

CHAPTER 5

Catchment assessment and planning for improving effectiveness of watershed development interventions: A case study from South Gujarat

A.J. James^a, James Batchelor^b, Nitin Bassi^c, Grant Milne^d

^aEnvironmental & Natural Resource Economist, New Delhi, India

^bDigital Specialist, Atkins, London, United Kingdom

^cInstitute for Resource Analysis and Policy, Delhi Liaison Office, New Delhi, India

^dSenior Natural Resource Management Specialist, World Bank, Washington, DC, United States

5.1 Introduction

From 2013 to 2015, the World Bank supported a Catchment Assessment and Management Planning (CAMP) Study, aiming to improve the understanding of hydrology issues in watershed management in India.^a The study examined the utility of hydrological modeling as a tool to investigate the potential multiscale impacts of watershed development and to support planning at different institutional levels. It looked at the potential of integrating hydrological models into the planning methodology used by the flagship national watershed development scheme of the Government of India (GOI)—the Integrated Watershed Management Program (IWMP). The study's findings were expected to not only contribute to the design of new World Bank-supported watershed programs in India, the IWMP, and the

^a This work (James et al., 2015a,b) was funded by the Program on Forests (PROFOR), a multidonor partnership managed by a core team at the World Bank. PROFOR finances forest-related analysis and processes that support the following goals: improving people's livelihoods through better management of forests and trees; enhancing forest governance and law enforcement; financing sustainable forest management; and coordinating forest policy across sectors. In 2013, PROFOR's donors included the European Commission, Finland, Germany, Italy, Japan, the Netherlands, Switzerland, the United Kingdom, and the World Bank. Learn more at www.profor.info.

newly announced PMKSY, but to also guide hydrological assessments in watershed program development in other regions. The main motivations of the study were to understand how a greater focus on hydrology in planning and implementation can offset some of the unintended negative impacts of watershed development projects (Batchelor et al., 2002; Calder et al., 2008; Kerr et al., 2006; Kumar et al., 2006; World Bank, 2006).

While watershed development can and often does deliver significant beneficial impacts, it can also result in negative externalities that can affect downstream water users. The construction of rainwater harvesting structures to catch rainfall and subsequent surface runoff can enhance groundwater recharge and increase local water availability for irrigation and other uses. The increased water availability often encourages farmers to not just expand irrigated area but also to use irrigation more intensively (e.g., for double or triple cropping). This will normally lead to greater crop yields and higher farmer incomes, thereby achieving key social and economic objectives of national watershed programs.

At the same time however, enhanced water availability is not a guaranteed outcome of watershed development. Poor field designs, placement and/or maintenance of water-harvesting structures, unfavorable groundwater characteristics, and many other factors may reduce the effectiveness of these investments. Watershed development can also *increase* local water loss—both as a result of evapotranspiration from higher intensity of irrigation and due to evaporation directly from the water storage structures themselves—leading to reductions in downstream water flows. Any resulting reduction in downstream flows may not be a problem in areas of high rainfall or in basins that are still hydrologically “open.” However, the severity of water scarcity is growing across India and many basins are now “closed,” with all available water fully allocated to, or appropriated by, different water users and water requirements. The situation is likely to be exacerbated by factors such as climate change and an increasing demand for water. In addition, as watershed development is intensified and expanded to new areas, the downstream impacts are likely to accumulate and become more acute.

The Government of India has funded watershed development in selected watersheds across the country for several decades. National watershed guidelines were last revised in 2011 (MoRD, 2011). Under the current guidelines, states are now responsible for both the selection of watersheds to be “treated” and the field implementation of watershed programs. Watersheds are selected using multicriteria analysis that combines 13 different parameters and uses Geographic Information Systems (GIS) to identify those watersheds most in need of treatment. Although the guidelines implicitly recognize the

importance of hydrology, the criteria for the selection of watersheds are heavily weighted toward social and economic goals, with little account taken of the potential downstream externalities of, for example, intensification of agricultural water use. This is partly due to the lack of easily accessible hydrological data that can be used as inputs into the selection of watershed and the planning of watershed development, especially in the headwater areas where most watershed development is focused.

Assessing and monitoring the impact of watershed development at a catchment scale is challenging and time consuming, partly because recharge rates from individual rain water harvesting structures can be highly variable in both space and time. Consequently, there have been relatively few cases in which watershed development planning has directly accounted for the impact of watershed development at the catchment or landscape scale. One method that can be used to assess its impact on water resources is hydrological modeling. Hydrological models have been used widely in research studies for decades. An emerging global trend is to now use hydrological models in practical applications to support watershed development, for example in site selection, assessing downstream impacts of investments in soil and water conservation interventions, etc. This trend is driven by the falling costs of computing power, the increasing availability and utility of open-source modeling software, and remotely sensed digital data that can be downloaded from the web and used at various scales.

5.2 The issue

Although national watershed development programs have been implemented by various Ministries of the Government of India since the early 1970s, even the latest Common Guidelines for Watershed Development Projects (MoRD, 2011) do not define a “watershed” in the hydrological sense. Instead of defining watersheds on the basis of topography and drainage lines, contiguous plots of land measuring around 1000–5000 ha are designated a “watershed” and are intensively treated to control and capture the water in that area.^b The Guidelines advocate a “multitier ridge-to-valley sequenced approach” where the uppermost part of the catchment (usually

^b This used to be 500 ha till 2008, when Common Guidelines were formulated by the DoLR with the Planning Commission of India, recommending a “cluster approach” of “geo-hydrological units normally of average size from 1000 to 5000 ha comprising clusters of microwatersheds” (MoRD, 2008, p. 7), which was applied to all watershed projects taken up from April 1, 2008.

hilly and forested, is treated first) followed by the “middle tier” (intermediate slopes just above agricultural lands) followed by the lowest tier, which are the “plains and flat areas.” In India, as also in other parts of the world, such an approach, however, can have three key water-related consequences:

- **Reduced water flows to the lower parts of the catchment** and more importantly, the larger rivers that flow in the valleys—because of greater capture of water and increased evapotranspiration from resultant expansion in both the area that is cropped and the area that is irrigated in the upper parts of the catchment (where there are often farmers cultivating terraced fields).
- **Overabstraction of groundwater**, in the absence of decision making with a view to incorporating water use priorities and improvements to the productivity and sustainability of water use, as farmers benefiting from the additional water captured in new and existing Water Harvesting Structures (WHSs)—even in the upper and middle “tiers” of catchments—invest in more numbers of bore wells, deepen bore well depth, and increase pumping capacity to expand cultivation into previously unirrigated areas.
- **Less water in streams and aquifers**, because of increased cultivation, groundwater extraction, and increased evapotranspiration (from irrigated and rainfed farming systems), which, in some cases, can leave villages worse off than prior to the treatment—because (1) most options for augmenting water supply have already been exhausted and (2) that area is barred from benefiting from another IWMP project.^c

Following sustained critical analysis (e.g., [Batchelor et al., 2002, 2003, 2014](#); [Calder et al., 2008](#); [Kumar et al., 2006](#)), which were reiterated during the preparations for the World Bank-assisted Neeranchal Watershed Management Project of the GOI, the then Joint Secretary of the Department of Land Resources, Ministry of Rural Development of the GOI, asked what the ideal size of a watershed should be, and how could it be operationalized as part of a revamped IWMP. Accordingly, the three key objectives of the CAMP study were to:

- Derive a methodology to incorporate hydrological assessment into catchment management planning in the Indian context.
- Demonstrate this methodology in one subcatchment.
- Create practical tools to apply (relevant parts of this methodology) in the IWMP.

^c A village once selected for an IMWP project cannot be selected again for another IWMP project.

5.3 Study planning

5.3.1 Catchment choice

Following discussions with DoLR and Water Resources specialists at the World Bank, it was decided to carry out the pilot in the western Indian state of Gujarat, for the following reasons:

- The relatively better availability of data, given that a State Water Data Centre had been set up by the state Department of Water Resources, combining surface and groundwater data, as part of the Hydrology Project Phase 2 (HP 2), which was supported by the World Bank.
- The presence of a Bank-supported Integrated Coastal Zone Management project emphasizing a single-database approach to hydrology.
- The interest of the World Bank team in preparing HP3, which is aiming to take a more decentralized look at planning, right down to watershed level—an issue that was not addressed in HP1 and HP2.
- The willingness of the State-Level Nodal Agency (SLNA) for implementing the IWMP in Gujarat to support and assist the pilot.

Within Gujarat, it was decided to select the catchment of the Sukhi river, which lies within the Orsang sub-basin of the Narmada river basin, and where the IWMP was being implemented (Figs. 5.1, 5.2, and Box 5.1).

5.3.2 Choice of IWMP watersheds

A field visit to the Sukhi catchment confirmed ease of access and that data were available: the bridge over the Orsang river at Bodeli had a river-gauging station and there was a well-equipped weather station in Tejgadh near Bodeli. Also, if the area above the Sukhi reservoir was selected, there would be no dams, canals, or other structures in the catchment selected.

During the field visit, the DWDU office in Chhota Udeypur provided a map showing the locations and start dates of IWMP projects in Chhota Udeypur district. Since a softcopy of the data was not available, this information could not be overlaid onto the DEM and SWAT sub-basins. But by using the district boundary as a guide (a common feature to both maps), a rough assessment could be made of the location of IWMP watersheds in the upper Orsang catchment (Fig. 5.3).

Using SWAT and Google Earth allowed a detailed examination of each sub-basin and the identification of villages within them. By matching these with the villages in the IWMP map, it was possible to identify which

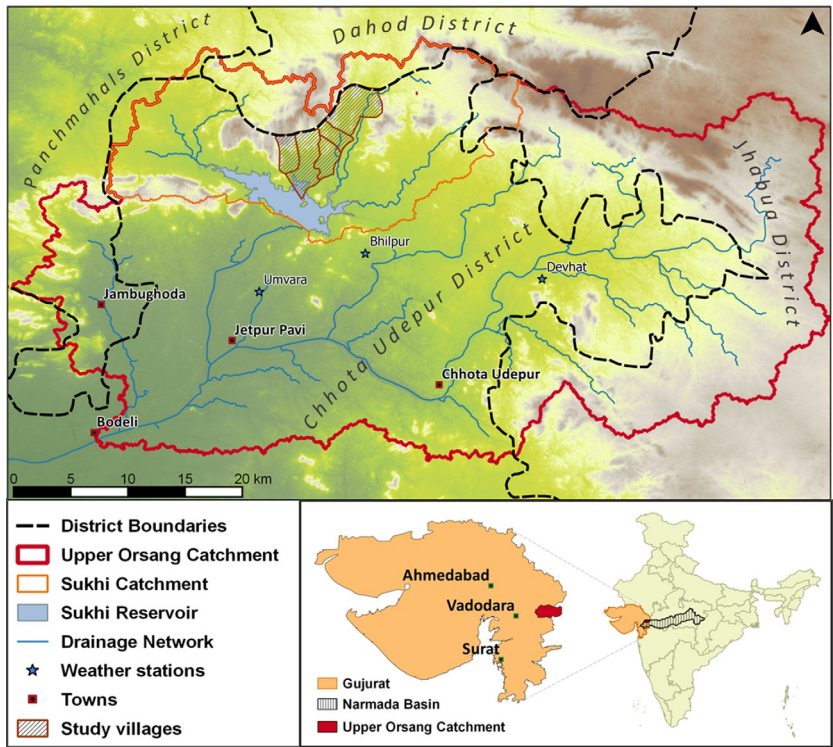


Fig. 5.1 Location of the Sukhi catchment.

sub-basins contained IWMP watersheds. This analysis showed that the area above the Sukhi reservoir had the most promising group of IWMP watersheds for detailed study. Further investigation (using QGIS and Google Earth) identified five IWMP Batch 1 (started in 2009–10) project villages (Kevdi, Dholisimel, Dungarbhint, Kundal, and Ghata) that looked to meet a key criterion (sloping from “ridge to valley”) as locations for the choice of catchment.

With sub-basins delineated at 10 km, these five villages cover the large majority of two sub-basins with Kevdi, Dholisimel, and Dungarbhint forming an upstream–downstream continuum within one 21.5-km² sub-basin (Fig. 5.3). Another advantage of these villages is that the sub-basins lie almost completely within Chhota Udeypur district (Fig. 5.1) with the small area lying in Panchmahal district covered almost entirely by forests. Hence, secondary data (on land use, irrigated and cropped area, etc.) needed to be procured only from one district.

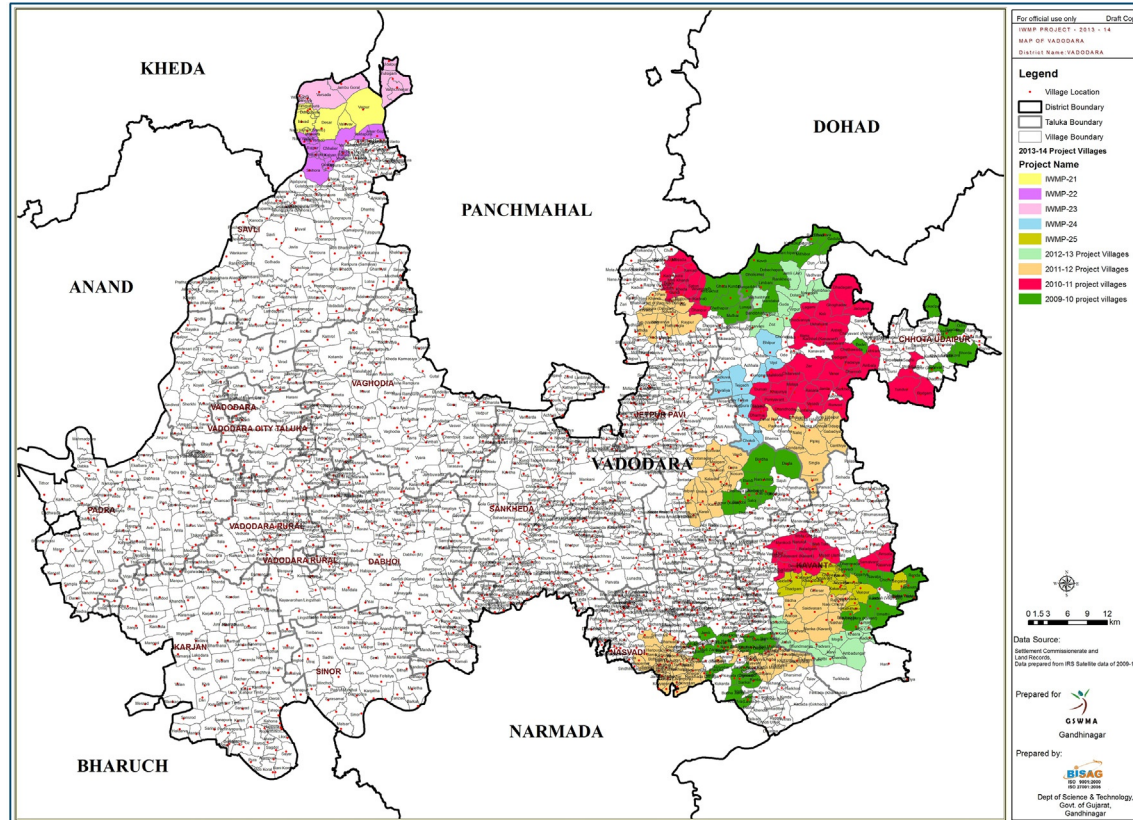


Fig. 5.2 Location of IWMP watersheds in the Sukhi catchment.

BOX 5.1 Key features of the Sukhi catchment

- **Location:** The major part of the catchment is in eastern Gujarat, with 79% of its area in Chhota Udeypur district, 15% in Dahod district, 1% in Panchmahal district, and the remaining 5% in Jhabua district in the adjoining state of Madhya Pradesh.
- **Area:** The catchment has an area of 393 km², which is mostly agricultural and forest land, and a significant part of the catchment falls within the Ratanmahal wildlife sanctuary.
- **Water infrastructure:** It contains a reservoir created by the Sukhi dam, which ought to have inflow data, and there is also a gauging site at Bodeli downstream of the Sukhi dam.
- **IWMP:** Around 50 villages in the part of the catchment lying in Chhota Udeypur district have been selected by IWMP to undergo watershed development.

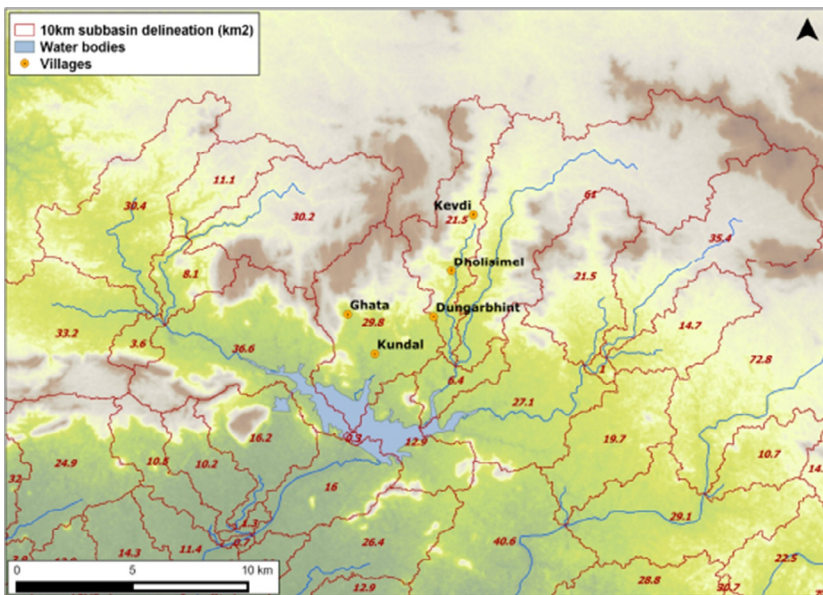


Fig. 5.3 IWMP watersheds above Sukhi reservoir (SWAT delineation).

5.3.3 Hydrological assessment

Two broad and mutually supportive methods can be used for hydrological assessments of catchments: a one-time assessment for a given hydrological unit and for a given time frame based on hydrological principles for aggregate-level assessment of catchments, using *conceptual* (or perceptual)

models; and, understanding and simulating the hydrological processes in the catchment on a spatial and different time scales, using *hydrological* models. Developing perceptual models is an important step in a modeling process, but it is not an alternative for a calibrated and validated hydrological model.

The fundamental difference between perceptual and hydrological models—that seek to simulate catchment hydrology (also called “simulation models”)—is that the former is static, not spatially and temporally distributed, rarely calibrated and only deals with the outcomes of hydrological processes. Simulation models, in contrast, are calibrated and validated to deal with the processes themselves (which are both time and space dependent); and can be run on various time scales (daily, weekly, monthly, and annually) and for different scales (small watersheds, sub-basins, and the whole basin).

Insights from the perceptual model, which are based on field visits and a basic analysis of available data, are invaluable inputs into the hydrological model and hence, a good starting point for the modeling process.

5.3.4 Choice of model

The ease of setting up and using SWAT for selecting the catchment, as illustrated here, for rapid assessment of catchment characteristics (using freely available global datasets) was one of the factors for considering SWAT as a serious option for the hydrological assessment. A review of the literature and discussion with experts confirmed several reasons why SWAT was a suitable model to study the impact of watershed development in India (see also [Box 5.2](#))^d:

- A large user base that has grown substantially over the last decade leading to frequent model improvements and updates.
- A large number of successful applications both in India and worldwide that give the model good credibility as a useful source of information
- An active online community that can provide useful support regarding all aspects of model use.
- It is a semidistributed model and can therefore account for spatial variation in important catchment characteristics such as land use.
- It is adept at using remote-sensing data, both as inputs and for calibration and validation, making it a good choice of model in locations where other sources of data are scarce.
- The delineation of subwatersheds during model setup is flexible allowing SWAT to be applied at any scale from the plot level up to the continental.

^d See, inter alia, [Mishra et al. \(2007\)](#) and [Glendenning et al. \(2012\)](#).

BOX 5.2 Key features of the Soil and Water Assessment Tool (SWAT)

- SWAT is a semidistributed hydrological model that operates on a daily time step and is designed to predict the impact of management decisions on the water balance components and the sediment and agricultural chemical yields of a specified domain.
 - There are two primary interfaces available for SWAT: ArcSWAT and MWSWAT. Both options run the same version of the model but use different GIS interfaces: ArcSWAT uses ESRI's ArcGIS (including spatial analysis extension); MWSWAT uses the open-source MapWindow GIS (although it does require Microsoft Access).
 - ArcSWAT is the more widely used version, but the ArcGIS software needed is expensive. An advantage is the extensive online support and tutorials available for ArcSWAT. The extensive literature database is also a valuable resource.
 - The major advantage of MWSWAT is that the software needed is much cheaper than the ArcSWAT version. Although less supporting material is available for MWSWAT compared to ArcSWAT, useful online resources available can be accessed at <http://www.waterbase.org/documents.html> and <https://groups.google.com/forum/#!forum/waterbase>.
 - In most cases, the data needed for running SWAT at default settings can be found online, but the resolution/accuracy of the data is not always sufficient, especially for smaller catchments.
 - SWAT can be combined with other models such as MODFLOW and WEAP.
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- It is open source, which allows users to access the source code, both to see how the model works and to make changes to the model so that it better suits their needs.
 - It can be easily linked with other models including the US Geological Survey Modular Finite Difference Flow model (MODFLOW), and the Water Evaluation and Planning model (WEAP).
 - It is computationally efficient, which allows detailed modeling of large catchments.
 - Simulation of crop growth and yields means that it can be used to examine the economic outcomes of different scenarios.
 - Additional software, such as SWAT-CUP and SWAT-Check, help the modeling process and improve model outputs.
 - There are several interfaces available for different GIS including ArcGIS, MapWindow, and QGIS, which allows users to choose one with which they are familiar.

Given these advantages, and despite the fact that other models had been suggested by some other experts consulted (e.g., WEAP by the National Institute of Hydrology, Roorkee), the Team decided to use SWAT for the hydrological modeling.

5.4 Setting up and using the model

5.4.1 Secondary data

Data inputs into SWAT were summarized and their various sources identified (Table 5.1), based on discussions with Government Department officials in Gujarat (both in Gandhinagar, the capital, as well as on site in Bodeli, Sukhi, and Chhota Udeypur). Secondary data requirements are summarized in Table 5.1.

The secondary data, however, could not be used in the form in which they were obtained, and hence had to be cleaned and processed for input into SWAT. Gaps in the rainfall data were filled by considering the observed measurement in the neighboring gauging station, while solar radiation was estimated using a complex equation, which takes sunshine hours as an input among other parameters. The modeling, however, had started by using global datasets, the strategy being to replace these rather coarse datasets with more accurate datasets from Indian sources as and when they became available.

5.4.2 Primary data

Five villages on three different streams discharging into the Sukhi reservoir were selected to get an understanding of the extent of watershed interventions undertaken in the watershed and the impact of these interventions on resource conservation and on livelihoods (including crop yields and returns). These five villages comprised seven different subwatersheds as delineated by the SWAT model using global data sets.

The initial field visit identified numerous structures across the five villages including many non-IWMP structures and revealed a varied terrain ranging from flat areas close to the Sukhi reservoir, with many structures and irrigated areas, to steeper forested areas upstream. Discussions with local villagers and staff of the District Watershed Development Unit (DWDU) revealed that the Gram Panchayats wanted more large check dams (seeing the benefits from the ones already constructed) but since there was little room left for more (large) structures in the flatter areas, they were planning

Table 5.1 Data requirements for SWAT and their sources

Data type	Parameters	Central government sources	Location	State government sources	Location
Satellite and map data	DEM (Raster data)	India WARIS website, MoWR	Orsang sub-basin	Gujarat SWMA	Orsang sub-basin
	Land use (Raster data or shape file)			BISWAG	
	Soil type (Raster or shape file)			CSWCRTI, Vasad, Gujarat	
	Drainage network (shape file)				
	Village Cadastral Maps (shape files)				
	Shape files of village boundary and watersheds				
Canal network (shape file)	NBSSLUP, Bangalore				
Meteorological data	Daily minimum and maximum temperature	IMD	# Jetpur	Gujarat SWDC	# Dhandhoda
	Daily rainfall		# Jambugam	Gujarat SWMA	# Bhilpur
	Daily sun-shine hours or solar radiation		# Bhilpur		# Jetpur Pavi
	Daily average relative humidity		# Chhota Udeypur		# Devhat
	Wind speed		# Bodeli		# Bodeli
	Daily pan evaporation		# Jambughoda		# Umarva
	Daily river discharge				
Hydrological and ground-water data	Sediment	CWC	# Bodeli	SWDC	# Bodeli
	Water quality		# Chandwada (last site before Orsang meets Narmada)		# Chhota Udeypur

Reservoir data	Pre and post monsoon depth to groundwater level	CGWB	Observation sites at Pavi, Bodeli, Chhota Udeypur, and Kevdi	GSWMA SWDC	Observation sites in Chhota Udeypur, Pavi Jetpur, and Sankheda blocks
	Estimated groundwater recharge	CGWB	Different blocks in Vadodara district	GSWMA SWDC	Different blocks in Vadodara district
	Water inflows	CDO Gandhinagar		Gujarat SWRD	Sukhi dam
	Water release in canals and spillway during different hydrological years Gross and live storage (including storage at the beginning and end of the hydrological year) Evaporation from the reservoir				

BISWAG, Bhaskar-Acharya Institute for Space Applications and Geo-Informatics; *CDO*, Central Design Organization; *CGWB*, Central Ground Water Board; *CSWCRTI*, Central Soil and Water Conservation Research and Training Institute; *CWC*, Central Water Commission; *IMD*, Indian Meteorological Department; *MoWR*, Ministry of Water Resources, Government of India; *NBSSLUP*, National Bureau of Soil Survey and Land Use Planning; *NRSC*, National Remote Sensing Centre; *SWDC*, State Water Data Centre; *SWMA*, State Watershed Management Agency; *SWRD*, State Water Resources Department; *WARIS*, Water Resources Information System (India).

Table 5.2 Field formats for primary data collection.

Format	Type	Purpose
1	Well survey	Mapping of all wells (with GPS coordinates) and to assess the impacts of watershed interventions on water availability in the wells, a range of attributes were collected including type, date of construction, condition, funding source, and cost
2	Survey of water harvesting structures	Mapping of all water harvesting structures (with GPS coordinates) and to assess their impacts in terms of resource conservation and increased water availability
3	Information from village records	Understanding village social dynamics and agriculture (including irrigation) pattern
4	Household survey of socioeconomic, agricultural, and irrigation details	Water productivity analysis and assessing crop economics at the household level
5	Focus group discussions with the village community	Time series analysis on the condition water resources, forest, cropland, livestock, and returns from agriculture Capturing the impact of droughts and wet years on the natural resources and livelihoods Assessing effectiveness of local institutions (such as GPs, WCs, SHGs, UGs) in resource management

to use funds under available government programs, including the IWMP, to construct additional structures in upstream areas as well. To collect primary data more systematically from these villages, however, five different questionnaires were prepared (Table 5.2).

A dedicated field team member organized the primary data collection, which was completed in parallel with the secondary data collection, in two months (mid-September to mid-November 2014). The primary data collection from the five villages in a part of the Upper Sukhi Watershed was greatly facilitated by the fact that the IWMP projects were still ongoing in these villages. This not only gave access to the information collected by the IWMP baseline survey but also facilitated entry-point discussion and rapport building with the villagers.

5.5 Understanding the catchment and its problems

The collected data were used not just as inputs into the modeling process but were also analyzed separately. The main findings are summarized below.^c

5.5.1 Watershed characteristics

- **Rainfall varies sharply between wet and dry years:** Average annual rainfall for the study period (1999–2013) was 1062 mm with a standard deviation of 386. Nearly all the rainfall falls during the monsoon during the months of June, July, August, and September. The majority rainfall occurs on days with more than 25 mm of rain. On average, 62% of rain occurs on days with rainfall of more than 25 mm, while only 14% of rainfall occurs on days with between 0.1 and 10 mm of rain. This has large consequences for runoff, erosion, and the effectiveness of rainwater harvesting (RWH) structures. The rainfall in the watershed also varies sharply across dry and wet years, as shown by the rainfall statistics:
 - *Total rainfall:* Thus, total annual rainfall was 1724 mm in 2006, the wettest year in the period from 1999 to 2012, while it was 358 mm in 2009, the driest year—which is just about 20% of the 2006 figure.
 - *Daily rainfall:* The highest amount of rainfall recorded in a day was 290 mm in 2006 and just 80 mm in the driest year in the period from 1999 to 2012.
- **Annual inflows into Sukhi reservoir also vary sharply with rainfall:** This variation impacts inflows into the Sukhi reservoir and, by extension, the water released for irrigation in downstream villages. The Sukhi dam, completed in 1987, has a reservoir with an effective storage capacity of 178.47 million cubic meters (MCM) and a surface area of 29.04 km² when full. Built for irrigation, two canals flow downstream with a total command area of 31,532 ha. Inflow data for the Sukhi reservoir showed that while the annual inflow into the reservoir for the period 1990–91 to 2012–13 was around 175 million cubic meters (MCM), it ranged from a high of around 450 MCM (in 2006) to a low of around 30 MCM (in 2009).

5.5.2 Village-level information

- **All five villages have large elevation ranges and steep topography:** The five villages surveyed, Kevdi, Dholisimel, Dungarbhint, Kundal, and Ghata, are situated toward the center of the Sukhi watershed and are contiguous, with Kevdi being the uppermost and Kundal and Ghata edging

^c Further details are in the Technical Note on SWAT Modeling (James et al., 2015b).

the Sukhi reservoir (Fig. 5.3). The villages are characterized by large elevation ranges and steep topography. All five lie on the boundary of the wildlife reserve, and can be divided into flatter areas (e.g., in the villages of Kundal and Ghata near the Sukhi reservoir) where agriculture is the dominate land use and steeper areas (e.g., in Kevdi) that are mainly covered by forest.

- **Forest and degraded forest are the dominant land cover in all the villages:** Kundal has the highest proportion of forest, at over 40% of the village area, while in Dungarbhint the area of degraded forest is larger than the area of forest. The areas of both forest and degraded forest stay relatively stable through the study period.
- **There has been a large shift from kharif only to double cropping:** The main crops include cotton, rice, and maize during the monsoon (*kharif*) season and maize during winter (*rabi*) season. The major change in cropping pattern over three periods, 2004–05, 2008–09, and 2012–13 (for which land use data were procured from National Remote Sensing Centre (NRSC), Government of India) is a large shift from *kharif* only to double crop agriculture—most evident for the two villages closest to the reservoir, Ghata and Kundal. While in 2004–05 the majority of agricultural land is *kharif* only for all villages (apart from Ghata where the areas of double crop and *kharif* only agriculture are relatively similar), in 2008–09 and 2012–13 all the villages see a major shift to double cropping.
- **Wells doubled in number since 2000 and are heavily concentrated along drainage channels:** There are 402 wells in total, of which 70% are dug wells and 30% bore wells, giving a well density of roughly 10 per km² for the village areas. These wells, however, are heavily concentrated along the drainage channels and very few are located in the forested areas. The highest concentrations are in the villages of Dholisimel and Dungarbhint. Areas closest to the Sukhi reservoir have the highest proportion of wells with year-round availability, a probable reason why the proportion of agriculture that is double cropped is higher in that area than further upstream. A noteworthy feature about the wells in these villages is their growth over time, which more than doubled from 2000 to 2014. The 77 wells of 1990 doubled to 178 wells in 2000, while the 265 wells in 2007 increased to 402 wells by 2014. The primary survey data and discussions in the villages showed that while there are very few dry or defunct wells and more than half (54%) of wells have water round the year, a large number (around 40%) of wells are seasonal, running dry after March (the festival of *Holi*). The “best wells” are found in the villages of Ghata and Kundal near the Sukhi reservoir, which are also the villages with the highest proportion of wells with year-round availability.

- **Water Harvesting Structures increased prior to the IWMP:** In total, the survey mapped 251 RWH structures in the five villages, of which 77 were funded IWMP. Only 9 check dams, from a total of 72, were funded by IWMP, as the most optimal locations had already been used by the time the project started in 2009. No structures have been built within the forest itself due to opposition from the Forest Department. Many of the larger check dams were funded by the Irrigation Department. The density of structures is similar in all the villages apart from Dungarbhint where only a few structures have been constructed by IWMP. Many of the structures are located along, or close to, the edge of the forest. For example, in Ghata, nearly all the streams and gullies that flow from the forest have been blocked by check walls or gully plugs. The majority of RWH structures funded by IWMP in the five villages were built in 2012 and 2013. Prior to this, the number of structures built on an annual basis was relatively low in comparison. However, the average number of structures built from 2007 to 2011 was around 10 per year compared to an average of around 5 per year from 2001 to 2006. This increase in the number of structures built is clearly related to the parallel increases seen in double cropped area and the number of wells and indicates that watershed development was occurring in the area prior to the investments by the IWMP. In total 55% of the structures are in good condition, 23% are damaged but still working, and 22% are defunct.

The survey could not capture structures that were built earlier in the period, but which were subsequently completely destroyed by floods: Kevdi village has the highest proportion of damaged and destroyed structures that can still be observed and currently there is no check dam still standing on the main stream. The local community identified high runoff from steep slopes during large rainfall events as the cause, as this brought branches and boulders down from the upstream forest and along the main stream (the number of large rainfall events and the steep topography of the villages support this observation.)

- **There is significant interannual variability in ground water levels:** The depth to water levels during summer is generally very low after an abnormally good monsoon year and very high after a very low rainfall year. This suggested that not all the water that goes into the hard rock aquifers underlying the watershed gets discharged after the monsoon, in spite of the steep terrain.^f

^f The option in SWAT to use expert knowledge to specify some parameters was used to incorporate these insights.

- **Water-level fluctuation is greater for very low rainfall than for abnormally high rainfall:** The four observation wells selected for detailed analysis (Ambala, Chhota Udeypur, Ferkuwa, and Kevdi) showed the highest water level fluctuation was in a drought year (1987, when the values varied from 3.05 to 0.47 m), and was much less in an abnormally wet year (1988, when the values varied from 6.37 to 5.25 m).
- **Following years of drought (e.g., 1985–87) a good monsoon (in 1988) results in excessively high groundwater recharge,** owing to the emptying of the aquifer in the previous years, which helps store extra water in the formation from the deep percolation.
- **The postmonsoon depth to water level in a high rainfall year is lower than in very low rainfall years.** Along with the high fluctuation between pre- and postmonsoon water levels, this suggests high rates of recharge.
- **There is neither long-term decline nor long-term rise in water levels overall,** in spite of increase in number of wells and bore wells in the area and presumably increase in groundwater draft. This could be because natural groundwater discharge also plays a significant role in altering groundwater balance along with groundwater draft through wells. The increase in groundwater draft is limited by the insignificant amount of static groundwater in the area, which is underlain by hard rock formations. Village-level discussions and cropping data from local government sources confirmed the survey findings and also detailed three key trends:
- **Increase in cropped area** in both monsoon and winter seasons
- **Increase in irrigated area** and more so for winter crops such as maize although the area under irrigated maize and rice during monsoon season has also increased. It is to be noted that the entire cropped area during winter and summer seasons is irrigated.
- **Expansion to irrigated crops:** There is a growing trend of cultivating irrigated long-duration cotton varieties, which grows over both the *khari* and *rabi* seasons, replacing single-season cotton. Also, groundnut is a minor summer crop introduced in 2006–07 in Ghata and Kundal, the two villages nearest to the Sukhi reservoir, but cultivated only by farmers who have access to wells with year-round water availability.

5.5.3 Villagers' perception of water problems

The population of these five villages is largely tribal and poor.[§] Most households (78%) have agriculture as their main occupation, while around 15%

[§] According to GoI classification, they are Scheduled Tribes (ST) and Below-Poverty Line (BPL) households.

work as farm labor. Around 60% of farmers have marginal land holdings (less than 1 ha), while 24% have small holdings (1–2 ha). While farmers generally see their future prosperity in shifting to long-duration cotton, only a few farmers with the necessary resources can afford the shift. To supplement their agricultural incomes, many migrate from these villages, especially after the *kharif* cropping season (August–November), to fairly distant locations such as Kachchh at the western tip of Gujarat and also to Mumbai.

Since rainfall is relatively high, and there are many open wells, water is not generally perceived to be a problem for drinking or livestock, but there are two cases where villagers reported problems:

- **Water scarcity in summer months and during *rabi*:** Many wells run dry after the *holi* festival in March, creating both drinking water problems and for providing the last two irrigations of the winter *rabi* crop. The problem increases as one goes further upstream from Kundal up to Kevdi. Even in these villages, drinking water is not a problem faced by all farmers but only by those who do not have wells with all-round water supply. The scarcity of water for the *rabi* crop, however, is more widespread although, as noted earlier, some farmers in the lowest villages if Kundal and Ghata are able to grow a summer groundnut crop.
- **Low rainfall years bring acute scarcities:** Water scarcities are acutely felt by a large number of villagers in all five villages during low rainfall years (as in 2009). Consecutive years of drought—a possible consequence of increasing climate variability—would create serious water problems in this area.

5.5.4 The challenge for watershed management

The hilly and rocky Upper Sukhi watershed has relatively high rainfall, occurring in a few months in a year resulting in high-velocity flows that do not allow water harvesting structures to remain intact and functional along the main streams. More wells and RWH structures built in the last decade has supported a growth in irrigated agriculture in (micro) watershed villages.

Although the local community is tribal and poor, mostly farming small and marginal land holdings during the single crop monsoon season, some farmers have wells with year-round water to support irrigated agriculture. Cropped and irrigated areas have increased in the last decade, with a preference for longer-duration cotton, a cash crop. All the area under winter crops (mostly maize) and the small area under the summer groundnut crop are irrigated.

Wells also provide water for drinking and livestock although there is a shortage in summer months even in normal rainfall years, which affects the last irrigations for the winter (*rabi*) crop. Low rainfall years and droughts worsen the situation considerably. Many in this agriculture-dependent community migrate for work after the monsoon *kharif* crop to supplement their livelihood.

Watershed management in this must take account of the following:

- The relative lack of treatment of the uppermost parts of the watershed which are forested, uninhabited, and directly under the control of the state Forest Department
- A large number of structures already built on the (smaller) drainage lines, implying that there are few suitable sites left to build more numbers of large RWH structures, such as check dams
- Most structures built on the upper reaches of the main streams flowing into the reservoir have been broken by the monsoon rainwater carrying branches and boulders, and there is not much space in villages to build additional RWH structures.
- There are large variations in rainfall, evapotranspiration, and runoff across dry and wet years that affect inflows into the reservoir, which, in turn, affect canal releases to downstream communities.

This basic understanding of the characteristics of the watershed is an essential first step to modeling the watershed, based on which the impact of watershed interventions on the water resources in the local villages and in downstream villages can be assessed.

5.6 Modeling the catchment characteristics

The aim of the hydrological assessment was not just to understand the key hydrological features of the watershed but also to create “what if” and “what’s best” scenarios of potential impacts of watershed management interventions, especially in downstream communities. Only when a model captures the dynamics of the watershed well can it be used to generate scenarios of potential impacts.

Since experience suggested that data collection would take time, the team decided to start the modeling using freely available global data sets simultaneously with the collection of national, state, and local data, i.e., from mid-September. As data became available, the rather coarse global datasets would be replaced, thereby improving the results. The results, in this case,

BOX 5.3 Basic steps in modeling

- Calibrate and validate for current conditions.
- Identify which hydrological processes are impacted by the management interventions.
- Select SWAT parameters that represent these processes
- Change sensitive parameters to represent management practices and different scenarios (different combinations, locations, and magnitudes of interventions). It's important that any parameter changes are realistic.
- Assess the reasonableness of results.
- Look at impacts (local and downstream) in wet, dry, and normal years. Validate against local data.

were how well the values predicted by the model match observed values of inflows into the Sukhi reservoir (see [Box 5.3](#)).^h

5.6.1 Model run with global datasets

The model set up in SWAT with global datasets (see [Box 5.4](#)) were checked against measured (or calculated) inflows into the Sukhi reservoir.

The global data sets are coarse-grained, as seen from the depiction of the Upper Sukhi catchment ([Fig. 5.4](#)).

Compared to actual inflows into the Sukhi reservoir, the SWAT run with global data was a reasonable but not very good fit to the data, either for monthly or annual inflows into the reservoir ([Figs. 5.5](#) and [5.6](#)). (Simplistically, this is seen by the fact that the bars are not of the same height, whereas in a “perfect fit” they would be the same.)

5.6.2 Model run with improved datasets

With the inclusion of some national and state data (32-m CartoDEM from NRSC, rainfall, and temperature data from Bhilpur and Dhandhoda stations and the reservoir dimensions from the State Water Resources Department), the performance of the SWAT model improved ([Figs. 5.7](#) and [5.8](#)).

The “goodness of fit” of the model simulated values to the actual values as also seen in the simple linear regression between the simulated and the actual inflows, both monthly and annual, also improved. The improvement in the “fit” of the model is seen in the fact that the R^2 values are much better

^h The modeling approach was discussed with Prof. Ashwin Gosain of IIT Delhi and Dr. Durga Rao of NRSC in Hyderabad, and suggestions incorporated.

BOX 5.4 Global data sets used

- Aster GDEM (30 m)—Global Digital Elevation Model produced by NASA and the Japanese Ministry of Economy, Trade and Industry downloaded from <http://gdex.cr.usgs.gov/gdex/>
- CFSR weather data (<http://globalweather.tamu.edu/>)—Global weather dataset that includes rainfall, minimum and maximum temperatures, wind speed, solar radiation, and relative humidity, for the period 1979 to present. The Climate Forecast System (CFSR) uses a high-resolution, coupled atmosphere-ocean-land model to resample conventional weather data to produce a global dataset with a 38 km resolution.
- FAO digital soil map of the world data at 10 km resolution downloaded from http://www.waterbase.org/download_data.html
- MODIS land cover (from US Geological Service)—500-m resolution global land use dataset developed using 10 years of data from the MODIS instrument aboard NASA’s Terra satellite. Downloaded from http://landcover.usgs.gov/global_climatology.php
- Reservoir areas delineated from satellite image using QGIS and capacity details acquired from the India WARIS website

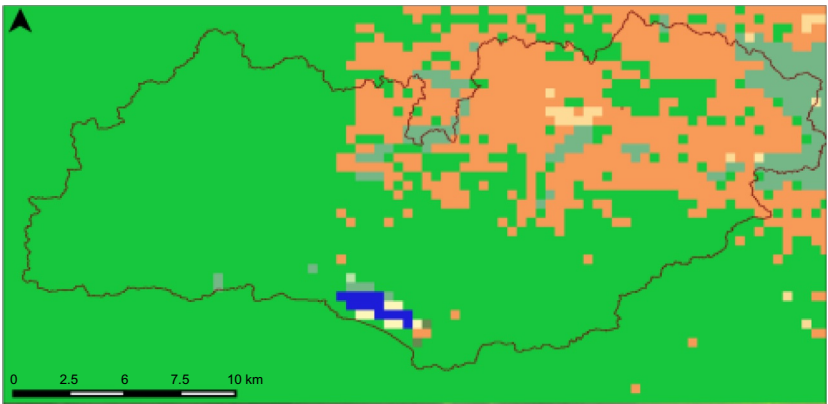


Fig. 5.4 Upper Sukhi catchment from global data.

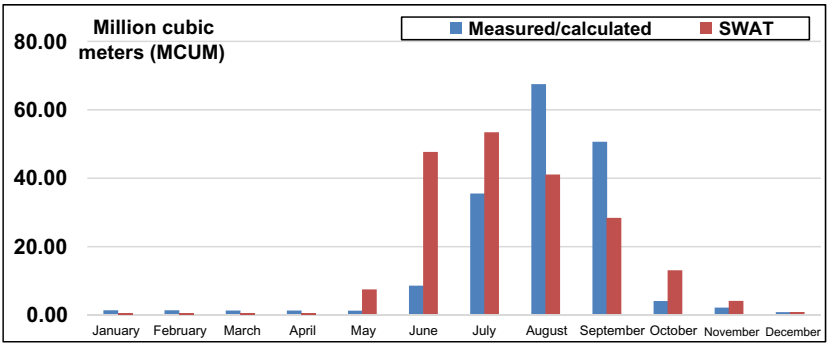


Fig. 5.5 Monthly inflows into the Sukhi reservoir, 1991–2012, global data.

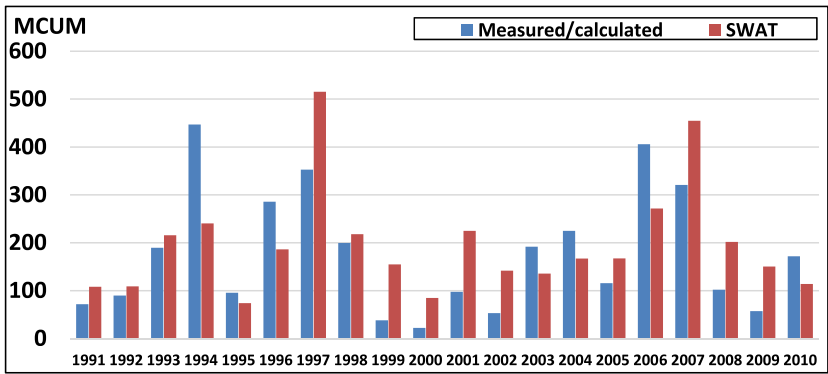


Fig. 5.6 Annual inflows into the Sukhi reservoir, 1991–2012, global data.

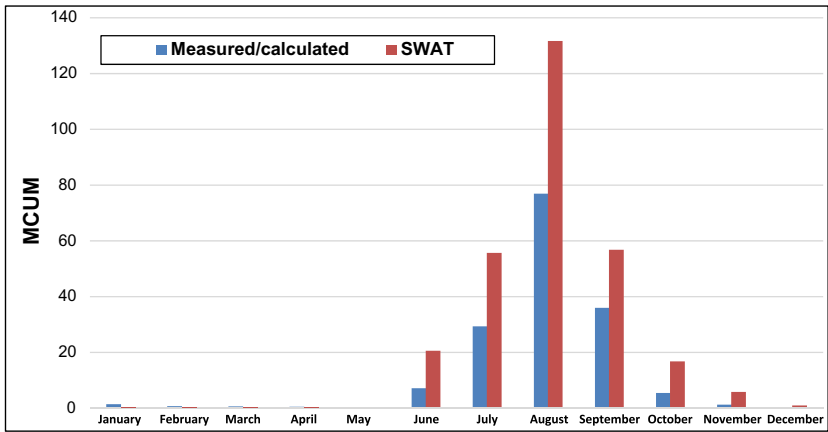


Fig. 5.7 Monthly inflows into the Sukhi reservoir, 1991–2012, improved data.

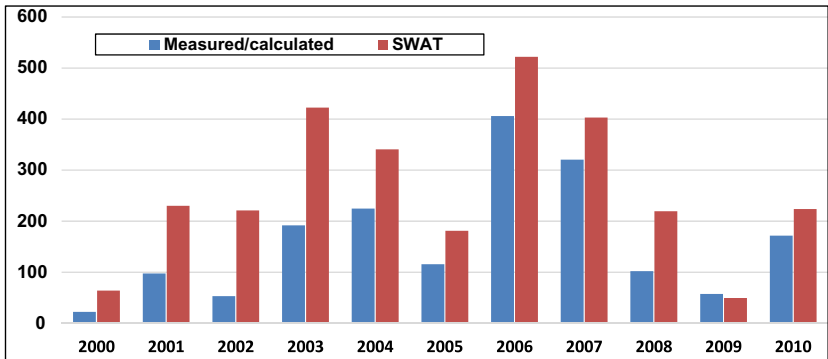


Fig. 5.8 Annual inflows into the Sukhi reservoir, 1991–2012, improved data.

for the SWAT model run with (some) local data compared to global data: for annual inflows into the reservoir, the R^2 improved from 0.45 to 0.81, while for monthly inflows it improved from 0.24 to 0.87 (Figs. 5.9 and 5.10).

5.6.3 Final model run

After replacing all the global data with national, state, and local data, including those from the primary survey (see Box 5.5), the outputs from the final run of the model were much better.

The final results showed that the model simulation of monthly inflows into the Sukhi reservoir was a good match to the actual data (Fig. 5.11).

The main results showed that the model captures the dynamics of the watershed quite well—as indicated both by excellent NSE and R^2 values and visual comparison of the observed and simulated reservoir inflows.

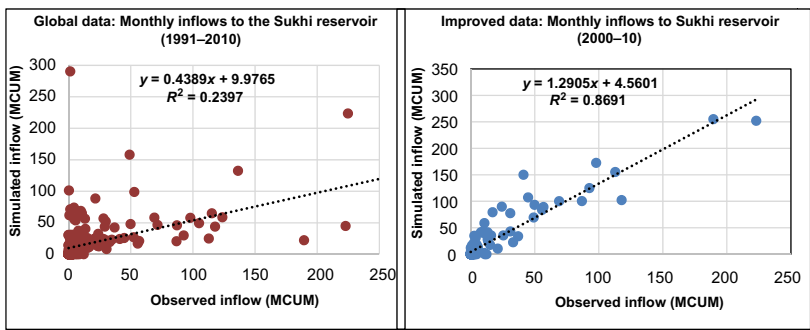


Fig. 5.9 Goodness of fit of the model for monthly inflows, global and improved data.

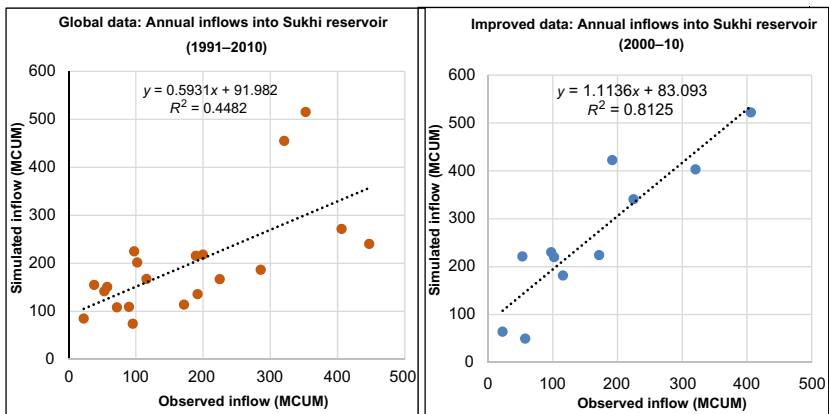


Fig. 5.10 Goodness of fit of the model for annual inflows, global and improved data.

BOX 5.5 Main data used in the final model run

Digital Elevation Model (DEM): CartoDEM from NRSC with 30-m resolution.

Land Use Land Cover (LULC): 250k LULC for 2004–05, 2008–09 and 2012–13 from NRSC.

Soil data: NBSLUPP Soil Handbook for Gujarat.

Climate data: Rainfall data from the three local weather stations nearest to the catchment and minimum and maximum temperatures, wind speed, solar radiation, and relative humidity from one station (Dhandhodi).

Discharge: Monthly data for the Sukhi reservoir from the State Water Resources Department.

Cropping patterns: State Agricultural Department and primary survey in five villages.

Irrigation data: Primary survey in five villages.

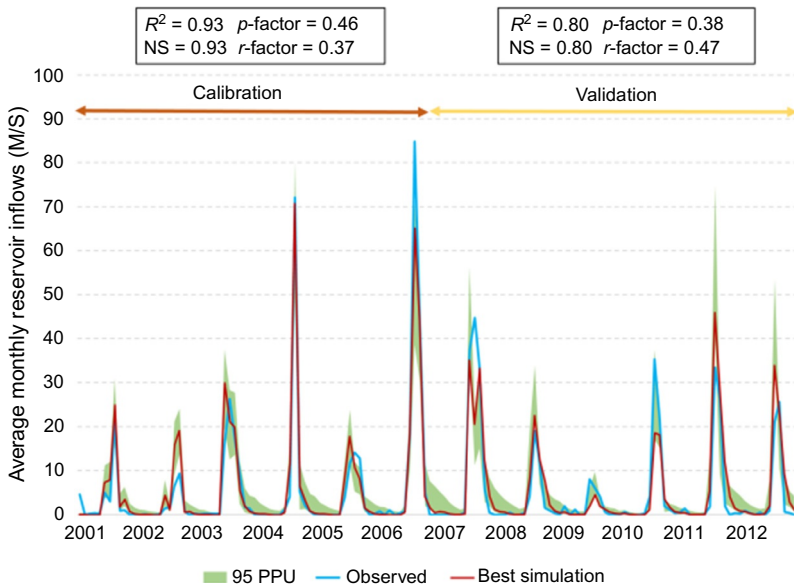


Fig. 5.11 Final model simulations and actual monthly inflows into Sukhi, 2000–12.

There was some uncertainty in the model outputs. The two obvious sources of uncertainty are: (1) the rainfall data (a common source of error in many hydrological models due to the difficulty of extrapolating point measures at rain gauges to areal estimates of rainfall) as they come from gauging sites outside of the watershed and at lower elevations; (2) the observed reservoir inflow data used for calibration, which were not measured directly

but calculated (by the Water Resources Department staff at the dam site) using a water balance equation and are therefore likely to be less accurate than discharge data recorded at a control structure. Outflows from the Sukhi reservoir occur not just over the spillway of the dam, but also through two irrigation canals, which makes the accurate measurement of total outflows more difficult. Calculation of evaporation from the reservoir could also introduce errors into the water balance equation especially because of the need to account for large and rapid changes in the surface area of the reservoir. Finally, neither the seepage from the reservoir nor pumping of water from the reservoir by the surrounding villages was accounted for in the water balance equation.

The model, nevertheless, was adjudged ready for simulations.

5.7 Scenarios of impact

The development of model scenarios enables an analysis of the potential impacts that investments in water infrastructure and other factors (e.g., changes in climatic variables) may have on the hydrology and water resources of the area of interest. Such analysis makes it possible to explore tradeoffs involved in decision making, for example, at what level of watershed development does the reduction in downstream flows start affecting downstream benefits such as irrigation and drinking water supplies—and become politically, economically, socially, or environmentally unacceptable?

Scenario development is a stage at which all stakeholders can provide their input based on their vision of the future of the watershed (see [Box 5.6](#)).

BOX 5.6 Useful characteristics of scenarios

- Must be a realistic vision of the future conditions of the study area, as far as possible.
- Focuses on two or three key factors (such as proposed water and land management interventions, environmental change, and economic development) that are *important* (i.e., they can have relatively large impacts) but also relatively *uncertain* (i.e., their potential impacts are not entirely predictable in either their effects or magnitude).
- Relative accuracy is often greater than that of the underlying model is compared to observed values. This means that model scenarios can still provide useful outputs for watershed planning even if there is some uncertainty regarding baseline model performance.

Source: *Kauffman et al. (2014)*

The development of scenarios for the Sukhi watershed focused on two main factors:

- **Changes in the levels of in situ and ex situ rain water harvesting (RWH)** in the watershed and
- **Changes in cropping intensity**, in particular, the expansion in double-cropped area

The study team felt that model scenarios based on these two issues could provide useful information for planning watershed development in the Sukhi watershed, and consider the important and uncertain impacts it may have downstream, in view of the criteria outlined in [Box 5.6](#)

- *Importance:* These two factors are likely to have a big impact on the watershed in the future given the investments being made in watershed development by IWMP and other programs and the expansion in the double cropped area driven by population growth and the microeconomic needs of the agriculturally dependent communities.
- *Uncertainty:* Though the expected impact of increased RWH and expansion of double cropped area would be greater water use within the watershed, there is significant uncertainty on the magnitude of this increase and the impact on downstream flows.

Two versions of the scenarios were developed, one for the entire catchment and the second for the five villages where detailed analysis was undertaken.

5.7.1 Catchment-level scenarios

5.7.1.1 Scenario description

Two main scenarios were developed to look at the impacts of land use change and watershed development on the hydrology of the Sukhi watershed:

- **Scenario 1: The watershed prior to the modeling period:** The watershed in the absence of the watershed development and the intensification of agriculture that has occurred over the last two decades, when most of the agricultural land was *kharif* only and there were very few large RWH structures. Although it is difficult to envisage a return to the pre-1999 situation in the watershed, scenario 1 helps to illustrate the impact that agriculture and watershed development has already had on the hydrology of the watershed.
- **Scenario 2: A significant intensification of agriculture and watershed development from current levels.** This is the most plausible future for the watershed given the investment by IWMP and other programs in watershed development and the increasing demand placed on agriculture to produce more food and improve local livelihoods.

Both scenarios 1 and 2 are disaggregated into three parts:

- Part (a) models the combined impacts of changes in RWH and land use
- Part (b) models the impacts of changes in RWH alone
- Part (c) models the impacts of changes in land use alone

The best simulation from the model calibration was used as the baseline and the scenarios evaluated for the period 2007–12 (Table 5.3).ⁱ

Table 5.3 Description of model scenarios.

Scenarios		Description
1	A. No development	This scenario models the watershed as if no watershed development or increase in the area of double cropped agriculture had occurred. This is represented by the removal of all reservoirs, apart from Sukhi, Jamli, and Jogpura, and by using the 2004–05 land use dataset for the entire modeling period
	B. No watershed development	Removal of all RWH structures (represented as reservoirs in SWAT) apart from Sukhi, Jamli, and Jogpura
	C. No land use change	Use of the 2004–05 LULC for the entire modeling period
2	A. Intensification of agriculture and RWH	This scenario represents the more likely future for the watershed: intensification of agriculture and RWH, represented by (1) an increase in RWH structure capacity to 40 m ³ /ha and implementation of reservoirs in forested watershed areas; and (2) an increase in double crop area from 30% to 40% of watershed area but no change in reservoir capacity
	B. Intensification of RWH	Increase in RWH structure capacity to 40 m ³ /ha and implementation of reservoirs in forested watershed areas
	C. Intensification of agriculture	Increase in double crop area from 30% to 40% of watershed area but no change in reservoir capacity

ⁱ This period was chosen because it witnessed significant land use change that was incorporated into the model and therefore provides a stable baseline from which to evaluate the impacts of the scenarios. If the whole modeling period had been used, land use change would have had to be considered when evaluating scenario outputs.

5.7.1.2 Scenario impacts

The overall impacts of the scenarios are as expected:

- **Inflows into Sukhi reservoir**
 - Scenario 1 (A, B, and C) increases inflows.
 - Scenario 2 (A, B, and C) decreases inflows.
 - Scenario 1A has largest increase in reservoir inflows
 - Scenario 2A has the largest decrease in reservoir inflows
- **Impact on downstream flows**
 - Watershed development has the largest impact on downstream flows dry years (i.e., the relative impacts of the scenarios are greatest in 2009, the driest year)
 - Scenario 1A increases downstream flows by 24%
 - Scenario 2A decreases downstream flows by 19%.

Whether it is a dry year or a wet year also affects various water balance components—evapotranspiration (ET), percolation, artificial recharge from RWH structures, and reservoir inflows. The changes in these components for the baseline and other scenarios, as a percentage of rainfall, show the following for 2009, the driest year; and 2011, the wettest year:

- **Changes in the double cropped area have the largest impact on the amount of water lost as ET from the watershed with the impacts largest in the driest year (2009).** In this year, ET for scenarios 2a and 2c, in which the double cropped area is increased to 40% of the watershed area, is close to 100% of rainfall, around 10% more than for the baseline. This is because a large amount of water is removed from the shallow aquifer for irrigation and is subsequently lost as ET. The water stored in the shallow aquifer is nearly exhausted in 2009, so two or more consecutive low rainfall years could have been calamitous for the local community. For scenarios 1a and 1c, in which the double cropped area is reduced to 9% of the watershed area, ET in 2009 is reduced to 77.4% of rainfall, more than 10% lower than the baseline figure.
- **The impact of the scenarios on ET in the wettest year (2011) is far less as a percentage of rainfall,** although the absolute difference is similar.
- **Recharge from RWH structures in the driest year (2009) is double the average recharge as a percentage of rainfall.** Differences in percolation rates between the scenarios are mainly a result of recharge from RWH structures, which more than doubles from an average of 0.4% of rainfall for the baseline, to 1.1% for scenario 1a. This is in line with the increase in RWH structure capacity from 15 to 40 m³/ha for scenario 1a and an expansion of structures into the mainly forested subwatersheds.

5.7.2 Village-level scenarios

5.7.2.1 Extracting village areas

While simulation models can create scenarios that enable insightful inferences to be drawn about the behavior of the watershed in response to watershed development interventions, it is the impacts of interventions in the five villages that are of direct interest. The choice of the watershed was, however, largely decided by the data needs of the model, viz., the availability of reliable data from the Sukhi reservoir. This situation, where the availability of data for calibration and validation requires the modeling of a watershed much larger than the area of interest, is likely to be found for other areas where IWMP watersheds are located, as many are found in headwater areas, a long way upstream of any gauging point that could provide reliable data for calibration and validation.

One of the advantages of SWAT is that the subwatersheds can be delineated at a user-specified resolution, which allows results to be analyzed at local levels, even for large watersheds. A tradeoff is that models of large watersheds with many subwatersheds can substantially increase model runtime and make processing model outputs a time-consuming process. One solution is to vary the resolution of subwatersheds across the watershed so that areas of interest are defined in more detail (Notter et al. 2012). *This process is of particular interest as it allows the selection of a larger catchment for modeling and simulations, and a focus on a smaller part within the catchment for detailed analysis.*

The process of extracting model outputs for areas of interest from within a larger model is demonstrated here by analyzing model outputs for the five survey villages. During model setup, the subwatersheds were defined so that they were of similar size to the village areas used by IWMP for watershed development to allow model outputs to be more closely associated with each village. It was not possible, however, to match the boundaries exactly as neither the village boundaries nor the boundaries of the government-delineated microwatersheds matched the hydrological boundaries as defined by the DEM. Although watershed development under IWMP is meant to be planned for the government-delineated microwatersheds, it appears that in the Sukhi watershed most of the planning was done using village areas. The SWAT subwatersheds overlain onto the areas of the five survey villages shows that the village areas cover parts of a number of different subwatersheds, but the majority of the areas are covered by nine (numbered) subwatersheds (Fig. 5.12).

The land use of each subwatershed has a large impact on its hydrology and therefore on the impact of the scenarios. The nine subwatersheds shown in Fig. 5.12 can be divided into three distinct groups based on their dominant land uses:

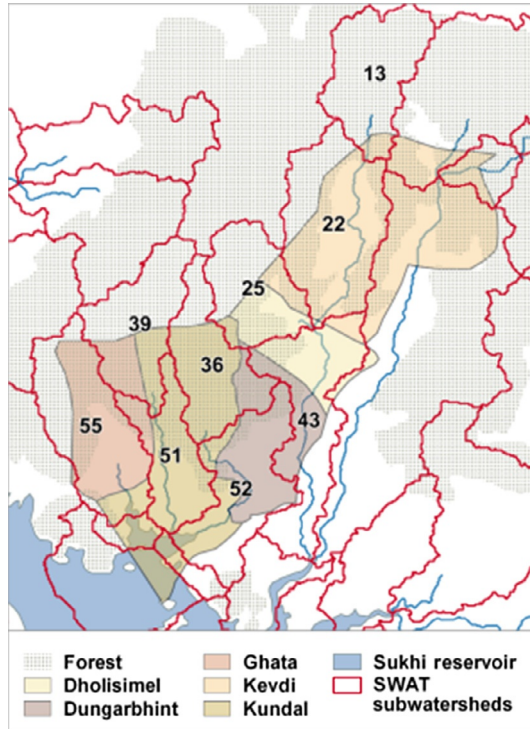


Fig. 5.12 SWAT subcatchments covering the five survey villages.

1. **High degree of forest cover:** Subwatersheds 13, 36, and 39
2. **Mix of forest and agricultural land:** Subwatersheds 22, 25, 51, and 55
3. **Mix of agricultural land, grassland, and degraded forest:** Subwatersheds 43 and 53

These nine subwatersheds can be divided into four subcatchments, all of which drain directly into the Sukhi reservoir, making them a useful unit of analysis (Fig. 5.13).^j

A detailed (water infrastructure) plan was developed for Kevdi village for RWH structures based on preliminary model findings, analysis of satellite images, and consultation with the local community. The main aim of the plan was to ensure that sufficient water was available for the whole *rabi* irrigation, as villagers reported that on a majority of farms away from the river,

^j The only large area of the five villages that falls outside of the nine subwatersheds is the eastern half of Kevdi village, which covers a small part of a much larger subcatchment. This illustrates the difficulties of using administrative units, such as village areas, when analyzing and planning hydrological interventions.

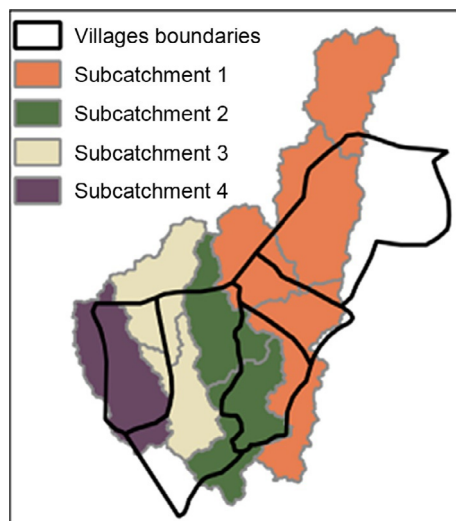


Fig. 5.13 Microcatchments covering the five surveyed village.

wells run dry before the end of the *rabi* season even during normal rainfall years, and to minimize reductions in downstream surface water flows. This plan was extrapolated to the other survey villages by calculating the amount of extra capacity needed for each hectare of agricultural land (Table 5.4). The split between on- and off-channel storage was 45:55, based on the number of structures of different types recommended in the plan for Kevdi village. (The off-channel storage is higher due to the large number of farm ponds recommended.)

5.7.2.2 Scenario description

The $40 \text{ m}^3/\text{ha}$ figure applied in scenario 2A earlier (to represent intensification of RWH) is slightly lower than the average of $42 \text{ m}^3/\text{ha}$ capacity of RWH structures calculated as a function of village area (Table 5.4). The capacity calculated is also higher than the figure of $40 \text{ m}^3/\text{ha}$ for all the villages other than Kevdi. In the next round of village-level scenario generation, therefore, these revised figures for additional RWH structures were applied to the nine subwatersheds covering the village areas (rather than for the village areas per se). Using information from the village plans, the generic scenarios applied to the whole watershed were adapted to investigate the impact of these plans at the local level (Table 5.5).

Table 5.4 Extrapolation of the Kevdi Village Demo Plan to the other survey villages.

	Ghata	Kundal	Dungarbhint	Dholisimel	Kevdi
Village area (ha)	533	1052	517	373	1287
Total agricultural area (ha)	121	231	104	62	179
Rabi area (ha)	114	228	95	38	127
Baseline RWH capacity (m ³)	7995	15,780	7755	5595	19,305
Additional off-channel storage	14,911	28,791	13,341	8490	26,164
Additional on-channel storage	8602	16,455	7425	4429	12,719
Total extra storage (m ³)	19,116	36,567	16,500	9842	28,265
Total RWH capacity (m ³)	27,111	52,347	24,255	15,437	47,570
Total RWH capacity (m ³ /ha)	51	50	47	41	37

Table 5.5 Description of village scenarios.

Scenarios		Description
V1	No development	Identical to scenario 1A and models the watershed as if no watershed development or increase in the area of double cropped agriculture had occurred. This is represented by the removal of all reservoirs and by using the 2004–05 land use dataset for the entire modeling period
V2	Village plan	This scenario represents an increase in RWH capacity based on a watershed plan developed for Kevdi village. The plan is extrapolated to all the subwatersheds covering the village areas based on the RWH capacity needed for each hectare of agricultural land. The split between on and off channel storage for Kevdi village is also applied to all subwatersheds. Reservoirs are also implemented in forested subwatersheds 13, 25, 36, and 39, the size of which are calculated using a 15-m ³ /ha figure
V3	Intensification	This scenario represents a 25% increase in double cropped area within each subwatershed and an associated increase in RWH capacity, calculated using the per hectare figure from the Kevdi village plan. The capacity of reservoirs in subwatershed 13, 25, 36, and 29 is doubled compared to scenario V2

Note that for scenarios V2 and V3, reservoirs are also implemented in the forested subwatersheds upstream of the villages (i.e., in subwatersheds 13, 25, 36, and 39).^k

5.7.2.3 Scenario results

Water balance components: Extracting data on the water balance components for the nine subwatersheds reveals differences to the Sukhi watershed as a whole for the baseline, due to the differences in the proportions of the different land uses, topography, and soil characteristics:

- **Evapotranspiration (ET) is lower than for the watershed as a whole:** 30.8% compared to 40%. This is due to the large areas of forest and degraded forest in the nine subwatersheds, which have lower ET than irrigated double cropped areas, which make up a higher proportion of the rest of the watershed.
- **Variations in reservoir inflows the driest and wettest years are significant:** While baseline reservoir inflows for the nine subwatersheds are like those of the whole watershed—the average over the period is 40.5% compared to 40%—reservoir inflow in 2009 under the baseline scenario is only 15% of rainfall compared to 19% for the whole watershed.
- **Percolation and (artificial) recharge from RWH are like those for the entire watershed.**
- **Removing RWH structures and decreasing double cropped area, sees only small increase in average reservoir inflows:** While this change is only from 40.5% to 41.2% of rainfall, Scenario 1A for the whole watershed saw an increase from 40% to 43% of rainfall. This highlights the fact that the study villages are located in an area of the watershed that so far has seen relatively less intensive agricultural and hydrological development.
- **Reservoir inflows decrease in scenarios V2 and V3, as expected, but the decrease is larger for scenario V3.** This is due to increase in double cropped area and the larger increase in RWH capacity.

^k Although no structures are allowed to be constructed in the forest, many new structures constructed by IWMP are concentrated at the edge of the forest where gullies and streams emerge. As reservoirs are conceptually placed at the outlet of sub-watersheds in the model, adding reservoirs to these subwatersheds is an effective way of representing the concentration of structures at the forest borders.

Scenario V2, which models the plan developed for Kevdi village, sees a large increase in recharge from RWH structures compared to the baseline, especially in 2009, the driest year. The increase in ET is not large due to the fact that there is sufficient groundwater in the baseline scenario for full irrigation of the *rabi* crop. Therefore, in scenario v2, the additional groundwater is not needed for irrigation and is instead stored in the shallow aquifer with a proportion contributing to stream flow. This is a key area in which the model does not accurately reflect reality at a local level, as the local community has reported that in most years there is insufficient groundwater available to irrigate the entire *rabi* crop. Groundwater in the area is very shallow and drains quickly into the reservoir following the end of the monsoon.¹

Impact on yields: SWAT also models average crop yields and those in the nine subwatersheds, for the period 2007–12, compared well with those reported in the primary village survey, with the exception of *kharif* maize (Table 5.6).

Table 5.6 SWAT estimated and farmer-reported crop yields, five villages, 2007–12.

Crop	Season	SWAT baseline scenario estimate	Average farmer estimate
Rice	Kharif	2112	2193
Maize	Kharif	3796	2087
Maize	Rabi	1886	2181

¹ The problem is also highlighted by the fact that reservoir inflows are lower in 2009 for scenario V2 than they are for V3, due to increased runoff that results from irrigation of a larger double cropped area. In reality it is unlikely in 2009, even with intensive RWH, that enough groundwater would be available such that runoff resulting from irrigation would increase reservoir inflows. Limitations in the modeling of groundwater affect the ability to use the model to assess the beneficial impacts of watershed development and highlight the need for further model development. Groundwater representation is acknowledged as a weakness of the SWAT model, which is why in many studies, where groundwater plays an important role, it is coupled with MODFLOW, a groundwater model, which allows groundwater to be represented in far greater detail (Kim et al., 2008). This would be an option of the Sukhi catchment but would obviously increase the amount of data and time needed to complete the modeling.

There is little variation in crop yields between the scenarios because in all of them there is deemed to be sufficient water available for irrigation in nearly all the subwatersheds. Only in 2009 does the water in the shallow aquifer come close to being completely depleted, which limits irrigation for some HRUs in the following year.

5.7.3 Discussion

Overall, the model helps to provide a solid hydrological foundation to the behavior of water in the watershed, putting concrete numbers on hydrological phenomena such as evaporation, transpiration, groundwater recharge, and percolation, and thus explaining the observed inflows into the Sukhi reservoir downstream of the selected watershed. Such information is vital in planning the management of the (larger) watershed and also in the prioritization of (smaller) watersheds to be taken up for treatment.

The simulation of watershed hydrology by the model enables the creation of scenarios to assess the impacts of watershed management interventions both locally, in villages within that particular watershed, and downstream of it. Supplemented by multistakeholder interactions, the main observations made possible by the use of this approach are the following:

- **Watershed inflows exceed outflows:** With “watershed inflows” referring to rainfall falling over the watershed (the basic source of the water) and “outflows” referring to the water that reaches the Sukhi reservoir (as “inflows into the reservoir”), this observation is borne out by the fact that there are inflows into the Sukhi reservoir even in very low rainfall years. While good rainfall years swell the Sukhi reservoir, increasing its ability to provide water to downstream farmers, dry years see a huge shrinkage, even compared to the average rainfall years.
- **Water demand exceeds supply:** The demand for water for domestic uses, livestock, and irrigation is more or less met in the five villages studied in detail, although villagers reported summer scarcities and problems even in a single low-rainfall year. Consecutive years of low-rainfall or droughts could severely constrain drinking water demand for human and livestock populations. The demand for water for irrigation has been growing over the last decade or so, illustrated by the large increase in wells and RWH structures, and is likely to grow further. While population increases could further increase water demand even in average rainfall years.
- **Need alternative rain water harvesting options:** The substantial rain-water harvesting prior to the IWMP projects of 2009–10 had resulted in

check dams and gully plugs being built in the best possible locations, leaving few options for such interventions in the IWMP. There are, however, still several options for decentralized storage and recharge structures, such as subsurface tanks and dykes and farm ponds, which can provide the farmers the extra *rabi* irrigation water that they mentioned as a major issue. All these, however, have to be considered in the specific local context as what may work well in one ecological, sociopolitical, and cultural context may not perform similarly in another context. Careful evidence-based analysis will be necessary before deciding on such options.

- **Need increased water productivity:** A shift to crops that use the available water but give higher profits per unit of water could improve agricultural livelihoods. This is not easy to realize in practice, however, as international experience has shown. Even strategies to reduce crop water use, such as shifting to less-water intensive crops, microirrigation (drip and sprinklers) and (plastic or organic) mulching to reduce evaporation from crop lands (and thus reduce the need to irrigate), appear sensible and practical (as do options to raise agricultural profits, by reducing cultivation costs and increasing output prices), but these can only be achieved by careful formulation of these strategies, based not only on strong local evidence of impact but also on the local (social, political, regulatory, legal, and cultural) contexts, besides effective implementation. This apart, whether it is considered necessary to improve livelihoods in upstream areas at the cost of improvements with higher social value in downstream areas, is an issue for multicriteria policy analysis and decision.
- **Nonwater-based livelihoods must be encouraged:** The unmet demand for irrigation water is reflected in the inability of all farmers to grow a *rabi* crop, causing many to migrate for work after the *kharif* season. Providing support for feasible nonwater-based livelihoods that are at least as profitable as migration could help to stem such stress migration. This again is a policy decision to be taken at the level of the watershed as a whole, where local perceptions and priorities will have to be considered along with government interests (e.g., for long-term development of the region as a whole and for future generations).

5.8 Lessons for hydrology-based watershed management

5.8.1 Approach and methodology

The basic lesson is the fundamental need for sound hydrological analysis and sustained and well-facilitated stakeholder consultations to underpin

decisions on watershed management strategies. This has, however, to be undertaken within an integrated policy and institutional framework based on (economic, environmental, social, and cultural) development priorities for water allocation across large watersheds. As in countries like Australia, this will require political cohesion and broad agreements but the actual frameworks for action will have to be context-specific.

The six key steps in the methodology developed for the hydrological assessment are the following:

- Field visits, stakeholder dialogue, transect walks, and model selection
- Model set up and modeling using data from open-access global datasets
- Acquiring, quality controlling, and using secondary data from (nonopen access) national, state, and other databases
- Participatory collection of biophysical primary data (e.g., well and RWH structure surveys)
- Participatory collection of societal primary data (e.g., development time-lines of water and other natural resources)
- Modeling and scenario analysis to assess and map the scale of current and future watershed management benefits and externalities

The more innovative aspects of the methodology piloted in this study include the following:

- **Using data from global and regional databases as a starting point.** Being readily available, this could enable the setting up the model very quickly—which is very different to normal modeling practice
- **Iterative incorporation of official and primary data over a period of time.** Refining the model as better-quality (official) data became available.
- **Using only open source software.** While projects and organizations are still willing to spend on software, this is not necessary currently—and thus the use of GIS and modeling software should no longer be constrained by the cost of licenses.
- **Savings in the cost of modeling work.** This is due not only to the availability of freely available open source software, but also because models can be set up fairly quickly with available global data and refined as better data are made available.

The planning of management interventions, however, requires a longer process of sustained and well-facilitated engagement with the key stakeholders, within clear policy and institutional frameworks of water allocation and water use.

5.8.2 Application: Watershed management projects

The basic steps for applying the methodology in a stand-alone watershed management project are the following:

- (1) the selection and prioritization of watersheds
- (2) the hydrological assessment (with stakeholder interaction) and
- (3) intervention planning.

Steps (2) and (3) are interactive and iterative, with inputs from primary surveys and discussions feeding into model set up, preliminary model outputs informing discussion on intervention planning, and monitoring and evaluation of project impacts being used to rerun the model to track changes in the watershed.

5.8.2.1 Selection of project area

- **The ridge-to-valley approach is a good starting point**, as in the case of the IWMP, but multiscale biophysical analysis is now possible, with the expansion of data availability, and can be used to decide the starting point. River basin maps and topology provide an overview of the various smaller watersheds in the basin-level watershed, and the subwatersheds of each watershed. In the case of preselected project sites, placing the selected site within its larger hydrological unit would give a better context to project planning and management (than treating it as a standalone site with no hydrological connections either upstream or downstream).
- **Accessibility issues may affect site selection**: Even if selected, the hilly and forested upstream areas of watersheds may not be accessible for a variety of reasons. For instance, in many places, including India, these areas are under the jurisdiction of the Forest Department and no project can be implemented there without their supervision and control. Some areas have military installations (e.g., wireless and microwave repeater stations) under the control of the Ministry of Defence and are therefore inaccessible. The project area to be selected for interventions thus depends as much on the access to the site as on budget and development priorities (e.g., the criteria for selection of IWMP projects).
- **The size of the watershed for the hydrological simulation modeling depends more on the need for accuracy of model findings**. Freely available global data sets and improved “open source” software means that modeling can be done at any convenient scale, but generally speaking, the larger the watershed, the easier it is to find stream gauging points or reservoirs, and better the (simulation) model at simulating

watershed hydrology. As demonstrated in [Section 5.3](#), the area selected for project interventions can lie within this larger watershed selected for modeling.

- **Hydrological unit vs administrative boundary is an “old chestnut”** (e.g., [Farrington et al., 1999](#)) and while it would be helpful for model predictions if the project area were determined by hydrological criteria (e.g., the subwatersheds delineated by SWAT), these rarely coincide—and most projects prefer administrative boundaries for ease of planning and implementation. However, rather than planning project interventions without any reference to hydrological dynamics (as in the case of the IWMP), it is possible to carry out the modeling for the larger area and extract outputs for the project area (as demonstrated for the five villages in the Upper Sukhi watershed) and thus use available hydrological information in project planning.
- **Overall, however, the best starting point depends on the context.** Given a choice, however, it is best to start in the upper reaches of the watershed in the project area (to reduce the velocity of rain water and thus prevent adverse impacts such as soil erosion and increase groundwater infiltration) even though the entire watershed is not being taken up for treatment under the project. The modeling can provide watershed-level information and scenarios that can be used for planning interventions.

5.8.2.2 Hydrological assessment

- **A review of earlier hydrological assessments is a necessary first step to a new or updated hydrological assessment.** This essentially involves understanding the watershed, its dynamics and complexities, usually from experience with other similar watersheds elsewhere. Collecting secondary information, trawling and mining the internet, and undertaking a drive-through or a fly-over the watershed are useful parts of this activity, and can be undertaken in any order that is convenient, but discussions with key stakeholders are a must, not only to add details of interest and to assimilate local information but also to create support for the proposed management activities.
- **The choice of model is a key step in the hydrological assessments.** There are a large number of suitable models and the final choice has to be based on a number of issues including the skills and experience of the modeler, the availability of suitable data, and the time and resources budgeted for the modeling exercise. As explained earlier, SWAT was a good choice for the Indian context.

- **Model set up involves deciding values for a large number of technical parameters in these simulation models**, using available data, the literature (for approaches used by other researchers), and expert opinion (of specialists who have worked in the area). These will have to be adjusted as better information emerges, but some parameters (like subwatershed size in SWAT) have to be fixed at the beginning, keeping in mind the need to extract information later about the smaller project area. As mentioned earlier, the watershed size will be decided not only by data availability and accessibility to the site for the field visits but also by the nature of “what if” and “what’s best” questions to be answered by the model.
- **Collecting primary and secondary data depends on the model chosen**. But listing the data requirements of the model and identifying potential sources of each dataset is the first step. There are three basic sources of data for any modeling exercise: (1) global datasets (DEM, soils, weather, etc.); (2) country-specific data sets (on reservoirs and canal networks, soils, crop yields, weather, etc.); and (3) local information (on cropping seasons, crop durations, irrigation applications, the number (georeferenced) location, and development timelines of wells and RWH structures, etc.). Thus, while the model can be set up quite easily using global data sets, additional information can be added to improve the quality of the model outputs. The primary and secondary surveys can start simultaneously, not only to reduce time but also to ensure that the primary information is available to input into the model.
- **Model calibration and validation are essential to checking how well the model is able to represent watershed hydrology**. Here it is important to note that not only is the “goodness of fit” to be checked but also the extent of uncertainty inherent in the model predictions.^m The assumptions that went into detailing the model specifications as well as the data need to be reviewed and revised till the “goodness of fit” is as close to ideal as possible and uncertainty is minimized. Also, incorporating land use changes into the model set up and scenarios is essential in areas where land use has changed substantially during the period taken for modeling. It would also be helpful to have an expert or group of experts review the modeling process at regular intervals during the modeling process, as done in the demonstration detailed in [Section 5.3](#), to assess the technical details of the modeling (e.g., the separation of the data set for use in warm up, calibration and validation, the setting of model parameters, and the use

^m In the SWAT, these are represented by the p and r statistics.

of manual functions instead of automatic functions as in the case of SWAT).

- **Main model outputs are the basic water balance components of the watershed** (including key features such as evapotranspiration, groundwater recharge, and runoff outside the watershed), which can be used to classify the watersheds along with information from stakeholder interactions about demand and supply
- **Understanding future watershed behavior requires the creation of a baseline and other scenarios that work in relation to the baseline.** Interpreting the scenarios in relation to the baseline produces more reliable results than the absolute value of the scenario outputs. While watershed-wide baselines and scenarios are useful and necessary, the model can also be used to create scenarios for the project area in detail.

5.8.2.3 *Intervention planning*

- Although discussed under separate headings, the hydrological assessment and the stakeholder-led planning are part of the same mutually supportive process and need to be undertaken synchronously and iteratively. Building cohesion and trust among the key stakeholders is vital as is the creation of an appropriate institutional platform and conducive conditions for effective multistakeholder discussions.
- **Management planning can be initiated as a part of the process of stakeholder consultations.** Using information from the earlier stakeholder interactions and field visits and supplemented with model scenarios, this needs to be viewed as iterative and adaptive. Participatory village planning can be done more easily by involving villagers in discussions of local watershed characteristics and problems using maps based on remotely sensed data. While Google Earth is a relatively cheap and simple tool to create such interactive map-based discussions, it can also be done with more sophisticated maps and tools. Detailed planning, however, will involve visiting each farmer's field to discuss specific options to improve water productivity (e.g., leveling, bunding, terracing, crop choice, cultivation techniques such as mulching, irrigation options such as drips and sprinklers and farm ponds), visiting village water bodies (streams, ponds, wells, and RWH structures) to assess what can be done to augment water supply (and protect and prioritize drinking water for humans and livestock) using traditional knowledge and skills.
- **Assessing plan implications using the model is an iterative next step.** This will introduce the key features of the watershed plan (including

the total additional capacity of wells and RWH structures planned and options to reduce water demand and improve water productivity) into the model and creating a separate scenario to assess potential hydrological impacts in terms of the water balance components.

- **Addressing downstream impacts will become important as planned interventions are likely to reduce surface and or ground-water outflows.** At the minimum, discussions will have to be held with downstream stakeholders to see if some part of the plan can be scaled down (to reduce such adverse impacts) or if adverse impacts can be minimized. Water productivity enhancements can be suggested and introduced, so that even reduced quantities of water may produce the same level of profit per unit area. It would be ideal if the community benefiting directly from the project undertakes to guide the downstream community in the adoption of these practices, based on their experiences through project interventions. But this is a much larger issue if there are interbasin transfers, dams, urban areas, and ecological requirements in the selected watershed. These will require locally relevant and effective sociopolitical institutions and mechanisms, as well as policy frameworks, to be set up and operate to resolve the tradeoffs that are inevitable when downstream flows reduce.
- **Finalizing the management plan will require additional considerations:** These include understanding the support required to promote nonwater-based livelihoods and assess the strength and capability of local organizations and local government officials in order to plan for the capacity building of individuals and groups and the strengthening of local institutions. The Watershed Plan will also have to include arrangements for the participation and contribution of local villagers to construction, implementation, monitoring, and management of these planned interventions. Provided the budget is sufficient to implement the plan, all these options can be aggregated into a Village Plan, to be discussed and finalized with the villagers and their representatives, for implementation. Implementing, managing, and monitoring the plan will require continuous hand-holding by project staff to ensure that these activities proceed as per the agreed Village Plan.

5.9 Postscript

To answer the question posed by the Joint Secretary in the Ministry of Rural Development GOI: No, there is no “ideal” size of a watershed, but yes, it is

possible to use a hydrological model at a suitably large scale (e.g., 400 km², so as to get data to run the model), get a good fit to the observed data, and then “zoom in” to any set of contiguous villages within the basin to guide the planning of watershed management interventions therein—but within an iterative and participatory planning process. Applied hydrology can indeed improve watershed management!

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