Chapter 6

Implications of the modelling framework

6.1 Introduction

The modelling framework developed in the preceding chapters has major implications for the hydrology of the Indian subcontinent. There is a dearth of information on the hydrological variables in the country [Shankar et al., 2004]. Apart from a fairly consistent and long-term data set on rainfall, data on other hydrological variables is non-existent: river discharge is another variable for which some data is available. Only a few of the rivers have sufficient data length; data for the rest of the rivers is available only for the short term. Most of this data is scanty and not easily available. The number of stream gauges is declining world over [Radhakrishna, 2003]. The situation is worse for other hydrological variables like evapotranspiration [Rao et al., 1971; Rao, 2001; Narasimhan, 2008; Maréchal et al., 2009], soil moisture, infiltration rate, for which data on the catchment scale is non-existent. A much bigger problem, though, is the dearth of modelling studies or quantitative frameworks. The focus of modelling studies in the country is limited to small catchment scales for managing hydrological projects, or to solve very specific problems using complex hydrologi-
cal models. There is also a spate of work on climate-change scenarios and their related feedback systems on the hydrology of the country. Hydrological simulation studies on the catchment (or larger) scale are not readily available: discharge simulations on daily scale are much rarer. Most of the information on hydrology in the country is available on either very small scale or based on some gross statistics over a region (state level) [Shankar et al., 2004; Rao, 1975; Jain et al., 2007]. This is despite the fact that freshwater (river discharge) is crucial for climate and water resources. Shankar et al. [2004] realised and addressed this problem: they initiated the building of a hydrological framework consistent with the realities of the data availability of the country. They proposed that any framework should follow these four basic guiding principles.

1. The framework should include a simple hydrological model that can provide a reliable water balance of a river system.

2. Demands on the database required by the model should be consistent with the realities of the country.

3. 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.

4. The models and their ancillary software should be freely accessible.

Hence, while developing our modelling framework, we have kept these guidelines in mind. Instead of going for a complex procedure with a very specific application, we have opted for a more simple approach, with a view to make it applicable in the general scenario.

6.2 Generality of framework: West-coast rivers

The modelling framework was tested for the Mandovi river. Simulations showed that the framework was able to simulate daily discharges for the Mandovi river basin remarkably well. There
were three reasons for choosing the Mandovi river for model-building. First, the Mandovi is typical of the westward flowing west-coast rivers; if the framework works here, it is expected to work elsewhere on the west coast also. Second, both the rainfall and discharge data were available for it, allowing us to build the parameterisation by validating discharge simulations with the observation. Third, it is the largest and the most important river of Goa (flowing near the National Institute of Oceanography in Panaji).

The most critical assumption is that the Mandovi is a river typical of the west coast. Successful application of our method to other west-coast rivers is contingent on the validity of this statement. We have selected two more rivers for which we had observed discharge data: Ulhas river to the north of Mandovi and Aghanashini river to the south (Figure 6.1). Combined with Mandovi, the three rivers cover a considerable fraction of the west coast, enabling us to examine the variability along the coast. A plot of the observed discharge (normalised for comparison) of these three rivers suggests (Figure 6.2) that the discharge patterns are comparable across most of the coast: the inter-river variability is no more than the interannual variability for any river. A similar result is obtained by performing a Kolmogorov-Smirnov test on the discharge data: the inter-river spread in the curves is comparable to the interannual spread for a river (Figure 6.3), suggesting that this method should work for the other rivers.

### 6.2.1 Annual variability and spatial variability

The rivers (on the west coast) for which the parameterisation is likely to require modification are the ones in Kerala because it experiences rain during the winter monsoon too, the longer west-coast rivers like the Narmada and the Tapti because their basins encompass a wider spectrum of hydrological regions, and the dry-region rivers like the Mahi ([Ramakrishnan et al., 2009]) and the Sabarmati.
Figure 6.1 The location of discharge gauges for the Ulhas (blue, discharge gauge at Badlapur) Mandovi (black, Ganjem), and Aghanashini (red, Santeguli). The three rivers cover a large fraction of the Indian west coast. The catchment area of the Mandovi, Aghanashini and Ulhas are 872 km$^2$, 1070 km$^2$, and 785 km$^2$ respectively, at the location of the discharge gauge.
Figure 6.2 Daily normalised discharge for 1990–1994 for three west-coast rivers (Figure 6.1). The discharges are normalised by the highest daily discharge among any of the rivers occurring in the particular year. The rivers are Ulhas (blue), Mandovi (black), and Aghanashini (red).
Figure 6.3 Kolmogorov-Smirnov diagram showing the cumulative distribution plot for daily discharge during June–September for 1990–1995 for the Ulhas (blue), Mandovi (black), and Aghanashini (red) rivers.
6.3 Assessment of the framework and future directions

6.3.1 Caveats of the modelling framework

The modelling framework simulates the daily discharges for Mandovi river across the whole range of seasonal variability. This was achieved by improving the SCS parameterisation. Obtained using limited data, this parameterisation needs further improvement. One notable drawback is the need to specify a minimum duration \((MD)\) of 60 days for the peak-monsoon regime. This specification was necessitated by the need to preclude a prolonged weak spell or break, triggering a transition to the post-monsoon regime. Would such a constraint be valid in a year as exceptional as 2002, which saw one of the worst droughts on record, with the July rainfall deficit across India being almost 50\% \cite{Gadgil2002}? If such a break dries out the soil, a tendency for which was noted even in the simulations for 1992 and 1998, it is likely that the AMC thresholds and the \(CN(II)\) values would be different. A more elaborate parameterisation scheme is needed to handle such singular cases.

Another caveat is the specification of absolute rainfall thresholds as one of the criteria for Transition \(BC\). Absolute thresholds are prone to giving erroneous results when the rainfall is “not normal”.

A more serious caveat is the averaging of AMC thresholds across a region. There is considerable variation in rainfall even within a region, with the rainfall changing by a factor of over two in the Ridge and Foothills regions (Figure 2.4). The thresholds should therefore be allowed to vary across the region. Likewise, the absolute rainfall thresholds used to determine the Transitions \(EA\) and \(AB\) should also be allowed to vary within a region.

Hydrologically, monsoon onset, as defined here, is a process, not an event. This phase begins with sustained, continual rainfall with its occasional showers marking the end of the dry season. This phase ends when the discharge starts mirroring the rainfall. Since discharge gauges are not available in most basins, it is not convenient to use the discharge as a parameter to define Transition
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$BC$, making it the most difficult transition to capture. Improvements in this part of the algorithm are needed to preclude the overestimation of discharge just before the transition occurs.

6.3.2 Strengths of the modelling framework

The framework simulates the hydrology of integrated terrestrial freshwater systems. It has the capability of resolving linked terrestrial hydrological systems, which include lakes and wetlands. Although lakes and wetlands are not important for the Mandovi basin, it is still advantageous to have such capabilities. The framework is also highly scalable and can be used to simulate river basins ranging from a very small scale to the continental scale.

Figure 6.4 Simulated runoff for July 1992 (in m$^3$ s$^{-1}$) in the Mandovi river basin. The catchment area is shown in colour along with the position of two discharge gauges: Ganjem and Kulem (black circles). The spatial variability in runoff is captured well. Some of the major tributaries (Rivers Khandepar, Mhapsa, Dicholi, Valvat) are identified on the map. The modelling framework allows one to calculate the freshwater discharge at any point along the river including the total river discharge into the Mandovi estuary at its mouth at Panaji (red circle) for which there is no information available. From Ganjem to Panaji, discharge doubles approximately, with major contribution from tributaries in between.
Apart from temporal variability in discharge, a major feature of this modelling framework is that it resolves spatial variability in discharge also (Figure 6.4). In addition to its obvious implications on water resources, spatial variability of discharge has crucial implications in many applications. For example, ocean models require discharge at the mouth of the river and also as a function of the coastline. Even to study the estuarine systems, discharge all along the estuarine network is a necessary requirement. For Mandovi, the discharge gauge at Ganjem, located at the upstream end of the estuary, is \( \sim 50 \) km upstream of the mouth of the river. This is typical of the river discharge measurements; gauges were put beyond the influence of tidal action. There are no observations for events that happen from the gauging locations to the mouth of the rivers. For estimating river discharge at its mouth, the normal practice is to use the discharge observation as it is, or in some cases by some means of extrapolation; this is an unsuitable measure of the discharge at the mouth.

For example, an estimate of the Mandovi’s discharge was reported by Rao [1975]. The Ganjem gauge did not exist then and Rao [1975] used a classification and extrapolation scheme to estimate the discharge. Based on the data for gauged rivers in India, Rao [1975] estimated that the discharge for river basins with ‘high’ rainfall was of the order of 65 Mm\(^3\) per 100 km\(^2\) of basin area. This method yielded a value of \( \sim 1320 \) Mm\(^3\) for the Mandovi, which is almost a third of the discharge measured at Ganjem. This result is not surprising because the data used by Rao was from rivers spread across India, and rainfall varies from over 600 cm to less than 20 cm across the country. Our estimate of the discharge at Panaji was over 6004 Mm\(^3\), with a standard deviation of 890 Mm\(^3\). The ratio of the simulated discharge at Panaji to that at Ganjem varied between 1.8–2.1. Thus, discharge in the Mandovi increases almost two-fold from Ganjem to Panaji (Figures 6.5 and 6.6). A large fraction of this increase comes from the tributaries Khandepar (\( \sim 45\%\)), Valvat (\( \sim 25\%; \) includes Dicholi and Kudnem rivers), and the Mhapsa (\( \sim 14\%; \) includes Moide and Asnoda rivers); the balance (\( \sim 16\%) \) directly flows into the estuary from the land adjoining it (Figures 6.4 and 6.6). The model river channel terminates at the point where the height falls
below mean sea level in the GLOBE DEM. For the Mandovi, this point (where the river ends) is in the vicinity of Panaji. The rest of the Mandovi basin, which consists of the Aguada Bay, does not form a part of the river-runoff computations in THMB because the bottom of the bay is below mean sea level and therefore forms a part of the sea.

**Figure 6.5** Similar to Figure 3.5 with simulated discharges at Panaji included. The observed and simulated discharge at Ganjem are plotted for comparison with Panaji simulation.

This modelling framework makes very low demands on hydrological data. Apart from some information on the soil type in the basin, the entire model parameterisation is built using only the rainfall forcing. All model parameters are derived on the basis of the rainfall, which is a basic requirement for any hydrological model. In this low demand on input data lies the strength of the modelling framework. Furthermore, the results (Figures 6.2 and 6.3) suggest that the model should work for other basins on the Indian west coast too. That the model does not need to be calibrated separately for each river is an important point because most of these basins are ungauged. Hence, though the model has been validated only for the Mandovi, its potential region of application is considerable and spans most of the Indian west coast. In the context of Prediction in Ungauged Basins (PUB) [Sivapalan et al., 2003], this potential of the model is significant because, although most of these basins are ungauged, the discharge of these rivers into the eastern Arabian Sea is not small [Fekete et al., 2002], making them an important element of the local climate system.
**Figure 6.6** Bar chart showing the spatial variation of annual simulated discharge on the model grid. The height of the bar represents annual discharge (in Mm$^3$) from Ganjem (on the right) to Panaji (on the left) for 1992 as a function of distance (abscissa is the number of grid cells from Panaji to Ganjem) along the main channel of river. Discharge in the channel increases almost two-fold from Ganjem to Panaji, most of this increase coming from the runoff from the Khandepar, Valvat (including Dicholi), and Mhapsa rivers (Figure 6.4). The contributions of these tributaries are shown in black.

### 6.3.3 Future directions

Our modelling framework provides a tested tool to simulate the hydrology of the west coast of India. The next logical step is to apply it to the remaining west-coast rivers. In the course of this study, we have already collected an exhaustive data set of daily river discharge (from CWC) and daily rain-gauge data (from IMD). Daily-discharge data were available for 47 stations in 34 river basins. Rain-gauge data were collected from 589 stations covering the whole of the west coast, from Gujarat in the north to Kerala in the south. Availability of this crucial data implies that the framework can be extended to the whole of the west coast. Nevertheless, we did not
implement this framework for the other west-coast rivers. One of the reasons for not doing so was the inability of GLOBE DEM to resolve the west-coast river basins accurately: as discussed in chapter 2, considerable editing of GLOBE DEM is required to resolve the narrow channel. Like any other DEM, GLOBE gives average elevation for a grid cell. Also, like most of the other west-coast rivers, the Mandovi river is much narrower (∼100 m) than the resolution of the GLOBE DEM, especially in its upstream reaches [Shankar et al., 2004]. Thus, GLOBE DEM topography and river directions derived from the topography required editing to represent the basin geometry accurately in the modelling framework. The DEM editing tool developed by Shankar et al. [2004] and Kotamraju and Shankar [2004] requires visual editing. High resolution of the GLOBE DEM (large number of grid cells) and the presence of a complex topography of the coast along with narrower streams, implies investment of large amount of time. So, instead of extending the framework to other rivers, we chose the more important task of building the model parameterisations. It is worth noting that this issue is not only related to the coarser resolution of GLOBE DEM with respect to west-coast rivers. Even a high-resolution DEM like SRTM [Farr et al., 2007] was unable to resolve the Mandovi channel. We tested the SRTM data (original resolution 3 arc seconds) by averaging the 3-arc-seconds elevation to the 30-arc-seconds GLOBE grid. The resulting DEM was used for a simulation. The results show that there are far fewer pits in the coarsened SRTM than were seen in the GLOBE DEM (Figure 6.7 (Figure 5 of Shankar et al. [2004])), implying that the elevations are reasonably good. The river does not, however, flow to the sea, the map of river flux showing instead a large number of short, unconnected channels (Figure 6.8). This lack of a well-defined river implies the need for manual, subjective editing. Hence, at least at coarsened resolutions like 30 arc seconds, the SRTM DEM is also unable to capture the river valleys sufficiently well (Figure 6.8). Using a higher-resolution DEM increases the computational expense considerably. Since a major potential application of this study is to estimate the river discharge into the Indian seas, even the 30 arc seconds resolution is sufficient for most of the oceanographic applications. Extension of this modelling framework to the rest
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of the west coast is, however, a logical course for future studies. We envisage achieving this goal in two steps. First, as discussed earlier, application of the framework requires editing of the DEM, an exhaustive task in terms of the available resources. What is required is an automated editing algorithm to make the DEM hydrologically correct and resolve the river basin geometry. In GRASS GIS, watershed analysis tools like r.watershed and TerraFlow are available and they can be used to obtain a hydrologically correct DEM.

**Figure 6.7** Figure 5 in Shankar et al. [2004]. The stream network is not resolved, most of the local runoff piles up in 30–50 m deep pools, none of which exist in reality. The water level (in metres) is also shown. This was owing to the inability of the DEM to resolve the Mandovi 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-low gauging station at Ganjem. Compare with the runoff map with the edited GLOBE DEM, where the stream network is resolved quite well (Figure 6.4).

Module r.watershed uses a least-cost search algorithm designed to minimize the impact of DEM data errors [Ehlschlaeger, 2001]. Module TerraFlow, a part of a software project called computations on massive grids [Toma et al., 2001, 2003] derives a hydrologically correct version of high resolution DEMs such as SRTM [Arge et al., 2000]. The project is designed using efficient algorithms for flow computation on massive numbers of grid cells containing terrain, such as SRTM DEM. TerraFlow computes the flow routing (path when a volume of water is poured on the terrain) and flow accumulation (amount of water flowing through the terrain) from
Figure 6.8 Runoff \( (m^3 \text{s}^{-1}) \) simulated for July using (a) GLOBE DEM (edited) and (b) the 3 arc seconds SRTM downscaled to 30 arc seconds (unedited). As with the unedited GLOBE DEM, the river does not flow in a continuous stream to the sea.

A given DEM. It is much faster (2 to 1000 times) than the other algorithms and has been used on massive datasets, up to \( 10^9 \) (1 billion) in size \cite{Toma et al., 2003}. It uses a flooding algorithm to fill the sinks in a DEM \cite{Arge et al., 2001}. Module \texttt{r.watershed} is more accurate than module \texttt{r.terraflow}, but this accuracy comes with the drawback of large computer time. A more careful approach (using case studies) is required to ascertain the relative accuracy of these two algorithms, which will require stream-network data (rivers digitized from toposheets). For a recent work on flood-assessment methodology in Goa \cite{CFFSC, 2009}, we used both the algorithms to resolve the river basin geometry. We filled the SRTM DEM with the \texttt{r.terraflow} algorithm and then used \texttt{r.watershed} for watershed analysis. This combination of modules resolved the basin geometry of the rivers of Goa (Figure 6.9).

This result is significant, because once the need for manual editing is eliminated, hydrologically corrected DEMs can be used in the framework for the whole of the west coast. Implementation of format conversion between these two geometries and incorporation of the algorithms to the modelling framework is not expected to be as big an issue as managing the much greater computer time required when using the higher resolution SRTM DEM: running THMB with SRTM requires 1000 times more grid cells than the GLOBE DEM, implying much higher computational cost per simulation. Possible solutions to this problem are to use an averaged SRTM DEM, i.e., a coarser
Figure 6.9 GRASS GIS modules are used to generate the hydrologically corrected and filled SRTM DEM for Goa. Again the GRASS module `r.watershed` can be used to derive the basin geometry. The areas plotted in grey are the watershed area over the location (red star) mentioned for the rivers of Goa. The place names mentioned on the map are the nearest town. Inclusion of these modules in the modelling framework is the next step.
resolution, or even parallelising THMB to run on a cluster computer.

Second, since rainfall is the main forcing field, we plan to prepare a high-resolution spatial rainfall data set for the west coast of India using the available rain gauge data and the method described in Chapter 3.

Thus, our work can be interpreted as a move in the right direction to address the problem of developing a modelling framework to quantify the hydrological variables, an important but often neglected issue. We hope that this thesis will provide a much needed impetus and a modest beginning in the direction of preparing a quantitative water budget for the whole country and an estimate of the discharge into the Indian seas. Simulated river discharge on the subcontinent scale can then be used for a variety of studies, including ocean and estuarine modelling, terrestrial ecosystem modelling, GCM studies, and water-resource studies.