Chapter 5

Spatio-temporal variability in rainfall-runoff model

5.1 Introduction

Simulation S1 was a major improvement over S0. The reason for this improvement was incorporation of the SCS method into THMB: THMB’s simple parameterisation (a single parameter $\alpha$) was replaced by the more complex parameterisation of the SCS method ($CN$, $\lambda$, and AMC thresholds). In Simulation S1, the SCS parameters used were constant in both space and time. Constant parameters represent an average condition of the basin. This parameterisation ignores spatial and temporal variability in rainfall (see Figures 3.3 and 4.1). It also ignores spatial variability of other runoff-generating parameters (such as soil, land cover and use and other physical properties of the basin). This variability in runoff-generating parameters implies a spatio-temporal variability in runoff and therefore in the SCS parameters. Incorporation of this spatio-temporal variability in SCS parameters in order to improve the discharge simulations is the subject of this chapter.\(^1\)

\(^1\)Work reported in this chapter is compiled in a manuscript for publication [Supriat et al., 2011].
5.2 Spatial variations

Ideally, estimating the SCS parameters requires rainfall and runoff data from the catchment area, or, in the case of a distributed model like THMB, from each grid cell. Though the rainfall-mapping procedure provides rainfall information for each grid cell, we do not have runoff information for the cells. The only information available on runoff is the discharge at Ganjem and Kulem. THMB is a distributed model, but we do not have the runoff data in the same distributed sense in order to build an empirical, cell-based parameterisation of the SCS parameters. Hence, for incorporating spatial variability into these parameters, we take recourse to a semi-lumped approach, wherein the basin is divided into four sub-basins or hydrologically coherent regions.

5.2.1 Regionalisation

The reason for spatial variation in the SCS parameters ($CN$, $\lambda$ and AMC thresholds) is the spatial variation in soil type, vegetation cover, land use, and hydrological and moisture conditions. As with runoff, we do not have cell-specific information for these characteristics: the only cell-based data available are elevation and rainfall. Hence, we use the elevation to divide the basin into four hydrological regions: the leeward side of the Sahyadris ($Lee$), the ridge and the windward slope above 200 m ($Ridge$), the foothills of the Sahyadris or the region on the windward side between elevation contours 40 and 200 m ($Foothills$), and the coastal plains or the region at an elevation below 40 m ($Coast$). (The names in the parentheses are used to refer to these regions.) The regions were delineated using the 40 and 200 m contours on the smoothed (using 5 cells × 5 cells averaging) DEM. The resulting regions were made uniform by eliminating pockets or enclosures. Thus, the basin was divided into four contiguous regions (Figure 5.1), and the SCS parameters were determined for each of these regions. It is evident from Figure 5.1 that the sharp change in elevation that marks the Sahyadris occurs around the 200-m contour. Likewise, the 40-m contour separates the low-lying Coast region from the relatively higher Foothills.
5.2.2 Estimation of parameters

The $CN$ was estimated on the basis of the runoff-generation capacity of the soil in a region because detailed information on soil cover was not available. The dominant soil type and land usage for the four regions are listed in Table 5.1. The Ridge region is dominated by forests with a thin layer of laterite soil over an impervious layer of rock [Gokul et al., 1985], implying that it belongs to Soil Group D. As the hydrologic condition of the Ridge region is not known, we average the $CN$ over the three types of hydrologic conditions tabulated by SCS (Table 4.2), yielding $CN = 75$. From the soil type listed in Table 5.1, it is evident that the Ridge region has the maximum runoff-generation capacity, followed by Foothills, Lee, and Coast.

The estimation of $\lambda$ was done similarly. The minimum value used in the literature (Table 4.1)
Table 5.1 Basin soil and hydrologic characteristics and SCS parameters for Simulation $S_2$ (SCS parameters allowed to vary in space).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lee</th>
<th>Ridge</th>
<th>Foothills</th>
<th>Coast</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Red, laterite</td>
<td>Shallow soils over rock</td>
<td>Red, Sandy loam</td>
<td>Sandy soil,</td>
<td>Representative</td>
</tr>
<tr>
<td>Hydrologic soil group</td>
<td>B/C</td>
<td>D</td>
<td>C</td>
<td>A</td>
<td>—</td>
</tr>
<tr>
<td>$CN(II)$</td>
<td>65</td>
<td>75</td>
<td>70</td>
<td>60</td>
<td>—</td>
</tr>
<tr>
<td>AMC (mm) Dry</td>
<td>&lt; 100</td>
<td>&lt; 150</td>
<td>&lt; 100</td>
<td>&lt; 100</td>
<td>5-day antecedent rainfall</td>
</tr>
<tr>
<td>AMC (mm) Wet</td>
<td>&gt; 100</td>
<td>&gt; 400</td>
<td>&gt; 250</td>
<td>&gt; 200</td>
<td>—</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.3</td>
<td>0.05</td>
<td>0.1</td>
<td>0.3</td>
<td>SCS value (0.2)</td>
</tr>
</tbody>
</table>

was used for the Ridge region because of its steep slopes and impervious, rocky soil. The highest value of $\lambda$ (0.3) was used for Lee (Table 4.1) because of its gentle topography and Soil Group ($B$ and $C$), which would allow more of the rainfall to be abstracted. The same value was used for Coast because it belongs to Soil Group $A$, which implies low runoff, and has a gentle topography.

As with $CN$ and $\lambda$, the AMC thresholds were prescribed for each of the four regions. The antecedent rainfall, however, was computed separately for each grid cell and the condition (dry or average or wet) is determined for each cell. As done earlier for the entire basin, the AMC thresholds for each of the four regions were determined on the basis of a histogram of rainfall during May–October and a cumulative frequency curve of the 5-day rainfall (Figure 5.2): the thresholds, listed in Table 5.1 were chosen such that $\sim 36\%$ ($\sim 14\%$) of the days had rainfall above the lower (higher) threshold.

5.2.3 Simulation $S_2$

We extended the SCS parameterisation in THMB to permit spatial variation in the SCS parameters (Simulation $S_2$, Table 5.1). The simulated discharge (Figure 5.3) is similar to that in Simulation
Figure 5.2 As in Figure 4.7 but for Simulation S2, in which the AMC thresholds depend on the spatial region: *Lee* (top left) or *Ridge* (top right) or *Foothills* (bottom right) or *Coast* (bottom left).

---

*S1* (Figure 4.8): the spatial variation of the SCS parameters has but a minor impact on the simulated discharge at Ganjem. The higher \( CN^{(II)} \) (75) in the high-rainfall Ridge region leads to an improvement in the simulated discharge during July–September: the peak discharge increases, and so does the baseflow during the weak spells and following the monsoon peak in September. This increase in the Ridge \( CN^{(II)} \), however, leads to an increase in the overestimate of discharge during the onset phase in May–June. Thus, only spatial variation of the SCS parameters is not sufficient to simulate the Mandovi discharge accurately. So, we explore the impact of the temporal variation of the SCS parameters on the generation of runoff.

### 5.3 Temporal variations

As discussed earlier, most of the west-coast rainfall (~90%) occurs during the summer monsoon (June–September), with negligible rainfall during December–April (Figure 1.8). Correspondingly,
Figure 5.3 Observed discharge (black), discharge simulated by Simulation S2 (red), and the catchment-integrated rainfall (blue) at Ganjem for May–October. (A) 1986. (B) 1992. (C) 1990. The units are Mm$^3$/day. The bold tick marks on the abscissa indicate beginning and end of a month.
the daily discharge during December–April is of the order of 0.1 Mm$^3$ in contrast to the 100 Mm$^3$ discharge observed in bursts during the peak of the summer monsoon (July–August, Figure 4.1).

The transition from the dry to the wet season occurs in May–June. There is considerable rainfall during this onset of the summer monsoon, but there is no hydrological response: the discharge remains low, responding only to rainfall bursts during this onset phase (Figure 4.1). Even during these bursts, however, the discharge is much lower than the catchment-integrated rainfall. Thus, most of the rainfall during the onset phase is abstracted or lost to the river flow.

After some time following the onset of the monsoon, the discharge starts mirroring the rainfall. The sharp discharge peaks observed during June–August coincide with the rainfall peaks, as is evidenced by the lack of any time lag between the rainfall and discharge on the daily time scale (Figure 4.1). This coincidence of peaks has two implications. First, surface runoff or overland flow dominates following the onset of the monsoon, and there is practically no subsurface runoff or baseflow. The Mandovi originates on the lee side of the Sahyadris and flows for \( \sim 37 \) km before reaching the gauging station at Ganjem. The time taken for this flow to reach Ganjem is just 2–3 hours, leading to the coincidence of rainfall and discharge peaks. Second, success in simulating the peak discharge during June–August is contingent on success in mapping these rainfall peaks accurately. As shown in Figure 4.1, the peak summer-monsoon discharge, even allowing for a 15% error in the discharge measurement, is invariably greater than the catchment-integrated rainfall. The rainfall-mapping algorithm is unable to resolve the peak rainfall events and underestimates the rainfall during these bursts. The cause of this underestimation lies in the sparsity of rain gauges (see Figure 3.1): there are too few gauges for an accurate mapping of the strong rainfall gradients across the Sahyadris and this problem is exacerbated for the shorter time scales. This underestimation of rainfall has implications for the simulated discharge.

Though the baseflow is negligible in the Mandovi, there are two seasons when it makes a contribution. First, the negligible discharge during the lean season (December–April) comprises primarily of baseflow. Second, the discharge during early September, at the conclusion of the
peak-monsoon season, exceeds the catchment-integrated rainfall (see Figure 3.1). This excess flow is also probably sustained by baseflow resulting from the heavy rainfall during the preceding bursts.

Therefore, our objective for incorporating temporal parameterisations is to focus on three aspects of the discharge in the Mandovi. First, we seek an improved simulation of the observed discharge throughout the rainy period from the onset of the monsoon in late May or early June to the end of October, by when the baseflow declines to negligible levels beyond the scope of this model. Second, though the baseflow following the peak monsoon is small, it is almost two orders of magnitude larger than the lean-season flow and is therefore significant enough (∼ 10 Mm³) to merit better simulation. Third, the large abstraction during the onset phase of the monsoon is important, but neither Simulations S1 nor S2 could simulate it correctly: simulating this large abstraction is important.

5.3.1 The seasonal change in abstraction

The excess rainfall in the Mandovi basin appears neither as streamflow (immediately following the rain) nor as baseflow (appearing after a lag) (Figures 1.9 and 4.1). This excess rainfall must therefore either recharge the groundwater or be returned to the atmosphere through evapotranspiration. On the catchment scale, groundwater recharge is a small quantity [Coe, 2000; Maréchal et al., 2009] and has been neglected in the THMB formulation. Evapotranspiration is therefore the only loss term in this model and it is parameterised using the initial abstraction, which is a function of CN and λ in the SCS method. In any case, evapotranspiration observations are rare in the region [Maréchal et al., 2009], and estimates of initial abstraction are non-existent.

Before monsoon onset, the soil is dry, temperature is high, and relative humidity is low. Transpiration through the vegetation canopy also leads to a loss of water from the basin [Maréchal et al., 2009]. Therefore, there exists a large potential for initial water retention and evapotranspiration whenever moisture becomes available. These conditions prevail till the system changes from a
moisture-deficient state to a moisture-saturated state. The rate at which these changes occur depends on the process of monsoon onset, i.e., fewer rainy days in June make this transition slow, allowing more abstraction.

The basin characteristics change dramatically once the monsoon sets in. The soil begins to soak up moisture, temperature decreases, and relative humidity increases. Evapotranspiration is highest during this transition period. It is higher than during the preceding dry season because the actual evapotranspiration is limited by the amount of water available. Hence, abstraction is at its peak during the onset phase. Not accounting for this high abstraction leads to an overestimate of the discharge at this time (Figures 4.8 and 5.3).

During the peak-monsoon season, availability of water is no longer a limiting factor, but lower temperatures and high relative humidity, in combination with the increase in the number of rainy days, ensure low evapotranspiration and low initial abstraction.

Immediately after the monsoon peaks, the soil is still saturated. Hence, the runoff responds rapidly to rainfall and the abstraction remains low. Therefore, the catchment rainfall at this time is comparable to the observed discharge (Figures 4.8 and 5.3), but the runoff generated in the model is low, leading to an underestimate of the discharge even if the SCS parameters are allowed to vary spatially (Figure 5.3). Later the soil dries out, but the availability of water becomes the limiting factor and abstraction remains low till the following year’s monsoon onset.

Thus, the SCS parameters exhibit an inherent seasonality that cannot be accounted for by the 5-day AMC parameterisation. In other words, there is a difference between a dry (or wet) spell, based on the 5-day antecedent rainfall, in the dry and wet seasons. Hence, temporal variation of the SCS parameters needs to be incorporated into the rainfall-runoff model.

One way to incorporate seasonality in the SCS parameters is implementing a similar parameterisation like AMC, but for a longer time scale of 30 days. The idea is that a 30-day parameterisation for \( CN(II) \) and \( \lambda \) might be able to capture seasonal or low-frequency variations by accounting for rainfall over a longer time scale in addition to the higher frequency variations. The
basis for this assumption lies in the lower rainfall in May–June compared to August–September, implying a lower (higher) $CN$ during monsoon onset (post-monsoon) for the same 5-day antecedent rainfall. This 30-day AMC-like parameterisation was used in addition to the 5-day AMC. The simulation is better than Simulation $S2$ over only a part of the rainy season, but it is worse at other times.

The reasons for the inability of a second, longer, AMC-like parameterisation to account for the low-frequency variability are the rapid decrease in rainfall following the peak of the monsoon and the sudden increase in rainfall during onset. The soil also does not seem to dry as much during the weak phases of the peak-monsoon season. Such weak spells are different from a similar rainfall regime either during the onset or following the peak monsoon. In other words, it is not enough that a longer, 30-day window is used for determining the runoff: equally important is the location of this window in the seasonal cycle of rainfall. Hence, the temporal parameterisation has to incorporate the seasonal cycle of soil moisture in order to generate the appropriate runoff.

5.3.2 Seasonal variation of SCS parameters

In order to build a time-dependent parameterisation of the SCS parameters, we need to distinguish the different rainfall-runoff regimes during the seasonal cycle and define objective criteria for transition from one regime to another. The only data available, however, are the daily rainfall used to force the model and the observed daily discharge. We use both rainfall and discharge to describe these temporal regimes, but use only the rainfall and its accumulation over the year, which we call cumulative rainfall (CR), as the criteria for transition from one regime to another.

5.3.3 The temporal regimes

The temporal regimes are described in Table 5.2 and depicted graphically in Figure 5.4. The discharge, rainfall, and CR curves show that there exist five distinct temporal regimes in the Mandovi basin. The first regime is the Lean-Season Regime ($A$) at the beginning and end of a calendar
Table 5.2 Classification of hydrological regimes (temporal) and of the transitions from one regime to the next. See Figure 5.4 for the corresponding graph.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Condition</th>
<th>Rain</th>
<th>CR</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Lean-Season</td>
<td>Very dry (scanty rainfall)</td>
<td>Very small</td>
<td>No discharge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transition AB</td>
<td>First spells of rain</td>
<td>Small inflection</td>
<td></td>
</tr>
<tr>
<td>B Onset-Monsoon</td>
<td>Wet unsaturated</td>
<td>Rain in bursts or continuous rain peaks</td>
<td>Rising</td>
<td>Does not respond to rain</td>
</tr>
<tr>
<td></td>
<td>Transition BC</td>
<td>Bigger burst that continues into peak-monsoon (3–6 days into the burst)</td>
<td>First large upslope inflection</td>
<td>Starts responding to rain</td>
</tr>
<tr>
<td>C Peak-Monsoon</td>
<td>Very wet</td>
<td>Intense and continuous</td>
<td>Rising rapidly (with plateaus during weak spells)</td>
<td>Follows rainfall curve</td>
</tr>
<tr>
<td></td>
<td>Transition CD</td>
<td>Rain break (little or no rainfall) for 5 (more) days</td>
<td>Second large downslope inflection</td>
<td>Recedes exponentially</td>
</tr>
<tr>
<td>D End-Monsoon</td>
<td>Wet saturated</td>
<td>late-monsoon active period or rain bursts</td>
<td>Flattening out some bumps</td>
<td>Still responds big rain bursts</td>
</tr>
<tr>
<td></td>
<td>Transition DE</td>
<td>Longer break of 10–15 days</td>
<td>Smooth decline continues</td>
<td></td>
</tr>
<tr>
<td>E Post-Monsoon</td>
<td>Moist unsaturated</td>
<td>Scattered bursts of low rain</td>
<td>Plateau</td>
<td>Stops responding to the rain</td>
</tr>
<tr>
<td></td>
<td>Transition EA</td>
<td>30 days of no rainfall</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>A Lean-Season</td>
<td>Very Dry</td>
<td>No or scanty rainfall</td>
<td>Maximum</td>
<td>No discharge</td>
</tr>
</tbody>
</table>
year. This regime is very dry and the discharge is due to a baseflow that is three orders of magnitude smaller than the peak discharge during the year. The transition (called $AB$) to the second regime, which is the *Monsoon-Onset* Regime ($B$), is marked by the first spells of rain. Regime $B$ is wet, but the soil is unsaturated. In other words, while there is frequent rainfall, the discharge does not respond to the rainfall. The transition ($BC$) to the third regime, which is the *Peak-Monsoon* Regime ($C$), is marked by a big rainfall burst and a sharp inflection of the CR curve; the soil is saturated by now and the discharge starts responding to the rainfall during this transition (instantaneous pooling). Rainfall is more sustained during this transition and lasts a few days, leading to a different slope for the CR curve during this regime in comparison to the Regime $B$. The transition ($CD$) to the next regime, called the *End-Monsoon* Regime ($D$), is marked by a break in rainfall. There is little or no rainfall for five or more days, the CR curve plateaus off (marking a second major inflection point), and the discharge recedes exponentially. During Regime $D$, there are some rainfall bursts, but they are weaker than during Regime $C$, and the discharge still responds to these bursts because the soil is wet and saturated. The transition ($DE$) to the next regime, called the *Post-Monsoon* Regime ($E$), is marked by a longer rainfall break, which lasts for 10–15 days. During this regime, the soil is moist (but unsaturated), and the discharge stops responding to the weak and scattered rainfall. The last transition ($EA$) is back to Regime ($A$): it occurs towards the end of the calendar year and is marked by a longer ($\sim$ 30 days) rainfall break.

### 5.3.4 Objective criteria for transition

The transitions described above need quantification, i. e., a set of objective criteria are needed to determine the period of transition. The criteria we use (see discussion below and Table 5.3) are applied to each grid cell of the Mandovi basin. Hence, a transition can occur on different days for different cells within a spatial region. The rainfall data, however, indicate that the transition occurs for most cells within a week of the first transition in the region.

The rainfall is cumulated starting in January every year because Transition $EA$, marking the
Figure 5.4 The temporal regimes, $A$–$E$, and the inter-regime transitions. The vertical lines mark the transition from one regime to the next. The observed discharge (dotted curve, in Mm$^3$), daily rainfall over one grid cell in a region (solid black curve, in mm), and the cumulative rainfall (CR; solid red curve, in mm) in the cell are shown. The cell chosen has the average rainfall in a region during May–October and is marked by the filled triangle in Figure 5.1. The four panels are for the Ridge (first), Foothills (second), Coast (third), and Lee (fourth) regions during 1992.
Table 5.3 Objective criteria for transition from one regime to the next. Note that CR is estimated starting from the beginning of a year.

<table>
<thead>
<tr>
<th>AB</th>
<th>BC</th>
<th>CD</th>
<th>DE</th>
<th>EA</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>≥ 75 mm</td>
<td>$CR1$</td>
<td>$CR2$</td>
<td>—</td>
</tr>
<tr>
<td>AMC</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>AMC ≤ 30 mm for 5 consecutive days</td>
</tr>
</tbody>
</table>

$P$

1. Sum of 3-day $P \geq 30$ mm.
2. $P \geq 5$ mm on each of 3 days

| $P$ | $P \geq 150$ mm | $P \leq 5$ mm for one day | $P \leq 5$ mm for 15 consecutive days | $P \leq 1$ mm for 30 consecutive days |

Note Both conditions

(1) If $P$ condition true, transition after 5 days. (2) If not, then $CR1$ condition. (3) Transition if one of the above is true

$CR1$
Fit a straight line to the CR data and compare the deviation of the curve from the line. Transition occurs if the deviation (concave-up inflection) exceeds one and half standard deviation for five consecutive days

$CR2$
Fit a straight line to the CR data and compare the deviation of the curve from the line. Transition occurs if the deviation (concave-down) exceeds one and half standard deviation for five consecutive days.
start of the lean-season regime, occurs in December. The first transition to be determined is \(AB\), i.e., the onset date (phase) of the monsoon. Since scattered pre-monsoon showers may occur in April and May, the first condition is that the cumulative rainfall (CR) should exceed 75 mm. A second condition to ensure that an isolated event is not taken to herald the monsoon onset, is that the accumulated rainfall over three consecutive days has to exceed 30 mm and the rainfall on each of these three days has to exceed 5 mm. This latter condition is similar to that used by IMD to determine the date of onset of the monsoon over Kerala [Ananthakrishnan et al., 1968; Pai and Nair, 2009]. A more complex criterion recently adopted by IMD results in a similar date for monsoon onset [Pai and Nair, 2009]. These two conditions constitute the criterion for Transition \(AB\) (Table 5.3).

The second transition, \(BC\), is marked by a sharp increase in rainfall, and the CR curve shows a sharp, concave-upward inflection (Figure 5.4), which we capture by noting the deviation of the curve from a line fitted to the CR curve over Regime \(B\). This procedure is implemented as follows.

1. First, Regime \(B\) is assumed to last at least \(LC\) (least count, set to 5) days. From the starting point (\(SP\)) of Regime \(B\), a least-squares regression line is fitted to the CR curve.

2. Once Regime \(B\) is \(LC\) days long, a comparison is made between the actual deviation (\(AD\)) of the curve from this line with the positive standard deviation (\(PSD\)) of the fitted line; the difference between these two deviations (\(IC\) is \(AD\) minus \(PSD\)) is a measure of the concave-up inflection of the CR curve.

3. If \(IC\) exceeds zero for a minimum number of days (\(MD\)), then transition is declared on the last of these \(MD\) days.

\(LC\) and \(MD\) are determined by the typical time scale associated with these rain events. Rainfall observations suggest that the time scale for this period is \(\sim 5\) days, the typical time scale for dry and wet spells [Kulkarni et al., 2006]. Thus, we set the minimum number of days for both
LC and MD to 5. It is worth mentioning here that MD is not equated to one so as to prevent an isolated rain event from determining the transition. Such an isolated event can, however, change the hydrological characteristics of the cell if the rainfall associated with this event exceeds some threshold. Hence, if the rainfall on some day during Regime B exceeds 150 mm, transition BC is assumed to take place five days after this event. Thus, two conditions constitute the criterion for BC, but only one of these two conditions has to be fulfilled for the transition to take place (Table 5.3).

The third transition, CD, is opposite to BC. The CR curve plateaus off, resulting in another sharp inflection, but now in the opposite direction, i.e., the inflection is concave-down (Figure 5.4). Regime C is assumed to last at least 60 days. This is a reasonable time-period since the core of the summer monsoon lasts through July and August. The procedure to detect CD remains similar, but opposite to that used for BC. In other words, if IC is less than zero for MD consecutive days and rainfall is less than or equal to 5 mm for a day, then transition CD is deemed to occur. As done for transition BC, MD was set to 5 for CD. The second condition, that rainfall is less than or equal to 5 mm for a day, is needed to ensure that the transition does not take place during a rainfall burst, even if it is a weak event (Table 5.3).

Once Regime D sets in, the CR curve is too flat to be used as a criterion to determine Transition DE (Figure 5.4). Hence, the following two conditions constitute the DE criteria. First, the 5-day antecedent rainfall has to be less than 30 mm for five consecutive days. Once the first condition is fulfilled, then the rainfall has to be less than 5 mm for 15 consecutive days for Transition DE to occur. Once the first condition is fulfilled, if the rainfall exceeds 5 mm after (say) 10 days, then only the second condition is used again: the first condition is applied only once, but the second is used more than once, if necessary, to determine the transition (Table 5.3).

The transition to the lean-period regime, EA, is deemed to occur if the daily rainfall is equal to or less than the trace rainfall (1 mm) for 30 consecutive days. Transition EA occurs in December, and from January, the next year’s CR is computed (CR is reset to 0 on 1 January) and the process
is repeated.

### 5.3.5 Estimation of the SCS parameters

The SCS parameters have to be estimated for each regime for each of the four regions. The AMC thresholds were determined the same way as done for \( S_1 \) and \( S_2 \) (Figures 4.7 and 5.2): \( 1/e \) (\( \sim \) 36\%) of the days in a regime had rainfall above the lower threshold and \( 1/e^2 \) (\( \sim \) 14\%) of the days had rainfall over the higher threshold; \( \sim \) 22\% of the days experienced the “average” rainfall. The AMC thresholds are listed in Table 5.4.

The exceptions to this rule were Regimes B and C. During Regime C, the Peak-Monsoon Regime, it rains on most days and the soil is wet and saturated. Therefore, the discharge curve follows closely the rainfall curve (Figure 4.1), and almost all the rain is expected to run off on most days even if the rainfall is relatively low. Hence, the thresholds for Regime C (Table 5.4) were determined using an inversion of the exponential cut-offs used earlier. We assumed that only \( 1/e^2 \) (\( \sim \) 14\%) of the days were dry, or had rainfall below the lower threshold (\( CN(I) \)), and \( 1/e \) (\( \sim \) 36\%) of the days were wet, or had rainfall below the higher threshold. Thus, \( \sim \) 22\% of the days had average rainfall (\( CN(II) \)) and \( \sim \) 64\% of the days had rainfall over the higher threshold (\( CN(III) \)).

During Regime B (onset of monsoon), the discharge does not correspond to the rainfall curve. Since it needs to rain more for the rain water to run off during this regime, we assumed that \( 1/e^2 \) (\( \sim \) 14\%) of the days had rainfall over the lower threshold and \( 1/e^3 \) (\( \sim \) 5\%) of the days had rainfall over the upper threshold. Thus, \( \sim \)9\% of the days in this regime experienced average rainfall, 5\% heavy rainfall, and \( \sim \) 86\% low rainfall; hence, most days in this regime were set to \( CN(I) \).

Just as the AMC thresholds show considerable variation with season, so must \( CN \) and \( \lambda \). We used the “mean conditions” to define the average basin \( CN(II) \) and used this \( CN(II) \) to estimate the dry-period and wet-period \( CN(II) \). The average conditions are represented for the Mandovi by Regime E, the post-monsoon season, when the soil is still moist but unsaturated.
Hence, the average $CN(II)$ used for the four regions were applied to this regime. We used this $CN(II)$ and Equation (4.8a) to estimate the dry-period $CN(II)$, which was applied to Regime B, the monsoon-onset phase, and used it and Equation (4.8b) to estimate the wet-period $CN(II)$, which was applied to Regime D, the end-monsoon phase. Regime A is even drier and represents an extreme case in which there is little spatial variation in the basin’s hydrological characteristics: hence, the lowest $CN(II)$ value (40) noted in the literature [Mishra and Singh, 2003] was applied to all regions in this regime. There is less spatial variation during the extremely wet and extremely dry periods in comparison to the moderately wet periods. Regime C is also an extreme case and almost all the rainfall is converted to surface runoff because the soil is completely saturated. Hence, for this regime, we set the $CN(II)$ for all four regions to 90. Empirical estimates of $CN(II)$ for Indian watersheds spanning a range of hydrological regimes suggest that a high value is appropriate during rainfall events [Mishra and Singh, 2003]. The $CN(II)$ values we use are comparable to, but less than, the ones reported by Mishra and Singh [2003] because their estimates were based on very few events.

Thus, $CN(II)$ varies in both space and time. The spatial variation for selected days during each regime is shown in Figure 5.5 and the temporal variation at the four locations marked in Figure 5.1 is shown in Figure 5.6. Shankar et al. [2004] and Suprit and Shankar [2008] also noted that another variable that might require parameterisation is the residence time for the subsurface-runoff reservoir ($T_D$ in Figure 2.2). Their conjecture was that the residence time was likely to vary in space and time, just as $\alpha$ seems to do. Simulations show, however, that the small baseflow in the Mandovi basin implies a minor role for $T_D$ in the water balance. Hence, for all the simulations, we keep $T_D$ constant (15 days).
Figure 5.5 Variation of $CN$ in the basin on selected days during each temporal regime in 1992. Regimes A (top left), B (top right), C (middle left), D (middle right), E (bottom left) and back to regime A (bottom right). Note that the scales are different.
Figure 5.6 Variation of CN in time for the four regions. The locations are marked by the filled triangles in Figure 5.1.
5.4 Results and discussion

5.4.1 Simulation S3

Simulation S3 was made using the spatio-temporally varying parameters listed in Table 5.4. The results (Figure 5.7) show a significant improvement over Simulation S2 (and Simulations S0 and S1; Figure 5.8). The simulated discharge matches the observed discharge better across a range of conditions. Specifically, the simulated discharge increases during the rainfall bursts in July, August, and September, resulting in a better match with observations. The increase in discharge, however, is also seen during the weak spells in early July, when Simulation S3 performs worse than Simulation S2. The sharp increase in CN with Transition BC increases the discharge even during the weak spells. It also leads to an erroneous increase in the discharge during the second rainfall burst at the time of transition: the lower CN in Simulation S2 leads to the simulated discharge being closer to that observed. The results for the other two years, 1986 and 1990, are similar (Figure 5.7).

The correlation for Simulation S3 is comparable to that for Simulation S2 (Table 5.5). Error histograms for Simulations S1, S2, and S3 show that the major improvement in S3 is the lack of underestimation of discharge (Figure 5.9). Though Simulation S3 has a greater tendency to overestimate the discharge during June–August, there is an overall improvement. Figure 5.8 shows that Simulation S3 is much better than S0, S1, and S2. It captures the variability better over the range of temporal hydrological regimes.

5.4.2 Evapotranspiration and abstraction

The initial abstraction represents the minimum amount of rainfall required to generate surface runoff. It is the only loss term in the model and represents the water lost to the atmosphere owing to evaporation and transpiration (evapotranspiration). In the model, this abstraction is a function of the initial abstraction coefficient (λ) and Curve Number (CN); the CN, in turn, depends on the
Table 5.4 SCS parameters for Simulation S3 (spatial and temporal variation). The numbers in parentheses in the first column represent the parameter choices for Simulation S2; these parameters are used for Regime E. The $CN(II)$ for Regime B is computed using Equation (4.8a) and the $CN(II)$ for Regime E, and the $CN(II)$ for Regime D is computed using Equation (4.8b) and the $CN(II)$ for Regime E. Regime E therefore represents the average or central hydrologic regime, Regimes B and D the dry and wet regimes, and Regimes A and C the extremely dry and wet regimes.

<table>
<thead>
<tr>
<th>Region</th>
<th>Lean Period (A)</th>
<th>Onset Monsoon (B)</th>
<th>Peak Monsoon (C)</th>
<th>End Monsoon (D)</th>
<th>Post Monsoon (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee (65)</td>
<td>Very dry (Unsaturated)</td>
<td>Wet</td>
<td>Very wet</td>
<td>Wet</td>
<td>Moist (Unsaturated)</td>
</tr>
<tr>
<td>Ridge (75)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foothills (70)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coast (60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Curve Number CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee (65)</td>
<td>40   44 90 81 65</td>
</tr>
<tr>
<td>Ridge (75)</td>
<td>40   56 90 87 75</td>
</tr>
<tr>
<td>Foothills (70)</td>
<td>40   49 90 84 70</td>
</tr>
<tr>
<td>Coast (60)</td>
<td>40   40 90 78 60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Initial abstraction coefficient ($\lambda$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee (0.3)</td>
<td>0.3  0.2 0.05 0.2 0.3</td>
</tr>
<tr>
<td>Ridge (0.05)</td>
<td>0.3  0.2 0.05 0.05 0.2</td>
</tr>
<tr>
<td>Foothills (0.1)</td>
<td>0.3  0.2 0.05 0.05 0.2</td>
</tr>
<tr>
<td>Coast (0.3)</td>
<td>0.3  0.2 0.05 0.2 0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>AMC (5-day antecedent rainfall range in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee (100–200)</td>
<td>30–40  200–250  50–100  20–40  5–20</td>
</tr>
<tr>
<td>Ridge (150–400)</td>
<td>40–70  300–450  100–200  30–60  5–20</td>
</tr>
<tr>
<td>Foothills (100–250)</td>
<td>50–70  350–450  50–100  20–50  5–20</td>
</tr>
<tr>
<td>Coast (100–200)</td>
<td>50–60  400–450  50–100  20–50  5–20</td>
</tr>
</tbody>
</table>
Figure 5.7 Daily observed discharge (black), discharge simulated by Simulation S3 (red), and the catchment-integrated rainfall (blue) at Ganjem for May–October for three validation years. (A) 1986. (B) 1992. (C) 1990. The units are Mm$^3$/day. The bold tick marks on the abscissa indicate beginning and end of a month.
Figure 5.8 Daily observed discharge (black), catchment-integrated rainfall (blue), and simulated discharge (red) for May–October 1992. The units are Mm$^3$. (A) Simulation S0. (B) Simulation S1. (C) Simulation S2. (D) Simulation S3. The bold tick marks on the abscissa indicate beginning and end of a month.
Table 5.5 A brief description of the simulations and their results (Figure 5.8). The last column lists the square of the correlation between the simulated and observed discharge over the period May–October. The first number is the correlation for the three years (1986, 1990, and 1992) used to calibrate the model; the second number (in parentheses) is for the other 15 years (model validation). The major improvement occurs with the inclusion of the SCS method in Simulation S1. The other refinements — spatial and temporal variation of the parameters — result in improvements over a part of the simulation, but the overall May–October correlation does not improve any more.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Detail</th>
<th>Parameters</th>
<th>Simulated discharge</th>
<th>r²</th>
</tr>
</thead>
</table>
| S0         | Only THMB  
(No SCS) | α = 0.3  | Figure 4.2  | 0.68  
(0.67) |
| S1         | THMB+SCS  
simulation  
(constant parameters) | CN (II) (70)  
λ (0.2)  
AMC  
(100–250 mm) | Figure 4.8  | 0.78  
(0.76) |
| S2         | THMB+SCS  
simulation  
(spatially varying parameters) | Table 5.1  | Figure 5.3  | 0.78  
(0.77) |
| S3         | THMB+SCS  
simulation  
(spatio-temporal varying parameters) | Table 5.4  | Figure 5.7  | 0.79  
(0.80) |
Figure 5.9 Absolute error histograms showing the difference between simulated and observed discharge (Mm$^3$) for the Simulations S1, S2 and S3. Histograms are drawn for the three calibrations year 1986, 1992, and 1990 during the summer monsoon (June–September). The ordinate shows number of days averaged over three years. The vertical lines indicate the standard deviation.
average-condition \( CN \) (\( CN(II) \)) and the AMC thresholds.

The simulations suggest high abstraction during the monsoon-onset regime (\( B \)) (Figure 5.10). Abstraction decreases sharply following monsoon onset and increases again slightly after the monsoon. It is low in the dry season because the limiting factor then is the availability of moisture. It is shown by Shankar et al. [2004] and Suprit and Shankar [2008] in their annual simulation that evapotranspiration is very small compared to rainfall. Therefore, in the Mandovi basin, the net fractional abstraction during the year is low because the abstraction is negligible when the rainfall peaks. It is only during the onset phase that the fraction of rainfall abstracted (\( \sim 68\% \) over the 18 years for June) matches the high values suggested for India by some recent studies [Jain et al., 2007; Narasimhan, 2008]. Similar profiles have been estimated for evapotranspiration using the Penman method for some west-coast cities [Krishna Kumar et al., 1987] and for reference (or potential) evapotranspiration using satellite data for the Krishna basin (Musı River) [Bouwer et al., 2008]. It is also evident from the simulations that large-scale data sets like those based on the NCEP-NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) Reanalyses [Kalnay et al., 1996] considerably underestimate the abstraction (Figure 5.10).

### 5.4.3 Discussion

We built the model parameterisation using data for only three of the 18 years (Figure 4.4) for which rainfall and discharge data are available. Validation of the model is done using the data for the other 15 years. The error histogram for these 15 years (Figure 5.11) is similar to that for the three years (Figure 5.11). The results of Simulation \( S3 \) for all the 15 other years are shown in Figure 5.12. The model parameterisation works as well for the entire data set as it does for the three calibration years (Table 5.5). Indeed, the strength of Simulation \( S3 \) lies in its ability to simulate the discharge better across the spectrum of variability from the seasonal to the inter-annual (Figure 5.13). The simpler 5-day AMC parameterisation fails to account for this spectrum
of variability not only over a season, but also across years.

Nevertheless, there is a tendency to overestimate the discharge at some times in some years. In 1990 and 1995 (Figures 5.7 and 5.12), Transition BC occurs a little earlier than it probably should, the peak-monsoon regime sets in early, and the simulated discharge is higher at the beginning of Regime C. In 1992 and 1998 (Figures 5.7 and 5.12), there is a long break during the peak-monsoon season and the soil probably becomes unsaturated; hence, the discharge is overestimated. Other than these discrepancies, the model performance is remarkable, and the simulated discharge correlates well with the observed discharge across all the regimes (Table 5.5). Note that the major improvement in the correlation (Table 5.5) was achieved by incorporating the SCS method, i.e., the correlation increased significantly from Simulation S0 to S1, but there was not much change in correlation from Simulation S1 to Simulation S3. The improvement brought about by incorporating the spatio-temporal variation is more subtle: the temporal variation helps improve the discharge simulation across all temporal regimes, and though it is not possible to verify it, the spatial variation probably helps improve the simulation across all regions.

In summary, even for a small basin like the Mandovi, the variations in space and time are significant enough for them to be incorporated in the rainfall-runoff model. Since the Mandovi is a typical west-coast river, our framework has major implications for the hydrology of other west-coast rivers. A discussion on the strengths and caveats of the framework, and of its applicability to other west-coast rivers is the topic of the next chapter.
Figure 5.10 Abstraction (blue curve) during May–October in Simulation S3. The observed discharge (black curve) and the evapotranspiration from the NCEP-NCAR Reanalysis (red curve) are also plotted. The units are $\text{Mm}^3$. The bold tick marks on the abscissa indicate beginning and end of a month. (a) 1992. (b) 1986. (c) 1990.
Figure 5.11 Absolute error histograms showing the difference between simulated and observed discharge (Mm$^3$) for the Simulations $S_1$, $S_2$ and $S_3$. Histograms are drawn for the 15 validation years (1981–1998 excluding years 1986, 1992, and 1990) during the summer monsoon (June–September). The ordinate shows number of days averaged over 15 years. The vertical lines indicate the standard deviation.
Figure 5.12 Daily observed discharge (black), discharge simulated by Simulation S3 (red), and the catchment-integrated rainfall at Ganjem (blue) for May–October (a) 1981, (b) 1982, (c) 1983, and (d) 1984. The units are Mm$^3$. The bold tick marks on the abscissa indicate beginning and end of a month.
Figure 5.12 (continued) Daily observed discharge (black), discharge simulated by Simulation S3 (red), and the catchment-integrated rainfall at Ganjem (blue) for May–October (a) 1985, (b) 1987, (c) 1988, and (d) 1989. The units are Mm$^3$. The bold tick marks on the abscissa indicate beginning and end of a month.
Figure 5.12 (continued) Daily observed discharge (black), discharge simulated by Simulation $S_3$ (red), and the catchment-integrated rainfall at Ganjem (blue) for May–October (a) 1991, (b) 1993, (c) 1994, and (d) 1995. The units are Mm$^3$. The bold tick marks on the abscissa indicate beginning and end of a month.
Figure 5.12 (continued) Daily observed discharge (black), discharge simulated by Simulation S3 (red), and the catchment-integrated rainfall at Ganjem (blue) for May–October (a) 1996, (b) 1997, and (c) 1998. The units are Mm$^3$. The bold tick marks on the abscissa indicate beginning and end of a month.
Figure 5.13 Correspondence plot between the daily observed discharge (abscissa; Mm$^3$) and simulated discharge (ordinate; Mm$^3$) for June–September for the 15 validation years. Simulation $S_3$ (red hollow circles) performs much better than Simulations $S_1$ (hollow blue stars) and $S_2$ (filled black triangles). The maximum daily observed discharge is 406.5 Mm$^3$, but we have truncated the abscissa to 200 Mm$^3$. Only seven data points were discarded over the 15 years (1830 days): discharge is in the range 200–250 Mm$^3$ on four days, in the range 250–300 Mm$^3$ on two days, and is 406.5 Mm$^3$ on one day. The underestimation seen in the simulations occurs mostly during July–August, and arises owing to the underestimation of peak rainfall events in the basin.