CHAPTER VII

ASSESSMENT OF SURPLUS RAINFALL USING THORNTHWAITE - MATHER SOIL MOISTURE ACCOUNTING METHOD DURING 1972-2005

7.1 Introduction

We live in the age of environmental alertness. For sustainability and effective utilization of resources, more refined information about the water balance components for management of the water resources is mandatory. Water availability, sufficiency or scarcity of a region greatly depends on its climate, topography, geology and the demand placed upon the existing water resources. The processes which influence the water scarcity can be broadly divided into natural and man induced processes. The natural climatic drivers are e.g. low average rainfall, high rainfall variability, large dry spells, frequent droughts, higher temperature, changing wind patterns, more evaporative demand etc. while man-induced climatic factors are like high temperatures, increased flood risks, changing vegetation conditions etc. Unfavorable climatic conditions coupled with unfavorable topography and geology affect the hydrologic characteristics of that region. Low infiltration, lower soil moisture, high erosion, low groundwater recharge changes the rainfall-runoff relationship and affects the general water availability of that region. (Pereira et.al.2009). The Intergovernmental panel on climate change (IPCC; Kundzewicz 2007) concluded the impacts of climate change on fresh water resources as,

- By mid-century, annual average river runoff and water availability are projected to increases by 10-40% at high latitudes and in some wet tropical areas, and decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics, some of which are presently water stressed areas.

- Drought-affected or water stressed areas will likely increase in extent.

- Heavy precipitation events are very likely to increase in frequency and intensity, and thus to augment flood risks.

- In the course of the century, water supplies stored in glaciers and snow cover are projected to decline, reducing water availability in the regions supplied by melt-
water from major mountain ranges, where more than one-sixth of the world population currently lives.

Unfortunately, there are many non-climatic drivers that affect fresh water resources at all scales, including the global scale. Water resources, both in terms of quantity and quality are critically influenced by human activity, including agriculture and land-use change, construction and management of reservoirs, pollutant emissions and water and wastewater treatment. Water use is linked primarily to changes in population, food consumption (including type of diet) economic policy (including water pricing), technology, lifestyle and society's views about the value of freshwater ecosystems (Bates et.al. 2008). Increase in demand for water for agricultural production can cause disturbances in the demand for natural ecosystems. These disturbances will affect the vulnerability of those natural ecosystems and produce imbalances in supply mainly in water scarce region (Kaiser and Drennen 1993, Rozenzweig and Hillel 1998). Data on the dynamics of water use and consumption shows that on global scale, the water withdrawals have nearly grown by 7 times since 1900, in Australia more than 29 times; in Europe 12 times; 10 times in North and South America; 6 times in Asia and elsewhere (Shiklomanov and Roddha 2003). This expansion of water use all over the world shows that the water scarcity is already a worldwide problem. Overall water availability will be diminished by the demand for water likely to increase. There is strong need to overcome these problems by improving management strategies, adaptation measures and creating awareness of water issues among the water users. Still there are many regions across the globe where potential water availability is above 10,000 m\(^3\)/capita/year and withdrawal is below 20%. In these regions just the requirement is to improve the water management while for water stressed regions, the problem is to find innovative approaches to cope with water scarcity.

In India the growing human population with raised lifestyle is the major non-climatic driver for water stress rather than climate change. It is estimated that gross per capita water availability will decline from ~1820 m\(^3\)/year in 2001 to as low as ~1140 m\(^3\)/per year (CWC, 2005; Gupta and Deshpande, 2004). Real-time climate-monsoon monitoring without any prejudice and heresy is however a necessity for development and management of water resources. According to Dam Safety Organization (DSO, CWC, Govt. of India) there were 3634 large dams in India in 1989, increase to 4291 dams in 1994, to 4525 in 2002 and 5101 in January 2009 (CWC, 2009).
In Chapter II, we provided a large-scale seasonal water balance using longest available instrumental monthly rainfall data (1813-2006) to understand fluctuations of seasonal rainfall and surplus rainfall. In the study, the surplus rainfall was grossly estimated. While this program was going on, a high resolution daily rainfall and maximum and minimum temperature data became available, albeit for short period 1972-2005. The two main objectives of the present study are,

1. To make a realistic assessment of surplus rainwater using available actual daily rainfall of 0.5-DSG (degree square grid), daily maximum and minimum temperature of 1-DSG spatial resolution for the period 1972-2005, and field capacity of 1380 locations; and
2. To evaluate against this assessment the assessment of surplus rainwater given in the Chapter II.

7.2 Data Used

1. Daily rainfall of 0.5-DSG spatial resolution for the period 1972-2005 (source: India Meteorological Department).
2. Daily maximum and minimum temperature of 1-DSG for the period 1972-2005 (source: India Meteorological Department).
3. Field capacity from well spread 1380 locations (source: National Bureau of Soil Survey and Land Use Planning or NBSS & LUP; Mandal et al., 1999).

7.3 Estimation of Potential Evapotranspiration (PE)

From the arithmetic mean of 1-DSG daily maximum and minimum temperatures, daily mean temperature is obtained, and from the daily mean temperature, monthly mean temperature is calculated. Although more than half a century has passed since its discovery, the Thornthwaite’s method of potential evapotranspiration (PE), soil water balance computation and climatic classification have provided acceptable solution in different environment. The empirical equation of Thornthwaite which relates to the (PE) with mean air temperature is as follows:

\[
PE = 1.6 \left(10^\frac{T}{I}\right)^a
\]  \hspace{1cm} (7.1)

where PE is the monthly potential evapotranspiration, T is the monthly mean air temperature (°C), I is a heat index for the station which is the sum of 12 monthly heat indices i given by.
i = (T/5)^{1.514} \ldots (7.2)

and a is a cubic function of I (Thornthwaite and Mather, 1955 and 1957).

\[ a = 0.000000675 I^3 - 0.0000771 I^2 + 0.01792 I + 0.49239 \ldots (7.3) \]

This formula gives unadjusted values of thermal efficiency which means in the formula each month is of 30 days and duration of sunshine 12 hours. The adjusted PE can be obtained from the number of days in the particular month and actual duration of sunshine dependent on latitude of the station. In the present study monthly PE is divided into equal daily PE of the particular month. The monthly PE is distributed equally in the daily PE of the particular year and in the 0.5-DSG of the particular 1-DSG. Normal annual PE across the country is shown in Figure 7.1. The annual PE varies from ~300mm over upper reaches of the Western Ghats to ~2400mm over western Indo-Gangetic Plains and northwest India.

Generation of 0.5-DSG field capacity (FC) from the available field capacity data from 1380 locations is conducted by applying inverse square distance method. The distribution of FC from 50 to 250mm across the country is shown in Figure 7.2.

### 7.4 The Water Balance Computation

Following soil moisture budgeting scheme of Thornthwaite and Mather (1957), the daily water balance for each of 1100 0.5-DSGs has been carried out for the period 1972-2005.

\[ ST_i = \min [(ST_{i-1} + P_i - PE_i), \quad FC] \]

\[ if \ P_i \geq PE_i \quad then \quad E_i = PE_i \]

\[ if \ P_i \lt PE_i \quad then \quad E_i = P_i + [ST_{i-1}(1-e^{P_i-PE_i/F.C.})] \]

where,

- \( ST_i \) = soil moisture storage on day \( i \)
- \( AE_i \) = Actual evapotranspiration
- \( PE_i \) = potential evapotranspiration
- \( P_i \) = precipitation
- F.C. = Field Capacity
- D = Deficit = PE − AE
- S = Surplus = ST_{i-1} + P − AE - ST_i
The spatial distribution of mean annual actual evapotranspiration (AE) is shown in Figure 7.3 and surplus rainfall (S) in Figure 7.4. The mean annual AE across the country varies from 300mm in northwest India to 1000mm along the West Coast and the S from less than 50mm in northwest India to about 5000mm in parts of extreme northeast India. Climatology of the water balance parameters (P, PE, AE, D and S) for major and independent minor basins as well as for the whole country is given in Table 7.1. The time series of the area-averaged P, PE, AE, D, S, AE/P and S/P is shown in Figure 7.5. Visibly the different series are homogeneous and random. So for the whole country, the water balance parameters are stationary but on regional scale there are some differences in the fluctuations of the parameters. The time series of S for the major basins is shown in Figure 7.6 and for independent minor basins in Figure 7.7. Some decline in S can be seen in recent years over the basins in the north and central India and increase in peninsula. It may be noted that according to daily water balance also 60% of the annual rainfall returns to the atmosphere through the evaporation-transpiration processes and remaining 40% contributes to the deep aquifer recharge, surface water storage and flows in the rivers and extremes. On yearly basis, however a reliable estimate of S can be obtained from P using following the equation (Equ. 7.5; Figure 7.8)

\[ S = -261.55 + 0.6283 \times P \quad (r = 0.95) \quad \cdots \quad (7.5) \]

Further, for basin-scale hydrological water resource applications the S and P relationship for 12 major basins is given in Figure 7.9 and for 9 independent minor basins in Figure 7.10 along with scatter diagram and linear regression fit. The CC is lowest (0.89) for the Indus river basin and highest (0.99) for the WCDS. Nevertheless, for all the major and independent basins the CC is significant at 0.01% level and above.

### 7.5 Sensitivity of rainfall partitioning to Field Capacity

The FC of the underlying soil plays an important role in water balance computation. Wherever the FC is higher more rain is stored in the soil which return to the atmosphere through the evapotranspiration during dry spell, and lesser portion of rainfall is transformed into runoff. On the other hand, if the FC is lower greater portion of rainfall is transformed to runoff. As an academic exercise, a sensitivity experiment has been carried out to understand the role of FC on the portioning of rainfall into evapotranspiration and surplus rainfall. In the first leg of the experiment, the daily water balance for 0.5-DSG has been carried out for the period 1972-2005 assuming field capacity of each grid zero...
(compact, hard, rocky terrain). Mean AE and S has been obtained for the whole country, each of the 12 major basins and 9 independent minor basins. In the each new leg, the FC is increased by 10mm and continued till the FC became 1000mm (loose, porous, thick alluvial soil). variation in the mean AE/P ratio and the S/P ratio against FC is shown in Figure 7.11 for the whole country, in Figure 7.12 for the major basins and Figure 7.13 for independent minor basins. For the whole country, the AE/P increases in a nonlinear manner with the FC from 32% to 80% and the S/P decreases in a nonlinear manner from 68% to 20%. Similar behavior of AE/P and S/P by changes in FC can be seen for most of the major and independent minor basins. However, in the high rainfall basins of the Brahmaputra, the WCDS and the Surma basins the variations in AE/P and S/P is smaller. For the Brahmaputra, the AE/P varies from 30-50% and S/P from 70-50%; for the WCDS the AE/P from 18-42% and S/P from 82-58%; and for the Surma, the AE/P from 24-48% and the S/P from 76-52%. Hence, influence of FC on portioning of rainfall into AE and S in high rainfall basins is marginal.

**INDUS MAJOR BASIN**

There are six major dams in the basin: Bhakra Dam and Kol Dam on the Satluj River; Pong Dam on the Beas; Salal Dam on the Chenab; and Chamera Dam and Ranjit Sagar on the Ravi. The basin annually receives 68.26 bcm (billion cubic meter) of rainwater, 57.81 bcm of which evaporates and 10.46 bcm goes to different hydrological processes. It may be noted that the contribution of glacial melt to the annual river flow is 44.8%. According to the Central Water Commission (CWC) the average annual surface water potential is 73.31 bcm and the storage capacity 16.57 bcm. The correlation between the surplus rainwater according to large-scale water balance approach (LSWB-SRW) and that according to the Thornthwaite-Mather soil moisture budgeting method (TMSMB-SRW) is 0.77 (significant at 0.1% level and above; Table 7.2). So, the longest sequence of surplus rainwater reported in Chapter II (1844-2006) according to the LSWS can be reconstructed based on the surplus rainwater according to the TMSMB.

**GANGA MAJOR BASIN**

There are ten major dams in the basin: Ghandhi Sagar and Ranapratap Sagar on the Chambal River; Ramganga Dam on the Ramganga River; Tehri Dam on the Bhagirathi River; Matatila Dam and Rajghat on the Betwa River; Rihand Dam on the Rihand River; Kishan Dam on the Tons River; and Lakhwar and Vyasi Dams on the Yamuna River.
Further, there are two major dams on the Ganges River— one near Haridwar (built by the British in 1854; Uttrakhand State) and another Farakka barrage (completed in 1974-75; West Bengal State). The dam near Haridwar diverts much of the Himalayan snow-melt into the Upper Ganges Canal to irrigate the surrounding agricultural land. Farakka is the longest barrage in the world with 101 gates. The average annual surface water potential is 525.02 bcm and the storage capacity 60.66 bcm. The basin annually receives 829.68 bcm of rainwater, 588.8 bcm of which evaporates and 241.13 bcm goes to different hydrological processes. The contribution of glacial melt to the annual river flow is 9.1%. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.83 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1829-2006.

**Brahmaputra Major Basin**

The basin annually receives 480.04 bcm of rainwater, 211.35 bcm of which evaporates and 268.9 bcm goes to different hydrological processes. The average annual surface water potential is 585.6 bcm and the storage capacity 11.68 bcm. The contribution of glacial melt to the annual river flow is 12.2%. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.74 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1848-2006.

**Godavari Major Basin**

There are four major dams in the basin: Sriam Sagar and Jayakwadi Dams on the Godavari River; Isapur Dam on Penganga River; and Indravati on the Indravati River. The basin annually receives 356.83 bcm of rainwater, 236.77 bcm of which evaporates and 120.05 bcm goes to different hydrological processes. The average annual surface water potential is 110.54 bcm and the storage capacity 31.33 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.89 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1826-2006.

**Krishna Major Basin**

There are seven major dams in the basin: Nagarjuna Sagar, Srisailam (Pulichintala) and Almatti Dams on the Krishana River; Tungabhadra Dam on the Tungabhadra River; Koyna Dam on the Koyna River; and Ujjani Dam on the Bhima River. The basin annually
receives 217.34 bcm of rainwater, 160.23 bcm of which evaporates and 57.09 bcm goes to different hydrological processes. 31.33. The average annual surface water potential is 78.12 bcm and the storage capacity 49.55 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.57 (significant at 0.1% level). The longest surplus rainwater series for the basin can be reconstructed for the period 1826-2006.

**SABARMATI MAJOR BASIN**

The basin annually receives 31.56 bcm of rainwater, 22.39 bcm of which evaporates and 9.16 bcm goes to different hydrological processes. The average annual surface water potential is 3.81 bcm and the storage capacity 1.37 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.26 (statistically not significant).

**MAHI MAJOR BASIN**

There are two major dams in the basin: Kadana Dam and Mahi Bajaj Sagar on the Mahi River. The basin annually receives 44.58 bcm of rainwater, 29.22 bcm of which evaporates and 14.86 bcm goes to different hydrological processes. The average annual surface water potential is 11.02 bcm and the storage capacity 4.98 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.90 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1857-2006.

**NARMADA MAJOR BASIN**

There are three major dams in the basin: Bargi, Indirasagar and Sardarsarover Dams on the Narmada River. The basin annually receives 114.78 bcm of rainwater, 68.76 bcm of which evaporates and 46.05 bcm goes to different hydrological processes. The average annual surface water potential is 45.64 bcm and the storage capacity 23.6 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.90 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1844-2006.

**TAPI MAJOR BASIN**

There are two major dams in the basin: Ukai and Bham Dams on the Tapi River. The basin annually receives 58.74 bcm of rainwater, 44.62 bcm of which evaporates and 14.15 bcm goes to different hydrological processes. The average annual surface water potential is 14.88 bcm and the storage capacity 10.26 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.83 (significant at 0.1% level and above).
Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1845-2006.

**Mahanadi Major Basin**

There is one major dam in the basin: Hirakud dam on the Mahanadi River. The basin annually receives 189.54 bcm of rainwater, 119.38 bcm of which evaporates and 70.09 bcm goes to different hydrological processes. The average annual surface water potential is 66.88 bcm and the storage capacity 14.21 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.88 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1848-2006.

**Cauvery Major Basin**

There are two major dams in the basin: Krishnarajsagar and Mettur Dams on the Cauvery River. The basin annually receives 78.05 bcm of rainwater, 53.97 bcm of which evaporates and 24.22 bcm goes to different hydrological processes. The average annual surface water potential is 21.36 bcm and the storage capacity 8.87 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.22 (statistically not significant).

**West Coast Drainage System**

The basin annually receives 323.23 bcm of rainwater, 89.99 bcm of which evaporates and 233.29 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.77 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1838-2006.

**Luni Basin**

The basin annually receives 36.08 bcm of rainwater, 28.04 bcm of which evaporates and 8.03 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.85 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1856-2006.

**Surma Basin**

The basin annually receives 189.41 bcm of rainwater, 73.06 bcm of which evaporates and 116.36 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.66 (significant at 0.1% level and
above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1849-2006.

**Kasai Basin**

The basin annually receives 58.09 bcm of rainwater, 35.18 bcm of which evaporates and 18.02 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.70 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1831-2006.

**Damodar Basin**

There are two major dams in the basin: Panchet and Tenughat dams on the Damodar River. The basin annually receives 94.78 bcm of rainwater, 65.76 bcm of which evaporates and 29.05 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.67 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1829-2006.

**Suvarekha Basin**

There is one major dam in the basin: Chandil Dam on the Suvarekha River. The basin annually receives 54.62 bcm of rainwater, 37.97 bcm of which evaporates and 16.66 bcm goes to different hydrological processes. The annual average surface water potential is 12.37 bcm and the storage capacity 2.32 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.74 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1848-2006.

**Brahmani Basin**

There is one major dam in the basin: Rengali Dam on the Brahmani River. The basin annually receives 73.22 bcm of rainwater, 48.14 bcm of which evaporates and 25.07 bcm goes to different hydrological processes. The annual average surface water potential is 28.48 bcm and the storage capacity 5.52 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.66 (significant at 0.1% level and above). Reliable longest instrumental surplus rainwater series for the basin can be reconstructed for the period 1871-2006.

**Penner Basin**
There is one major dam in the basin: Somasila Dam on the Penner River. The basin annually receives 85.05 bcm of rainwater, 58.91 bcm of which evaporates and 26.19 bcm goes to different hydrological processes. The annual average surface water potential is 6.32 bcm and the storage capacity 4.82 bcm. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.56 (significant at 1% level). The longest surplus rainwater series for the basin can be reconstructed for the period 1813-2006.

**PALAR BASIN**

The basin annually receives 35.55 bcm of rainwater, 25.88 bcm of which evaporates and 9.74 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.52 (significant at 1% level). The longest surplus rainwater series for the basin can be reconstructed for the period 1853-2006.

**VAGAI BASIN**

The basin annually receives 17.96 bcm of rainwater, 13.58 bcm of which evaporates and 4.48 bcm goes to different hydrological processes. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.19 (statistically not significant).

**THE WHOLE COUNTRY**

After China and USA, the country is in third position concerning number of dams. Due to various constraints (e.g. topography, uneven distribution of resources over space and time etc) estimated utilizable water potential is only 1122 bcm (690 bcm is through surface water resources and 432 bcm by ground water). In India, planning, development and management of water resources is done by the state agencies. The state-wise distribution of 5101 major dams of the country is as: Union Territory of Andaman and Nicobar Islands 2; Andhra Pradesh 334; Arunachal Pradesh 1; Assam 4; Bihar 28; Chhattisgarh 259; Goa 5; Gujarat 666; Himachal Pradesh 19; Jammu and Kashmir 13; Jharkhand 77; Karnataka 236; Kerala 54, Madhya Pradesh 906; Maharashtra 1821; Manipur 5; Meghalaya 7; Orissa 157; Punjab 15; Rajasthan 203; Sikkim 2; Tamilnadu 108; Tripura 1; Uttar Pradesh 131; Uttarakhand 19; and West Bengal 28. The correlation between the LSWB-SRW and the TMSMB-SRW is 0.71 (significant at 0.1% level and above). The average annual water potential of the all rivers from natural runoff is about 1869 bcm. There exists a highly significant correlation between annual rainwater and annual surplus water for the states of the country. Longest possible instrumental surplus rainwater sequence has been developed for the individual states to understand the problem.
Chapter VII  
Assessment of surplus rainfall according to daily water balance

of water-stress due to climate change as well due to non-climatic drivers, population growth and raised lifestyle, and the result will be reported elsewhere. Further longest instrumental surplus rainwater sequence can be developed for the different physiographic divisions-subdivisions-provinces for the development and management of wet lands of the country. In India there are 1,193 wetlands, 572 natural wetlands, 542 man-made and seven included both natural and man-made habitats (the remainder were unclassified). Some 938 wetlands are freshwater, 134 brackish and 19 coastal (Woistecroft et.al., 2009).

7.6 Summary and Conclusion

1. Compared to the LSWB method (Chapter II), the assessment of the surplus rainwater by the TMSMB method is higher over the basins in the central and northern India and lower over the peninsula.

2. For the country as a whole, however, the estimate of the surplus rainwater according to both the methods, the LSWB and the TMSMB, is quite close, 1373.6 bcm and 1362.9 bcm respectively.

3. There exists a highly significant positive correlation between the LSWB-SRW and the TMSMB-SRW for most of the basins. Thus, the long period time series of the LSWB-SRW reported in the chapter II can be scaled (reconstructed) for necessary applications if so desired.

Further, the surplus rainwater assessment by the TMSMB method can be refined by incorporating Land Use/Cover Change (LUCC) information. In the country, the built-up area is expanding since 1901 at the rate of 1064 km²/year and cultivable land area 3948 km²/year and forest is shrinking at the rate of 3480 km²/year and grass land 1176 km²/year (Haynes, 1999). Progress in knowledge depends on improved data availability. Major gaps in observations of climate changes related to freshwater and hydrological cycles are identified as follows (Bates et.al., 2008):

- Difficulties in the measurement of precipitation remain an area of concern in quantifying global and regional trends. Precipitation measurements over oceans from satellite are still in the development phase. There is a need to insure ongoing satellite monitoring and the development of reliable statistics for inferred precipitation.

- Many hydro-meteorological variables e.g., stream-flow, soil moisture and actual evapotranspiration, are inadequately measured. Potential evapotranspiration is
generally calculated from parameters such as solar radiation, relative humidity and wind speed. Records are often very short, and available for only a few regions, which impedes complete analysis of changes in droughts.

The water-stressed basins are located in the tropical and subtropical belts, including southern Asia (Bates et al. 2008). A water volume of 1,000 m$^3$ per capita per year is typically more than required for domestic/industrial and agricultural water uses. Controlled human population with lifestyle requiring optimum water consumption can be a practical wisdom to reduce-solve problem of water stress in the country.
REFERENCES


Table 7.1. Climatology (mean, sd) of the water balance parameters for the major and independent minor river basins of India (1972-2005).

<table>
<thead>
<tr>
<th>Basin</th>
<th>P (sd) mm</th>
<th>PE (sd) mm</th>
<th>AE (sd) mm</th>
<th>D (sd) mm</th>
<th>S (sd) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Indus</td>
<td>352.56 (77.5)</td>
<td>970.08 (49.9)</td>
<td>298.59 (41.3)</td>
<td>671.49 (74.4)</td>
<td>54.01 (41.2)</td>
</tr>
<tr>
<td>The Ganga</td>
<td>959 (118.3)</td>
<td>1987.56 (88.0)</td>
<td>680.57 (62.9)</td>
<td>1306.99 (127.3)</td>
<td>278.71 (68.7)</td>
</tr>
<tr>
<td>The Brahmaputra</td>
<td>2601.49 (316.5)</td>
<td>1440.76 (167.3)</td>
<td>1145.39 (76.6)</td>
<td>295.37 (103.6)</td>
<td>1457.26 (309.4)</td>
</tr>
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<td>The Godavari</td>
<td>1092.23 (174.0)</td>
<td>1952.18 (83.1)</td>
<td>724.72 (60.7)</td>
<td>1227.46 (119.9)</td>
<td>367.46 (139.3)</td>
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<td>The Krishna</td>
<td>789.52 (264.7)</td>
<td>1683.65 (61.3)</td>
<td>582.08 (60.8)</td>
<td>1101.57 (101.1)</td>
<td>207.39 (222.7)</td>
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<td>The Sabarmati</td>
<td>695.58 (237.5)</td>
<td>1946.02 (106.0)</td>
<td>493.55 (108.6)</td>
<td>1452.47 (191.9)</td>
<td>201.87 (142.2)</td>
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<td>The Mahi</td>
<td>866.85 (253.1)</td>
<td>1956.03 (103.6)</td>
<td>578.01 (90.3)</td>
<td>1378.03 (162.9)</td>
<td>288.95 (192.9)</td>
</tr>
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<td>The Narmada</td>
<td>1084.14 (187.8)</td>
<td>1812.94 (67.2)</td>
<td>649.49 (59.2)</td>
<td>1163.46 (95.1)</td>
<td>434.96 (155.2)</td>
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<td>The Tapi</td>
<td>809.14 (143.8)</td>
<td>1779.35 (63.4)</td>
<td>614.65 (61.1)</td>
<td>1164.7 (92.0)</td>
<td>194.84 (94.4)</td>
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<td>The Mahanadi</td>
<td>1305.37 (229.9)</td>
<td>1866.94 (75.6)</td>
<td>822.21 (65.1)</td>
<td>1044.73 (115.6)</td>
<td>482.72 (193.3)</td>
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<td>792.67 (132.3)</td>
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<td>1128.26 (82.4)</td>
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Table 7.2 The CC between the Thornthwaite-Mather soil moisture budgeting—surplus rainwater (TMSMB-SRW) and the large-scale water balance—surplus rainwater (LSWB-SRW) and for the major and independent minor river basins of India (data period 1972-2005). The superscript indicates percentage level of statistical significance.

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<td>1373.63</td>
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Figure 7.1 Climatology of the yearly sum of potential evapotranspiration (mm) derived from Thornthwaite’s method across the country during 1972-2005.
Figure 7.2 Variation in field capacity (mm) over 1380 stations across India.
Figure 7.3 Climatology of the yearly sum of Actual evapotranspiration (mm) across the country during 1972-2005.
Climatology of yearly sum of Surplus rainfall: 1972–2005

Figure 7.4 Climatology of the yearly sum of Surplus rainfall (mm) using Thornthwaite-Matter soil moisture accounting method across the country during 1972-2005.
Figure 7.5 Inter-annual variations in components of water balance for the whole country during 1972-2005
Figure 7.6 Inter-annual variations in surplus rainfall over major river basins and West Coast drainage system during 1972-2005.
Figure 7.7 Inter-annual variations in surplus rainfall over independent river basins and all India during 1972-2005.
Chapter VII
Assessment of surplus rainfall according to daily water balance

Figure 7.8 Relationship between Surplus rainfall and annual rainfall for the whole country during 1972-2005

\[ S = -261.55 + 0.6283 R \quad (r=0.95) \]
Figure 7.9 Relationship between Surplus rainfall and annual rainfall for major river basins and West Coast drainage system during 1972-2005
Figure 7.10 and Relationship between Surplus rainfall and annual rainfall for independent river basins during 1972-2005
Figure 7.11 Variation in Actual evapo-transpiration (black curve) and surplus rainfall (red curve) with the variation in field capacity for all India.
Figure 7.13 Variation in Actual evapo-transpiration (black curve) and surplus rainfall (red curve) with the variation in field capacity over independent river basins.