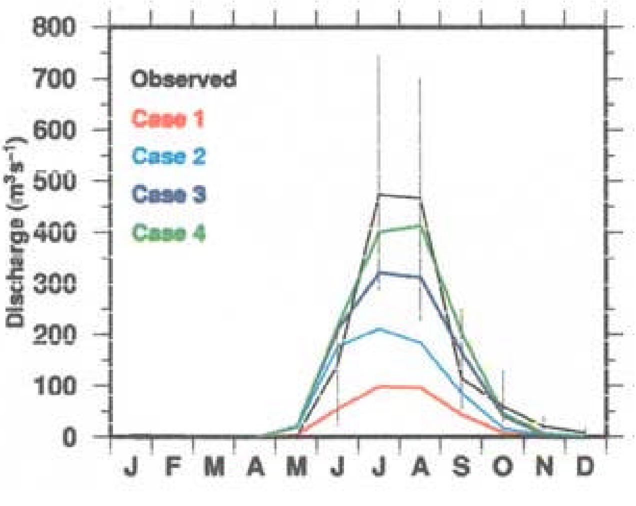

Figure 6. Comparison between simulated and observed discharge (m^3 s^{-1}) at Ganjem for the four cases listed in Table 1. The simulation forced by NCEP/NCAR precipitation (Case 1) considerably underestimates the discharge. The discharge estimates improve on forcing the model with precipitation data from the rain gauge at Panaji (Case 2) and on combining the precipitation data for Valpoi with that for Panaji (Case 3). Increasing the Valpoi precipitation for July and August by 30% (Case 4) to account for the possible increase in precipitation on the hill slopes, which form a large fraction of the catchment area of the Mandovi at Ganjem, shows the best match with the observations. With this forcing, the annual discharge (Table 1) matches the observations. Vertical lines indicate the range of discharge at Ganjem during 1980–87.

Table 2. Comparison of monthly climatology (for 1980–1987) of precipitation (mm/day) at Panaji[28] and Valpoi (Sulochana Gadgil, pers commun, 2002). Precipitation data for Valpoi were available to us only for June–September

Month	Panaji	Valpoi
January	0.00	–
February	0.01	–
March	0.01	–
April	0.17	–
May	0.46	–
June	32.58	36.53
July	23.83	38.61
August	23.17	35.55
September	6.91	12.47
October	3.90	–
November	0.88	–
December	0.19	–

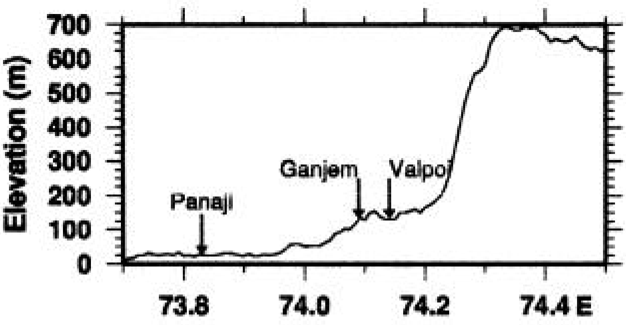

Figure 7. Meridional average (over the domain) of the elevation shows the Sahyadris rising steeply just east of Valpoi, which nestles at the foothills of the range. Since the precipitation on the west coast is influenced by orography[29,30], the Valpoi observations may also underestimate precipitation over the catchment area upstream of Ganjem.

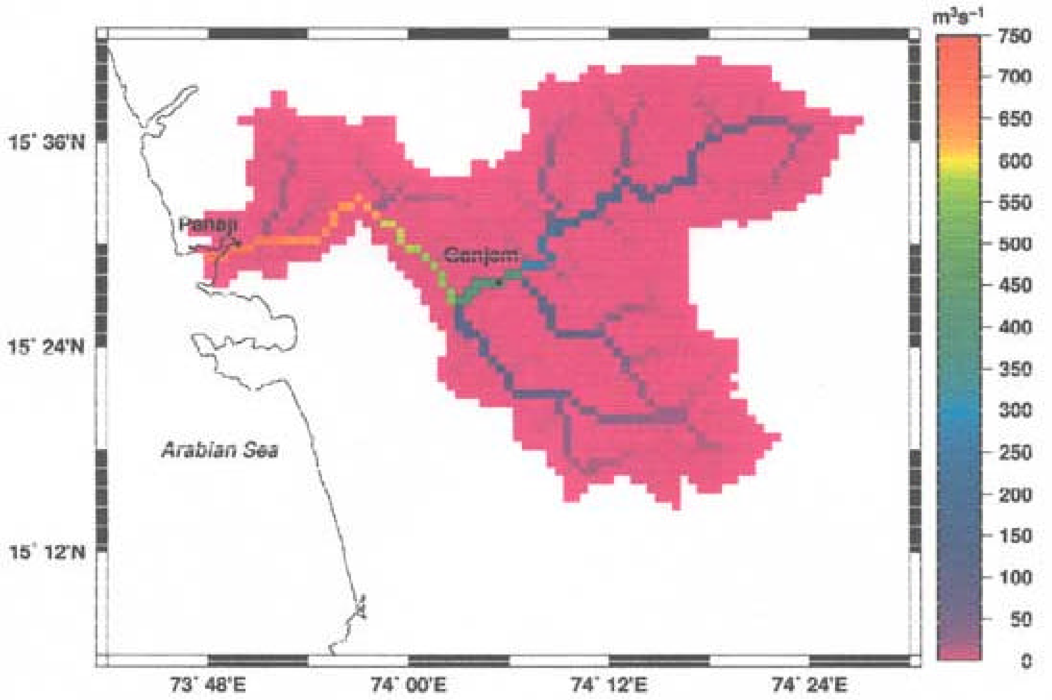

Figure 8. Run-off ($m^3 s^{-1}$) simulated for July in Case 4 in which HYDRA is forced with the precipitation at Valpoi (June–September) and Panaji (other months), but with the Valpoi precipitation for July and August increased by 30%. Evapotranspiration data are from the NCEP/NCAR Reanalyses, and the forcing is uniform in space. DEM used for this simulation was edited – either or both elevation and local flow direction estimated by HYDRA were modified at 25% of the grid cells encompassing the Mandovi basin, whose catchment area is in colour (compare with Figure 2).

Table 3. Comparison of observed and simulated discharge ($m^3 s^{-1}$) for Ganjem (Figure 2). For a brief description of the simulations, see Table 1. All climatologies (precipitation, evapotranspiration and discharge) are defined over 1980–1987

Month	Observed	Case 2	Case 3	Case 4
January	4.15	0.10	0.15	0.15
February	2.27	0.03	0.04	0.04
March	1.31	0.01	0.01	0.01
April	0.82	0.01	0.01	0.00
May	0.79	19.04	21.80	21.80
June	141.59	178.82	212.16	219.35
July	472.58	212.71	323.06	400.60
August	466.42	185.89	312.61	413.53
September	114.78	85.76	164.99	203.30
October	60.25	18.07	41.47	46.58
November	20.79	2.40	5.45	6.12
December	8.68	0.37	0.77	0.86

Table 4. Comparison of annual precipitation during 1959 (ref. 31) at some rain gauge stations in Goa. See Figure 2 for locations. Columns 2–4 show the distance (km) of the station from the sea, its altitude above mean sea level (m), and the annual precipitation during 1959 (mm); precipitation data during 1959 are not available for Panaji. Precipitation at Kulem, the easternmost station, exceeds that at Valpoi and Sanguem

Station	Distance	Altitude	Precipitation
Panaji	0	1	–
Sanguem	23	20	4758
Valpoi	32	30	5571
Kulem	35	100	6333

Getting the seasonal cycle of forcing right, however, is not sufficient for simulating correctly the peak discharge in July and August or the discharge during the ‘lean’ season that precedes the monsoon (Figure 6 and Table 3). It is important to simulate correctly both discharges, because the former is a measure of the flood potential and the latter is a measure of the potential yield of wells that tap groundwater. These discharge errors are due to the use of constant residence times for the surface run-off (2 h) and sub-surface drainage (15 days). The large amplitude of the seasonal cycle of precipitation (Figure 4) implies a large seasonal cycle of soil moisture. At the time of monsoon onset in June, the soil in the region is dry; hence, much more of the rainwater penetrates into the soil column than later during the summer monsoon. This would imply a larger fraction of run-off going into the sub-surface drainage reservoir and also an increase in its residence time, allowing the local run-off during June to move more slowly towards the river. This would not only decrease the discharge at Ganjem in May and June, but also increase it in July, by when the soil is almost saturated. Similarly, the precipitation in September must be retained in the basin much longer than permitted by the residence time of 15 days. It is this precipitation toward the end of the monsoon that is released as sub-surface flows or groundwater in the months preceding the next summer monsoon, when evapotranspiration exceeds precipitation and all the discharge is due to the sub-surface drainage (whose reservoir is represented by W_d in the equations listed above) still available in the basin.

It is in this period preceding the summer monsoon that the scarcity of freshwater is felt most in India. At this time, the availability of freshwater is dependent on two sources: storage of surface water and groundwater. Storage of surface water occurs in natural and man-made lakes. In HYDRA, this is strongly dependent on the DEM; hence, care must be taken to account for these water bodies when editing it. In HYDRA, groundwater is represented by the sub-surface drainage or baseflow. Therefore, a reasonable estimation of the available freshwater during the months preceding the rains requires better parameterization of the residence times and the separation between surface run-off and sub-surface drainage, and therefore, of soil moisture.

The sort of behaviour seen above with respect to soil moisture should also hold for the rest of India. Given appropriate data on local soil conditions, vegetation cover and surface meteorological observations, this can be attempted with a model of land-surface processes. One such model is the IBIS (Integrated Biosphere Simulator)[32,33], which has also been developed at SAGE, where HYDRA was developed. The data required for this also exist today: the meteorological observations are made at the several observatories of the India Meteorological Department, and data on soil type and vegetation cover are available from land surveys and satellite remote sensing. The challenge is to use the models and available data to simulate both the peak discharge in July, which is critical for estimating the potential of floods, and the two-orders-of-magnitude smaller discharge before the monsoon, which is critical for estimating the potential yield of freshwater from wells.

Discussion

We have demonstrated that the framework consisting of a freely available hydrological routing algorithm like HYDRA, the GLOBE DEM, the GRASS GIS, and the precipitation and evapotranspiration data available today can successfully simulate the observed monthly-mean discharge in the Mandovi river in Goa. A corollary is that it is possible to use the framework to estimate the discharge at any point along the river. This river being typical of those along the Indian west coast, the framework is equally applicable to the rest of the west coast, permitting an estimate of the water budget of the region. The framework is also applicable to other rivers in India; the global simulations of Coe[1] on a 5′ grid showed a reasonable match between the discharge simulated for the Ganga and the Brahmaputra and the discharge measured at the stream-flow gauges on the rivers.

The GLOBE DEM may also require less editing in the broader river valleys in the rest of India; some of the problems encountered with the DEM, like the presence of pits, can also be handled with available algorithms. The relative sparsity of rain gauges can be compensated for by the precipitation data from AGCMs and satellites; the NCEP/NCAR data, which underestimate the precipitation over the west coast owing to the inability of the model grid to resolve the steep Sahyadris, compare well with the all-India precipitation[34] estimated for the non-hilly subdivisions of the India Meteorological Department based on rain gauge observations (Figure 9). Along the west coast, where the AGCM is unable to account for the orographic effect because of its coarse resolution, statistical downscaling of AGCM precipitation[35] will have to be used in basins without rain gauges. A similar approach will be needed in the Himalayas, where several of the rivers of northern India originate.

The importance of this can hardly be overestimated. There is a dearth of stream-flow gauges in the country[6], and, like gauges elsewhere in the world, they are declining in number[22,36]. The framework described here, once validated using existing stream-flow data in the country, can be applied to all basins. It will also help fill the many gaps that exist in available stream-flow data, resulting in a more continuous dataset. This will permit an analysis of interannual variability of river discharge over longer periods than is possible with the observations alone. Since HYDRA also allows explicit inclusion of dams and irrigation outflows[1], the framework makes possible an estimate of a nationwide water budget. That HYDRA scales well is seen from the range of resolutions at which it has

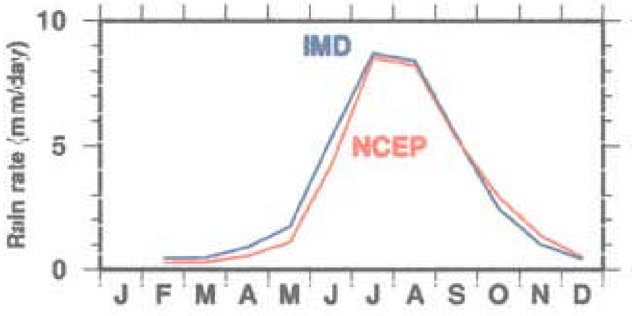

Figure 9. Comparison between climatological precipitation rates (mm/day) from NCEP/NCAR Reanalyses[23] and estimates[34], based on rain gauge observations, for the non-hilly subdivisions of India Meteorological Department. Climatologies are defined over 1982–94. NCEP/NCAR Reanalyses, which underestimate considerably the precipitation over Goa owing to the inability of the model grid to resolve the Sahyadris satisfactorily, perform better in the flatter plains and plateaus in the rest of India. Precipitation estimates from the Reanalyses can therefore be used to force HYDRA for large parts of India.

been used. Hence, this approach can be used to obtain a budget estimate for an Indian district, the average size of a district being of the same order as that of Goa.

Successful application of the framework will demand the collective efforts of several hydrologists. For this to materialize, the framework has to satisfy the four conditions listed in the beginning of the article. All the ingredients of the framework – HYDRA and its ancillary software, the GLOBE DEM, and the GRASS GIS – meet these requirements. These tools, however, only provide a means to synthesize available data into a coherent and quantitative picture. As the simulations described in the preceding section show, the quality of the synthesis is dependent on the quality of data it brings together. In the case of the Mandovi river, the unsatisfactory aspect is the absence of reliable data on precipitation on the slopes of the Sahyadris. As the assembly of tools described here is enlarged (for example, by incorporating IBIS), it is likely that we will encounter the unsatisfactoriness of the other hydrology data (for example, soil condition or vegetation cover) available in the country. We hope that application of the framework to tackling one of the major problems in the country, that of freshwater resources, will motivate collection of hydrology data, and more important, their open distribution.

The data also have to be integrated into a common database to ensure uniformity (condition (iv)). Building hydrologic databases is a major task and is being done by several groups worldwide[37–39]. For this also, the data that exist have to be available openly to facilitate interaction among various groups. As a step towards this end, we have taken care to ensure that the tools built around the GRASS GIS allow us to map the changes made to the DEM for the Mandovi basin to be mapped onto the much larger original database we started with – tiles ‘G’ and ‘H’, which were downloaded from the GLOBE website (http://www.ngdc.noaa.gov/seg/topo/gltiles.shtml). This makes it possible for many groups to work on different basins, with their work being dovetailed into a single database that is available to all.

The magnitude of the task can be gauged by comparing the area of the Mandovi basin with that of the Indian subcontinent (Figure 1). This is but a modest beginning in simulating hydrology on the scale of the Indian subcontinent. Such an endeavour, beginning appropriately in the International Year of Freshwater, would be a fitting tribute to those who have, over the years, tried to understand and find viable solutions to India’s water crises.

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