

CHAPTER 12

Conclusions and areas for future research

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12.1 Summary

Catchment management and basin management are complex and process oriented. The process of planning, designing, and implementation requires a multidisciplinary approach that integrates biophysical, socioeconomic, and governance aspects. The experiences regarding catchment management and basin management vary across countries. This book is an attempt to compile experiences with regard to catchment assessment, planning and management, and river basin planning and management across various countries, including those from developed countries and some countries in South Asia. It first presents the findings of the review of international experiences and then presents several case studies from India.

The review of international experiences covers the following: (1) the scientific tasks of carrying out hydrological assessments of the catchment (to quantify water availability in terms of quantity and quality), and analyzing the water allocation and water uses in different sectors, viz., agricultural use, urban use, industrial use, livestock use, and environment; (2) technical task of planning catchment management interventions and preparing river basin planning; and, (3) institutional processes of organizing catchment management and river basin management actions.

As regards the scientific task of catchment assessment, understanding the land-use and hydrology interactions, “interaction between upstream water withdrawals and alterations in downstream flows” and “surface water-groundwater interactions” are of prime importance, in addition to quantifying the amount of surface runoff from precipitation, base flows, and groundwater recharge. The former set of activities can tell us what kind

of land and water-based interventions can bring about alterations in hydrological processes of the catchment and to what extent, which is essential for arriving at sound catchment management decisions.

As regards water accounting, it is important for river basins that are already developed and from which water is allocated to estimate consumptive use of water in various sectors against the water supplied to examine whether current water uses are efficient from social, economic, and environmental points of view, and to identify the leverages for improving water management either through water saving or through supply augmentation. For instance, the actual water consumption by paddy crop against the total volume of water applied through irrigation in paddy fields is important, as a large part of the “nonconsumptive fraction” of the water applied in the field will recharge groundwater and will be available for reuse. Similarly, estimating consumptive water use in thermal power plants against the actual water required for running the plant including that for cooling is important for getting actual water accounts as the water used for nonconsumptive uses will be available for reuse after treatment.

The collection of case study papers in this volume demonstrates some of these scientific tasks through case studies from selected river basins/sub-basins/watersheds in India, viz., Krishna, Luni, and Narmada. In the case of Krishna, a sub-basin named Warna was chosen for the analysis. In the case of Luni, the entire basin was chosen for water accounting work. In the case of Narmada, a watershed of size nearly 450 sq. km of one of the sub-basins, viz., Orsang, was chosen for catchment assessment and planning. Two other sub-basins of Narmada, viz., Kundi and Hathni, were chosen for understanding the “scale effects” in hydrology, and this involved analysis of the downstream impacts of intensive watershed development upstream in the form of runoff change.

In the case of the large watershed in south Gujarat, the analysis (presented in [Chapter 5](#)), apart from assessing various components of the watershed hydrology (total rainfall, evapotranspiration, surface runoff, and base flow), helped us ascertain that catchment management interventions there should be capable of regulating the flows as there was sharp difference between dry-year flows and wet-year flows. Hydrological simulation using SWAT showed that the creation of permanent storage structures for watering crops in the catchment would reduce the flows into a reservoir downstream, whose storage is committed for irrigation, in drought years. In the absence of a stream-gauging point, the availability of reservoir mass balance data for a large reservoir at the end of the watershed, which acted as a hydraulic

response unit, enabled calibration and validation of the model for its robustness in computing rainfall data with high degree of accuracy. The chapter also drew lessons for the approach and methodology to be chosen for hydrology-based watershed planning, including that of project area selection, hydrological assessment, and intervention planning.

Analysis of time series data on groundwater level trends (between pre- and postmonsoon) of two sub-basins, viz., Kundi and Hathni (Chapter 5), showed that watershed development led to increase in recharge, as indicated by higher average value of “recharge fraction” in both the sub-basins post-watershed development. Further analysis for two watersheds (one treated and the other control) in Hathni sub-basin, done to nullify the effect of rainfall difference, showed an increased difference in average “recharge fraction” between the two watersheds postinterventions (1996), with higher difference in recharge fraction during high rainfall years in the case of the treated watershed indicating the effectiveness of recharge structures during high rainfall years. Sub-basin level analysis for Kundi also showed reduction in stream-flows postwatershed development. Such an outcome was the result of an increase in withdrawal from wells (followed by augmented recharge), as suggested by an analysis of groundwater balance of one treated and one untreated microwatershed. In the treated, not only the annual groundwater recharge, but annual draft was also higher. The study highlighted the need for considering groundwater-surface water interactions in watershed development and basin planning.

The scale of analysis of watershed interventions assumes importance in capturing the biophysical linkages. Chapter 10 demonstrated that changing the geographical unit of analysis of WSD against a strategic “whole-of-catchment” model would help evaluation process to provide general guidance in regard to the investment of essentially limited funds. This could provide an assessment on the basis of broad hydrological data and an estimate of the hydrological efficiency of differing patterns and intensities of WSD at a catchment level. The assessment of the impacts validated the hypotheses that mesowatersheds could generate differential benefits at scale (upstream/downstream). However, it was clear that there is some mismatch of perceptions of the outcome of WSD in terms of the benefits and costs to other parties that relate to hydrogeology and the biophysical characteristics of the location. Therefore, these aspects, which were hitherto not considered, need to be directly addressed in order to optimize as well as sustain the watershed impacts.

In the case of Luni basin, the water accounting exercise (Chapter 7) showed that with the total consumptive use of water exceeding the

renewable water resources, the basin's annual flows were overappropriated in most years, while groundwater resources were mined. The study found that the key intervention that is effective for managing the basin water resources is water demand management in agriculture, involving technologies and practices to reduce consumptive water use in crop production, while groundwater banking would be a good option in the abnormally wet years though those are very rare in the basin area.

A water accounting exercise for one of the sub-basins of Krishna river basin (Warna) was undertaken for the purpose of understanding water tenure in the sub-basin. The exercise used annual streamflow data for the gauging station at the drainage outlet of the sub-basin, historical data on inflows, and annual storage changes in a large reservoir located inside the basin and data on renewable groundwater resources and estimated annual groundwater storage change, and estimates of consumptive water use in various sectors. The analysis ([Chapter 6](#)) showed that the amount of water consumed in the sub-basin for various consumptive uses (irrigation, domestic use, industry, and livestock use) is far less than the total volume of water generated from the rainfall-rich upper catchments of the sub-basin. Further, water from a reservoir build on Warna river is also exported from the sub-basin to irrigate the command area in the districts of Kolhapur and Sangli, outside the basin. Yet the sub-basin has large amount of excess flows, which is quite critical to maintaining the overall water balance of Krishna river basin, which is on the verge of closure. The uniqueness of the sub-basin was that the climate (rainfall and humidity), land use, and water use patterns changed dramatically from the upper catchment to the middle and lower catchments.

The findings of the water accounting study undertaken for Kanpur Metropolitan Area ([Chapter 9](#)) suggests that there is not much physical risk in meeting existing or future water demand of in terms of water quantity. However, water quality is an issue as the infrastructure required to treat raw water and wastewater is absent. This scenario poses a major threat to the river ecology and poses a risk to livelihoods of the communities dependent on it. The economic risk for the industries alone is estimated to be around US\$ 540 million per annum. To mitigate these risks, it is suggested that various parastatal agencies involved in water supply and sewerage services work in a coordinated fashion to strictly enforce pollution control norms for the industries. The water accounting approach can be replicated in other major cities along river Ganga to assess their water risk and water security challenges.

In [Chapter 8](#), we have also demonstrated how water resources planning using the concept of IWRM (Integrated Water Resources Management) can be undertaken at the district level, through case study of one district in Rajasthan falling in Luni river basin for which a water accounting exercise was carried out. A lot of the data on renewable water resources, both surface and underground, were deduced from the data generated for Luni basin water accounting. The IWRM planning exercise determined the extent to which various agricultural water demand management interventions can be undertaken in the basin and their overall impact in terms of real water saving and on reducing the water demand-supply imbalance. It also quantified the total amount of runoff water that can be captured from the basin for groundwater banking.

The international literature review of institutional processes in catchment management and river basin management showed that there are several institutional models for watershed management, catchment management, and river basin management, with varying objective functions and mechanisms to achieve them. In the case of the National River Authority of England and Wales, protection of water environment through Catchment Management Plans was the prime objective.

The experience of watershed management (WSM) in South Asian countries has shown that WSM is an effective technology for addressing the broader issues of farm productivity and food security as well as soil and water conservation in arid and semiarid regions. The experiences of these countries in terms of technical as well as institutional aspects provide important lessons for countries like Afghanistan, which are just started implementing WSM. It is argued that there is an immediate need for creating policy environment to initiate WSM program, with a national policy and objectives ([Chapter 3](#)). A common framework for implementing the WSM programs needs to be provided on priority, given the potential of WSM in strengthening the natural resource base and ensuring food security.

In the case of Murray Darling Basin Authority of Australia, the main objectives were limiting surface and groundwater diversions from the basin for environmental sustainability; ensuring that sub-plans for each state are in line with the basin plan; and promoting water trading to maximize the social and economic benefits. The MDBA develops and implements the basin plan, which has legislative backing and is an enforceable document to be followed by all basin states while preparing their own plans. In the case of French river basin organizations that were active during 1970–92, the main objective was water resource management in major river basins,

by promoting efficient water use and pollution reduction through financial incentives to local agencies and private players.

The Catchment Management Agencies in South Africa implements the National Water Act and management of water at local level. These are participatory institutions in a decentralized format, but at the same time are also statutory bodies. The governing board of CMA is to have representation from present and potential future water users, local and provincial government, and environmental interest groups. Their objectives are planning of WRM at catchment scale; registration of water users; collection of water charges collection; water authorization and licensing; and, ensuring poor communities' access to water for domestic and productive needs.

The institutional mechanisms used for water management also differ. The French RBOs were financial investment institutions with no statutory powers. Under this set up, there were separate sets of agencies for performing various functions, the RBO for water quality monitoring and regulation, and separate (private) agencies for water supplies, and for setting up and running wastewater treatment plants. The RBO regulator, which is responsible for managing river water quality through financial incentives, ensured that private agency, which is responsible for investing in and running WWT plants, treats the effluent to conforms to water quality standards through water quality monitoring.

In the case of Murray Darling basin authority, the market instrument of "tradable water rights" was successfully used during years of drought to achieve higher economic efficiency of water use in agriculture to maintain the economic outputs at the level of normal years, with a 50% cut in water allocation. The establishment of separate "water entitlement for environment" at the basin level and creation of environmental water holder enabled securing water for environmental flows, though it created resentment among irrigators as it reduced their overall allocation.

The National River Authority of England and Wales was a centralized agency with range of regulatory powers on private and public bodies. The CMP formed the basis for NRA action within each catchment. The CMPs were consultative with respect to the planning process, with no ability to enforce on land users, developers, or local planning authorities. The NRA could do little to incorporate water management decisions in land-use planning as it had limited formal authority to influence land use, while the CMP had no immediate impact on statutory authorities.

In the case of CMAs of South Africa, the shift from a centralized management approach to a decentralized participatory approach enabled water

users from poor communities to discuss directly with the concerned agency on water resources management. The mismatch between catchment boundaries and local administrative boundaries led to poor coordination between CMAs and the water supply agencies.

The experience of countries like India in implementing integrated water resources management is almost nil. While the IWRM concepts and operational principles are largely understood, most often, the agencies are confronted with the question of where to start and where to end, i.e., whether the process should start with scientific studies or crafting of institutions. Another question is how to initiate the institutional processes. In one of the chapters ([Chapter 11](#)), we have therefore discussed the overall institutional regime for implementing integrated water resources management actions; described the key scientific and institutional processes that are necessary to operationalize them at the level of river basins, and in the same order and sequence in which they should be initiated. We have also highlighted some of the water management outcomes.

12.2 Areas for future research

In many regions of the developing world, reliable hydrological data essential for taking water resources development and management decisions are often sparse due to lack of sufficient number of precipitation and stream-gauging stations, weather stations, and groundwater monitoring stations spread well across river basins and catchments.

There are two major exercises that water managers have to undertake to arrive at sound management decisions. They are (1) hydrological assessment of catchments to know the catchment yield (the amount of runoff generated from the catchment plus the groundwater recharge from precipitation) and (2) water accounting to know how much of the available annual yield is consumed for various purposes (ET from both natural and cultivated vegetation in the catchment, evaporation from soils and water bodies) and how much is held in storages (surface and underground) and how much is discharged from the drainage outlet.

The hydrological assessment of catchments would help carry out water budgeting, and planning of water resources development and management interventions and water allocation. Catchment assessments if done at various scales will also help minimize the tradeoffs in watershed developments occurring due to scale effects of hydrology ([Chapter 2](#) of this volume). The water accounting exercise would help us estimate the consumptive

use of water in various sectors in volumetric terms in a year or in a season, and assess the total amount of water that remains unutilized in the basin, and how much of the water generated in the basin is consumed for beneficial uses (evapotranspiration) and nonbeneficial uses (evaporation from barren land, uncultivated areas within crop land, swamps, and reservoirs) (Chapter 1 of this volume and Molden et al. (2003)). This forms the basis for deciding on the nature of intervention that can be taken up in the basin for improving water management.

The most crucial data that are required for carrying out hydrological assessment of catchments and water accounting, but are often very hard to obtain, are of streamflow or river discharge, which is the net of the total runoff generated in the catchment minus the water effectively utilized upstream through the help of reservoirs and diversion systems, and water held in small and large reservoirs. If streamflow data for some gauging stations are available, then the virgin runoff can be estimated by doing backward calculation, on the basis of data on total effective diversions upstream of the gauging point. The streamflow data for the last gauging point in a catchment itself can give strong hints on whether there is scope for taking up more water resource development interventions in the catchment. Availability of sufficient flows at the last gauging point in all years is a strong indication of the fact that the catchment is “open,” and further development is possible unless these flows are committed for downstream uses.

The data, which are less scarce are rainfall as many regions in the developing countries, barring some countries of Africa, now have reasonably high density of rain-gauging stations, which record not only daily rainfall data but also have real-time monitoring data using automatic gauges. If we have good network of rain-gauging stations in a catchment that can measure the annual precipitation accurately, then the catchment water yield (the sum of runoff, groundwater recharge, and soil moisture storage) can be indirectly estimated if we know how much water is lost in evapotranspiration during the year. The catchment yield will be total precipitation–evapotranspiration (which also includes evaporation from barren soils and swaps).

Evapotranspiration from cultivated land can be estimated using the widely accepted Penman–Monteith equation, if we know the crop growing season, the date of sowing and harvesting and have the weather data for the nearest weather station. But estimation of evapotranspiration from the natural vegetation cover poses a major scientific challenge. Since the natural vegetation (forest) cover consists of a mix of large and small trees, grasses and shrubs, neither estimation using empirical methods nor actual physical

measurement (using lysimeters) in the field would be practical. Since the extent of natural vegetation cover is more for water-rich catchments in tropical regions, arriving at realistic estimates of annual and seasonal flows to assist water management decisions would depend heavily on the accuracy of estimation of evapotranspiration.

In some situations, even when streamflow data are available (like in the case of tributaries of many large rivers originating from the western Ghats of India such as Krishna and Cauvery), it might be important to get estimates of the volume of water consumed annually by the natural vegetation that covers large areas. The reason is that in many situations, we may have to consider altering the vegetation cover as one of the water management solutions for the catchment, to alter the total runoff volume or to reduce the sediment load in the runoff water. Since the direct method of using lysimeters for field measurement cannot be employed for estimating the actual ET, in such situations, indirect methods can be employed wherein the instantaneous evapotranspiration from the forest cover is estimated using satellite remote-sensing data for the exposure time with the help of SEBAL (Soil Energy Balance) model, and a coefficient called “evapotranspiration fraction”—which is the ratio of instantaneous ET and reference ET (ET_0)—is estimated. In this case, ET_0 for the exposure period is estimated using Penman–Monteith equation based on weather data. Using the ET fraction and the total reference evapotranspiration for the vegetation for a given period, the actual ET can be estimated as $ET_0 \times \text{Evapotranspiration Fraction}$ (Roby and Jose, 2018).

However, for using such hybrid models, it is necessary to have weather data for the nearest location so that reliable methods like Penman–Monteith equation can be employed to estimate reference evapotranspiration (ET_0).

Another major area of research in hydrology, which can immensely benefit water resources development planning and evolution of water management approaches, is the groundwater–surface water interactions. In developing countries, detailed hydrological investigations groundwater–surface water interactions are rare and often thumb rules are used. For instance, groundwater recharge estimates of official agencies of India for hard rock hilly regions are highly unreliable due to the nonscientific methods used for estimation of “groundwater discharge into streams,” an important variable crucial for estimating the utilizable groundwater resources in shallow aquifers. In the absence of gauging stations that are capable of measuring the lean season flows at appropriate scales, some simplistic norms are often employed to estimate the nonmonsoon (lean season) base flow,

and the estimated value is deducted from monsoon recharge into the aquifer to obtain utilizable recharge.

In many river basins, the small upper hilly catchments contribute majorly to the total annual runoff. Here again, the baseflows, which is the groundwater discharge into streams, is a major portion of the total runoff, and this include outflow during monsoon and as well as nonmonsoon period. In any catchment, as the rainfall increases, the runoff and base flow increase. But the baseflow as a fraction of the runoff reduces. This is because at lower magnitudes of rainfall, the baseflow component of the total runoff is generally very high for hilly catchments, and at higher magnitudes of rainfall, the surface runoff component increases. But such data are nonexistent for most river basins in developing countries. Estimating the “base flow coefficients” (ratio of total base flow and total runoff) of a catchment for different rainfall regimes is of great relevance in research on catchment hydrology, as it can help arrive at realistic estimates of utilizable groundwater resources from precipitation. For this, partitioning of base flow and surface runoff components of the total runoff from precipitation in these catchments using hydrographs is required. Since the effect of base flow is not visible in small microcatchments, setting up gauging stations at appropriate locations is an important starting point.

Data of stream discharge (along with quantum of precipitation) obtained from monitoring of major (runoff-generating) rainfall events, followed by analytical process of partitioning base flow, relationships (statistical regression models) can be established between: (1) rainfall and runoff and (2) rainfall and base flow coefficient.

If the “lean season base flow” is known (through gauging) for different magnitudes of rainfall in the catchment (for the same years for which data on total runoff are available), then the base flow during the monsoon can be estimated for different values of rainfall, using the regression model for “rainfall-baseflow coefficient.” This, when added to monsoon recharge (estimates), gives value of total infiltration during monsoon. Relationship can then be established between rainfall and total infiltration for any given catchment for different magnitudes of rainfall. Once this is done, the three models, viz., rainfall-runoff model, rainfall-base flow coefficient model, and “rainfall-total infiltration model” can be employed to compute the total utilizable recharge as “Estimated total infiltration-Estimated total base flow” (GSDA & IRAP, 2015). Such investigations and analysis need to be carried out for hilly and mountainous catchments in different hydrological settings.

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