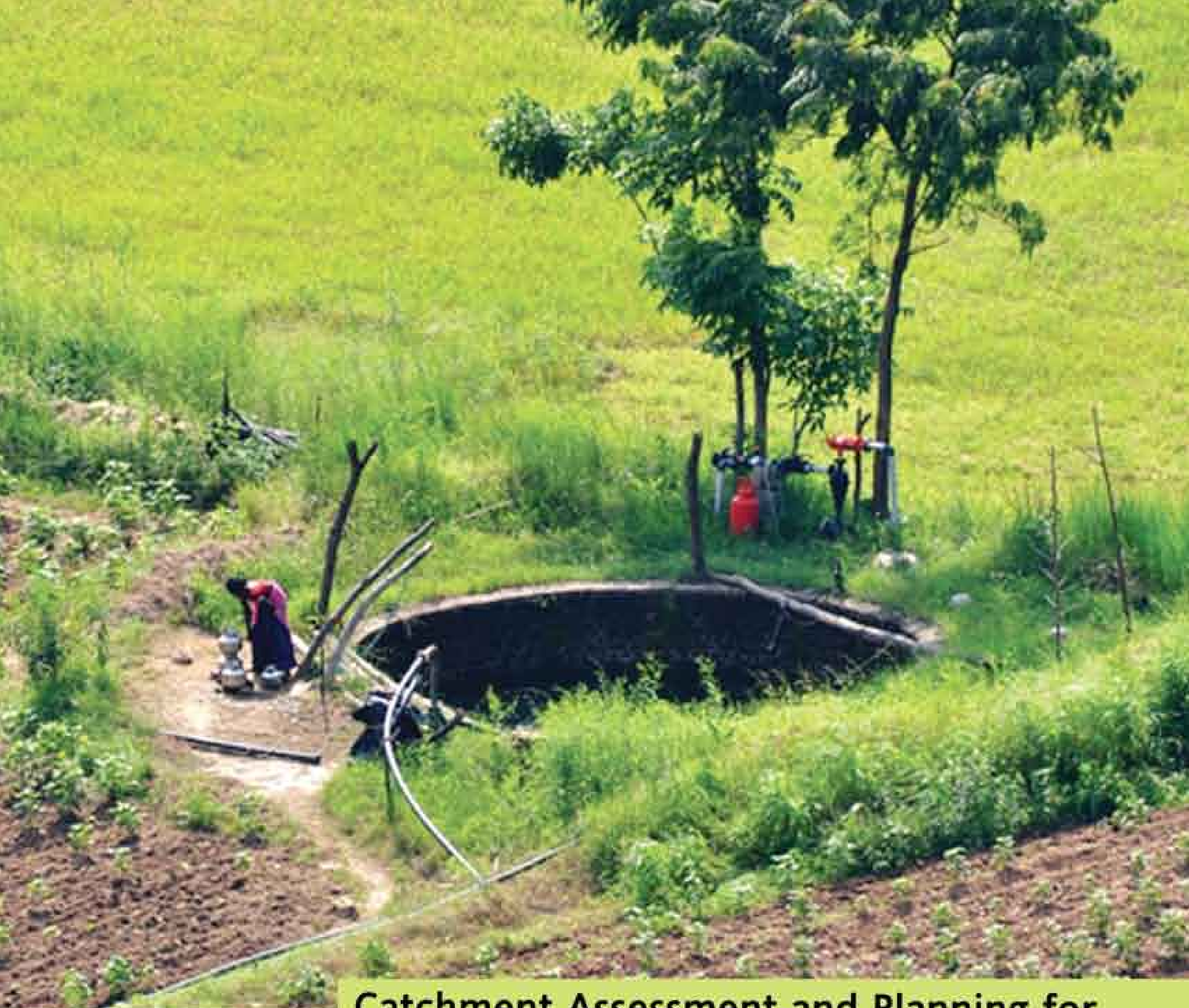

Catchment Assessment and Planning for

WATERSHED MANAGEMENT

VOLUME I – MAIN REPORT

JUNE 2015

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PROFOR

WORLD BANK GROUP
Agriculture Global Practice

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This Report, in two volumes (Main Report and Annexes), presents the findings of a Catchment Assessment and Management Planning Study, which is a major step by the World Bank toward improving the understanding of hydrology issues in watershed management in India, based on a detailed assessment of the Government of India's Integrated Watershed Management Program. The Report's findings will contribute to the design of new World Bank supported watershed programs in India as well as the IWMP and the newly-announced PMKSY. Further, the lessons learned in this report can guide hydrological assessments in watershed program development in other regions.

This work was funded by the Program on Forests (PROFOR), a multi-donor 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.

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ABBREVIATIONS AND ACRONYMS

ADB	Asian Development Bank
BISAG	Bhaskarcharya Institute for Space Applications and Geoinformatics
BRGF	Backward Regions Grant Fund
CDO	Central Design Organization
CEO	Chief Executive Officer
CFSR	Climate Forecast System
CGWB	Central Ground Water Board
CMA	Catchment Management Agency
CMP	Catchment Management Plan
CSWCRTI	Central Soil and Water Conservation Research and Training Institute
CWC	Central Water Commission
DDP	Desert Development Programme
DEM	Digital Elevation Model
DoLR	Department of Land Resources
DPAP	Drought-Prone Areas Programme
DPR	Detailed Project Report
DST	Decision Support Tool
DWDU	District Watershed Development Unit
EPA	Environment Protection Agency of the United States Government
ET	Evapo-Transpiration
FAO	Food and Agriculture Organization
FD	Forest Department
GGRC	Gujarat Green Revolution Company
GIS	Geographical Information System
GOI	Government of India
GP	Gram Panchayat
GPS	Geographical Positioning System
HRU	Hydrological Response Units
IAMWARM	Irrigated Agricultural Modernization and Waterbodies Restoration and Management
ICM	Integrated Catchment Management
IMD	Indian Meteorological Department
IRAP	Institute for Resource Analysis and Policy

ISRO	Indian Space Research Organization
IT	Information Technology
IWMP	Integrated Watershed Management Programme
LULC	Land Use Land Cover
MCM	Million Cubic Meters
MDB	Murray-Darling Basin
MNREGS	Mahatma Gandhi National Rural Employment Generation Scheme
MoA	Ministry of Agriculture
MODFLOW	Modular (Finite Difference) Flow Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MoEF	Ministry of Environment and Forests
MoRD	Ministry of Rural Development
MWSWAT	Map/Window interface for SWAT
NBSSLUP	National Bureau of Soil Survey and Land Use Planning
NRAA	National Rain-fed Areas Authority
NRSC	National Remote Sensing Centre
NSE	Nash-Sutcliffe Efficiency (Statistic)
NWDP	National Watershed Development Programme
PET	Potential Evapo-Transpiration
PIA	Project Implementing Agency
QGIS	Quantum Geographical Information System
RKVY	Rashtriya Krishi Vikas Yojana
RWH	Rain Water Harvesting
SC	Scheduled Caste
SHG	Self Help Group
SLNA	State Level Nodal Agency
SoI	Survey of India
SRI	System of Rice Intensification
ST	Scheduled Tribe
SWAT	Soil and Water Assessment Tool
SWDC	State Water Data Centre
UG	User Group
WARIS	Water Resources Information System (Ministry of Water Resources, GoI)
WC	Watershed Committee
WCDC	Watershed Cell cum Data Centre
WDM	Water Demand Management
WEAP	Water Evaluation and Planning System
WHS	Rainwater Harvesting Structures

EXECUTIVE SUMMARY

This study examines the utility of hydrological modelling as a tool to investigate the potential multi-scalar impacts of watershed development and to support planning at different institutional levels. It also looks at the potential for models, in particular the Soil and Water Assessment Tool (SWAT) model, to be integrated into the existing planning methodology used by the Government of India's national watershed scheme - the Integrated Watershed Management Program (IWMP).

While watershed development can and often does deliver significant beneficial impacts, it can also result in negative externalities that, in particular, can affect downstream water users. The construction of rainwater harvesting structures, which 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 both expand the irrigated area and 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, unfavourable groundwater characteristics, and many other factors may reduce the effectiveness of investments. As well, watershed development increases local water loss, both as a result of evapotranspiration from higher intensity of irrigation and evaporation directly from the water storage structures themselves. One consequence may be reductions in downstream water flows. Any resulting reduction in downstream flows may not be a problem in areas of high rainfall. 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. 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 multi-criteria analysis that combines 13 different parameters and uses Geographic Information Systems (GIS) to identify those watershed most in need of treatment. Although the guidelines implicitly recognise the importance of hydrology, the criteria for the selection of watersheds is heavily weighted towards 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 input 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, in part 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 modelling. 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 modelling software, and remotely-sensed digital data that can be downloaded from the web and used at various scales.

SWAT has become one of the most widely used hydrological models in India and internationally in a whole range of different hydrological studies and applications. Due to this trend and a number of other technical reasons, such as its open-source and semi-distributed nature, the SWAT model was chosen for use in this study. It was applied to the Sukhi catchment in Gujarat to examine the impacts of the watershed development work being carried out by IWMP in a number of watersheds within the catchment. The Sukhi catchment has an area of 393 km^2 and drains into the Sukhi reservoir, which in turn provides irrigation for a large downstream command area.

SWAT divides a catchment into sub-watersheds for which model outputs are generated. For the Sukhi catchment, sub-watersheds were delineated so that they were of similar size and followed similar boundaries to the micro-watersheds delineated and used by IWMP. Major land use changes during the modelling period, primarily a shift from single crop to double crop agriculture, were analysed using GIS and incorporated in the model.

Availability of data for the calibration and validation of the model defined the scale at which it was set-up. The model was calibrated and validated using monthly inflow data to the downstream Sukhi reservoir. This opportunistic use of reservoir inflow data and the success of calibration and validation efforts, gave greater confidence in model outputs and in the use of the model to develop scenarios for assessing the impacts of watershed development. The pilot work in Gujarat proved that hydrological models can be calibrated and validated using a range of different datasets and therefore have the potential to be more widely applied by watershed programs such as IWMP.

To support the SWAT model application, a survey was carried out for five villages in the Sukhi catchment that had been selected by IWMP to undergo watershed development. All the rain water harvesting structures built in the villages, by IWMP and other national schemes, were inventoried and mapped using a hand-held Global Positioning System (GPS) device; a range of information was subsequently recorded for each feature. This data allowed the intensity of watershed development in the villages to be determined. Borewells and dug wells were also surveyed using GPS to investigate how water use has changed in the villages in part as a response to watershed development. The survey showed that there were many rain water harvesting structures in the villages prior to the start of IWMP work, with a steady increase in the number of structures during the modelling period, from 1999 to 2012. During the same period the number of wells increased rapidly and GIS analysis of land use datasets for the period revealed a parallel increase in the area of double cropped irrigated agriculture. The survey provides evidence to support the contention that watershed development leads to an expansion of irrigated agriculture and more intensive water use. The survey also highlights the importance of studying the impact of land use change when investigating the impacts of watershed development.

A number of model scenarios were developed to assess the impacts of watershed development and land use change with results showing that both have generated significant hydrological impacts. Intensification of watershed development and an increase in the double-cropped area increased evapotranspiration within the catchment and reduced downstream flows. Impacts were greatest in years with low rainfall; for example in 2009, the driest year of the modelling period, intensified watershed development and an expansion of the doubled cropped area reduce reservoir inflow by 16.9% compared to the baseline, or from 35 mcm to 29.1 mcm. These kinds of off-site impacts from watershed development are therefore greatest in periods when water is most needed downstream. Additional model scenarios were developed for the 5 survey village based on specific watershed development plans drafted in consultation with local farmers. These scenarios also showed reductions in downstream flows although the magnitude was slightly less than for the catchment as a whole.

The scenario building and analysis used in this study demonstrated the value and potential of the SWAT model as a tool that national watershed programs in India (and elsewhere) could use to improve overall planning and monitoring procedures. However, converting the modelling process used in this study into a stepwise methodology that a watershed program could apply widely in a variety of different conditions is a challenge. Parts of the modelling process in this study, such as calibration and validation, took time and would require local modelling expertise or capacity. This capacity certainly exists in India at various national and state institutions, but would need to be focused on supporting the ongoing watershed program where needed. Where good field data are available in some states, the assessment process piloted in Gujarat could be replicated fairly well. Other catchments with contrasting characteristics, and varying data availability and quality, may present problems that require different solutions. In these states, lower quality data from open-access web sites would need to be used, with less accuracy resulting from the modelling. As a result, in some states, a process may be needed that is very different to the one followed in this study in Gujarat. That said, there is a rapidly emerging trend towards open-access of increasingly higher quality data from remote sensing platforms, and coupling these with evolving models. India can become a leader in this field with its own satellite platforms, scientific expertise, and gradual improvements in local hydrological data.

CHAPTER-1
INTRODUCTION

THE ISSUE

'A watershed is an area that drains to a common point and watershed development is a strategy to optimize the use of soil, water and vegetation in the watershed subject to local agro-climatic and topographic conditions, all for the purpose of strengthening the natural resource base, supporting more productive agriculture and improving livelihoods.'[1]

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 to 5000 hectares, are designated a 'watershed' and are intensively treated to control and capture the water in that area.[2] The Guidelines advocate a 'multi-tier ridge-to-valley sequenced approach' where the uppermost part of the catchment (usually 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:

1 Kerr J., *et al.*, 2006, pp. 1-2.

2 This used to be 500 hectares 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 hectares comprising clusters of micro-watersheds' (MoRD, 2008, p. 7), which was applied to all watershed projects taken up from 1 April 2008.

- **Reduced water flows to the lower parts of the catchment** and more importantly, the larger rivers that flow in the valleys, as a result of greater capture of water and increased evapo-transpiration from resultant expansion in both, the area cropped and the area irrigated in the upper parts of the catchment (where there are often farmers cultivating terraced fields).
- **Over-abstraction 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 un-irrigated areas.
- **Less water in streams and aquifers**, as a result of increased cultivation, groundwater extraction and increased evapo-transpiration (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.[3]

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

The starting point of the Catchment Assessment and Management Planning (CAMP) study was therefore to derive an approach and methodology for catchment assessment that could underpin the planning of watershed management programs, in India and elsewhere.[4]

STUDY OBJECTIVES AND EXPECTED OUTPUTS

The CAMP study, funded by the PROFOR Trust Fund of the World Bank, had three objectives:

- To derive a methodology for incorporating hydrological assessment into catchment management planning in the Indian context.
- To demonstrate this methodology in one sub-catchment (of around 100 square km).
- To create practical tools to apply (relevant parts of this methodology) in the Integrated Watershed Management Programme (IWMP) of the Department of Land Resources (DoLR) of the Ministry of Rural Development (MoRD), Government of India (GoI).

The main outputs expected at the end of the study were the following:

- **A Catchment Assessment and Management Planning Methodology**: Although it will have to be adjusted to other geo-hydrological conditions, this study would (1) detail the hydrological foundation of watershed management by laying out clearly all aspects including the selection criteria, the maximum possible area coverage, types of treatments and (2) how it can be applied, practically, on the ground in planning the management of watersheds.

- **The demonstration of the methodology**: The hydrological assessment would have three key components: (1) setting up of the hydrological models, (2) creating scenarios using the model to simulate the impact of different watershed intervention options in a specific sub-catchment and (3) stakeholder involvement in the discussion and selection of options:
    - *Hydrological modeling:* This included various steps – including model selection, data collection and checking, verification of assumptions and algorithms, calibration and validation, and checking the results with community perceptions – to ensure that the model is a good fit to the local conditions. It also blended in data from various datasets, starting with freely available but coarse global datasets and replacing these with better-quality national, state and local datasets as they became available.
    - *Scenarios of simulated impacts:* The running of the model with different scenarios of catchment management interventions and comparing with a base case to illustrate the differential impacts of different watershed interventions on catchment hydrology, was to provide a useful and first-hand understanding of upstream-downstream linkages, water inflows and outflows from the watershed, to inform the selection of treatment options.
    - *Stakeholder consultations:* These were to be undertaken not only to check the hydrological model outputs against local knowledge and perceptions of catchment behavior, but also to discuss the selection of treatment options and understand how best to incorporate their priorities in such decision-making.

- **Tools and procedures:** Based on the outcomes of the demonstration of the methodology, tools and procedures were to be devised to help the various staff and the local communities responsible for planning and implementing the IWMP to use the insights from the methodology. These tools were to try and streamline the steps and processes in the methodology so that these can be understood and applied more easily.

The new approach and methodology was to be piloted in selected sites under the proposed Neeranchal Project of the DoLR, co-financed by the World Bank, and after

4 The Terms of Reference of the study are in Annex 1. See Box 2.1 for the distinction between watershed *development* and watershed *management*. Also note that the terms 'watershed' and 'catchment' are used interchangeably in this report, unless otherwise specified.

learning lessons from the pilot, fine tune and modify these so that, ultimately, a tried and tested, and flexible methodology would be available for DoLR to use it in IWMP across the country.

STUDY COMPONENTS AND TEAM

The short-term study (May 2014 – April 2015) had the following components:

- **A Background Paper:** Summarizing international and national literature on catchment assessment and management planning.
- **Literature Compilation:** A Drop Box that collected a vast body of international literature on CAMP experiences, including Watershed Management Guidelines from the US Environment Protection (EPA), the Asian Development Bank (ADB) and the Food and Agriculture Organization (FAO) besides academic papers.
- **Demonstration:** The demonstration of modeling of an actual (sub) catchment and village-level planning to demonstrate a methodology for catchment assessment and management planning.
- **Process Guidelines:** Comprising clear bulleted action points for IWMP, to be piloted further in the Neeranchal Project areas and elsewhere in the future.
- **A Training Module:** To train field practitioners and supervisors on using the new approach and methodology in the field.

The study team under the overall supervision of Dr. Grant Milne, Senior Natural Resources Management Specialist of the World Bank, comprised national and international experts:

- Dr. A. J. James *Study Team Leader,* IDS Jaipur, India.
- Dr. M. Dinesh Kumar *Hydrology Expert*, IRAP, Hyderabad, India.
- Dr. Charles Batchelor *Hydrology Expert*, WRM Ltd., UK.
- Mr. James Batchelor Hydrology Modeling Specialist, UK.
- Mr. Nitin Bassi Field *Work Coordinator*, IRAP, Delhi office, India.
- Mr. Jitender Choudhary *Field worker*, Palampur, Gujarat, India; who worked with a set of local community workers in the field.
- Mr. David Gandhi, *Village Planning* Expert, Pune, India.
- Dr. Geoff Syme, *Institutions Expert*, Edith Cowan University, Australia.

The team worked in coordination with Dr. Vaisakh Palsodkar, Hydrologist, DoLR, MoRD, GoI and reported to Dr. Sandeep Dave, Joint Secretary, DoLR and proposed Mission Director of the Neeranchal Project. Ms. Priti Kumar of the World Bank, New Delhi office, joined the team in late 2014 as the Deputy Team Leader of the study.

Comments and suggestions on the approach and methodology, as it evolved, were provided periodically by a team of experts including Dr. William Young (Senior Water Resources Specialist, World Bank) Dr. Anju Gaur (Senior Water Resources Specialist, World Bank), Mr. Ranjan Samantaray (Watershed Management Specialist, World Bank), Professor Ashwin Gosain (Indian Institute of Technology, New Delhi), Dr. V. C. Goyal (National Institute of Hydrology, Roorkee), Dr. Chetan Pandit (retired Chief Engineer, Central Water Commission, Ministry of Water Resources, GoI), Dr. Sandeep Goyal (Senior Scientist, Madhya Pradesh Centre of Science and Technology, Bhopal), Dr. P.G. Diwakar and Dr. Durga Rao (National Remote Sensing Centre, Hyderabad).

STUDY MILESTONES

While a detailed time line of the study progress is in Annex 2, the main study milestones are described below.

The first step planned in the study was a Background Paper on catchment assessment and planning, summarizing international and Indian experiences (see Annex 2 for a detailed timeline of the study and Annex 3 for the Background Paper). The first draft was ready by June 2013, reviewed internally by the team and finalized by September 2013. The Background Paper was to be the base document for the Brainstorming Meeting that was to be the kick-off meeting for the study and was finally held in May 2014 (see Annex 4 for details of this meeting). The initial Study Plan was to have two follow up workshops, an interim workshop in September 2014 and a final workshop in December 2014 to conclude the study.

In August 2014, detailed discussions were held with DoLR staff, culminating in a discussion in mid-August with the Joint Secretary, DoLR, and his team at which the Concept Note for the Study was re-assessed. The Study Team was requested not to involve SLNA staff in state-level pilots (which would have involved some degree of trial and error) and to, instead, focus on one catchment to pilot the methodology and present the findings for review by DoLR before discussing it further with SLNAs. The study team, accordingly, amended the work plan to develop and pilot the methodology in a single catchment, starting work in September 2014.

It was also decided that the second workshop planned in September 2014 would be organized by the World Bank study team as an internal workshop for discussing study progress, focused on the hydrological modeling work. The second workshop was accordingly designated a technical meeting, aimed at understanding the draft methodology proposed and planning the demonstration It was held on 11-12 September 2014 and was to be followed immediately by the start of demonstration, from 15 September (see Annex 5 for details). DoLR was also clear that the study outputs should focus on improvements possible from within the IWMP and not involve other programs or Ministries. The modeling approach was discussed with technical experts at a Technical Meeting on 15 November 2014 (see Annex 6 for details) and the results of both the modeling and the stakeholder interactions were presented at the final workshop on 1-2 December 2014 (see Annex 7 for details). On 15 December 2014, DoLR requested for the village-planning process to be piloted and hence the study was extended and additional resources found to complete this task by April 2015.

STRUCTURE OF THE REPORT

Section 2 begins by discussing the extent to which hydrological aspects are addressed in the Guidelines of the IWMP and the implications of the same on upstream-downstream hydrological and socio-economic interactions in watershed development, and goes on to summarize international practice in catchment assessment and management planning (based on the Background Paper developed and the other literature compiled for the study).

Section 3 details the demonstration of the approach and methodology in a specific sub-catchment, comprising the modeling (conceptual model and simulation model), a village-level planning process and the assessment of potential downstream impacts. It also discusses possible ways to address potential upstream-downstream conflicts over water access and use.

Section 4 draws lessons from the demonstrated approach and methodology for watershed management program managers, for two cases; the first being a stand-alone watershed management project and the second being a watershed management program, like the IWMP, being implemented simultaneously in different areas, as a national or sub-national program.

CHAPTER-2

HYDROLOGY IN WATERSHED MANAGEMENT

HYDROLOGY AND THE INTEGRATED WATERSHED MANAGEMENT PROGRAMME

The Evolution of the IMWP

Watershed development is an approach that can, if well planned and managed, raise agricultural productivity, conserve natural resources and improve rural livelihoods in the regions suffering from land degradation, which are often characterized by high levels of food insecurity and income poverty (Hope, 2007; Farrington *et al.*, 1999). Watershed development has emerged as an important policy instrument for rural development in many developing countries, including India and, since the 1970s, India has invested significantly in watershed development as a driver of rural development (Hope, 2007; Joshi *et al.*, 2005). But, the focus of watershed development in India has evolved over the last 25 years from soil conservation to water conservation to now include a more participatory planning approach (Hope, 2007). Watershed projects in India have an allocation of nearly Rs. 2200 crores (US$340 million) per year at present (Reddy, 2012) and are a central plank in the poverty alleviation strategy of the Ministry of Rural Development (MoRD). In fact, the Integrated Watershed Management Programme (IWMP) is the latest in a long line of projects designed to improve the natural resource base and address issues of poverty, especially in rain-fed farming areas of the country (see Box 2.1).

From 1962 to present, a succession of national watershed schemes have gradually evolved to focus increasingly to rain-fed areas where the degradation of the natural resource base contributed to and reinforced rural poverty. These schemes included the River Valley Projects, Drought Prone Areas Program, the Desert Development Program, the Integrated Wastelands Management Program, the National Watershed Development Program in Rural Areas, and the current IWMP. There was thus a clear emphasis on improving the conditions of a large majority of the people living in rain-fed areas who are dependent on land and water for their livelihoods, and the thrust is on implementing activities which can be done by the local communities with minimum outside support on technical matters (Farrington *et al.*, 1999; Kerr, 2002; Hope, 2007). The thrust is also on taking up physical activities which will have immediate as well as medium and long-term impacts. In that respect, local employment generation is also given sufficient emphasis. These are the strengths of the watershed development approach as practiced in the Indian context.

By the 1990s, watershed development programs were being designed and implemented by three central government Ministries, the Ministry of Environment and Forests (MoEF), Ministry of Agriculture (MoA) and the Ministry of Rural Development (MoRD), with different norms and implementing guidelines. Following a review of the watershed development programs of the MoRD, a set of Common Guidelines were issued in 1994 that consolidated several other programs of the MoRD into the three key programs – the Drought Prone Areas

BOX 2.1 Watershed Development and Watershed Management

Although the two terms appear to have been used inter-changeably in the naming of programs, there are distinct differences between the two concepts.

Watershed development generally refers to land-based treatment works, using the 'ridge to valley' approach, for rehabilitation of degraded lands (farm land, forests and pastures), which contribute either directly to rain-fed production or indirectly increase domestic and productive uses of water through augmented surface water storage or groundwater recharge.

Watershed management is the process of creating and implementing plans, programs, and projects to sustain and enhance functions of a watershed that affect the plant, animal, and human communities within a watershed boundary. Watershed functions generally include: preservation of the top soils in the catchment, including that of agricultural land, for sustaining the primary productivity of land; conservation of moisture in the soil profile for supporting biomass production and combating drought; regulation of the runoff generated in the catchment to moderate the floods; preservation of wetland ecosystems within and outside the boundaries of the watersheds, to which the watershed contributes in the form of stream-flows and micro nutrients; and natural recharge to the groundwater system, with its upper limits decided by the geo-hydrological conditions of the watershed. Preserving the environmental sustainability and ecological resilience of a watershed are as important as providing for human needs and indeed may indirectly provide for them.

A malfunctioning or a degraded watershed is characterized by excessive soil erosion from the slopes, fast siltation and poor carrying capacity of the stream channels, high intensity runoffs with peak flows even from not so high intensity rainfall, and pollution of the runoff water. Socio-economically, a clear manifestation of a degraded watershed is poorer biomass production capacity (ton/ha of land) than what the agro-ecology permits in the natural condition. In a typical agricultural watershed, common contributors to water pollution are nutrients and sediment load, which typically enter stream systems after the surface runoff generated from rainfall washes them off poorly managed agricultural fields, or washes them out of the soil through leaching.

Programme, the Desert Development Programme and the Integrated Wastelands Management Programme – together called the National Watershed Development Programme (NWDP), which were to be implemented on a mutually exclusive basis but using a common 'watershed' approach.

In 1999, acting on the recommendations of the Mohan Dharia Committee (set up in 1993), a Department of Land Resources (DoLR) was created within the MoRD, to oversee watershed development on all types of land, wasteland, degraded land, drought-prone and good-quality land that may be susceptible to degradation. However, watershed-based development of forest land continued to be the responsibility of the MoEF while soil conservation programs on ravines and other problem lands as well as erosion-prone agricultural land continued to be the responsibility of the MoA.

The 1994 Common Guidelines issued by MoRD were revised in 2001, 2003 (the 'Hariyali' Guidelines), 2008 and 2011. These revisions were largely about objectives (broadened to encompass rural development, water management, natural resource conservation, poverty alleviation and livelihood promotion), program implementation (e.g., including or excluding NGOs and Gram Panchayats as Project Implementing Agencies in addition to government line departments; financial norms for project interventions) and convergence (with the drinking water programs, the Mahatma Gandhi National Rural Employment Generation Scheme {MNREGS}, the National Horticultural Mission, etc.). They also identified the relevant institutional structures for implementation (e.g., from the District Rural Development Agency to dedicated state-level bodies such as the State Level Nodal Agencies).

In 2009-10, the DoLR created the Integrated Watershed Management Programme (IWMP) consolidating the Drought-Prone Areas Programme, the Desert Development Programme and the Integrated Wastelands Development Programme, which was to be implemented using the 2008 version of the Common Guidelines, which were revised in 2011 (Table 2.1).

Using hydrological[5] assessments as a basis for catchment management does not feature in this list although there is some mention of defining watershed

5 Note that that the term 'hydrological' is being used throughout this report in the sense that encompasses both hydrological and hydro-geological.

TABLE 2.1 SALIENT FEATURES OF THE REVISED COMMON GUIDELINES OF 2011 OF DoLR

Delegation of power	State governments empowered to sanction and oversee the implementation of watershed projects within their states, following these Common Guidelines
Institutional support	Dedicated institutions with multi-disciplinary experts at different levels: ❖ National-level – National Rain-fed Areas Authority (NRAA) ❖ State-level – State Level Nodal Agency (SLNA) ❖ District-level – Watershed Cell cum Data Centre (WCDC) ❖ Project-level – Project Implementing Agency (PIA) ❖ Village-level – Watershed Committee (WC)
Duration and phasing	From 4 to 7 years, depending on the nature of activities, and spread across three phases: preparatory phase, works phase and consolidation phase
Livelihoods orientation	Priority to productivity enhancement and livelihood promotion, along with resource conservation measures Systematic integration of livestock and fisheries management and encouragement of dairying and marketing of dairy products
Multi-tier approach	Multi-tier 'ridge to valley' sequenced approach to be adopted, where first, the upper catchments that tend to be hilly and forested are to be taken up, wherever possible, and with support from the MoEF or the State Forest Department (the onus of implementation lying mostly with the FD and its Joint Forest Management Committees); followed by the intermediate tier or slopes; and finally by the third tier of flat lands and plains
Cluster approach	Broader vision of geo-hydrological units normally of average size of 1000 to 5000 hectares comprising clusters of watersheds (although smaller size projects may be sanctioned in hilly and difficult terrain areas) If resources permit and the areas exist, additional watersheds in contiguous areas may be taken up, in clusters
Scientific planning	The use of information technology and remote-sensing inputs for planning, monitoring and evaluation of the program; GIS facilities for planning and for monitoring and evaluation
Cost norms	Rs. 12,000 per hectare (plains); Rs. 15,000 (hilly and difficult areas)
Capacity-building	Training and capacity-building of all functionaries and stakeholders involved in implementation 'on a war footing'

Sources: DoLR (2015) and DoLR (2011).

boundaries and creating contour maps for assessing runoff and planning rainwater harvesting structures elsewhere in the Guidelines, which are detailed below.

Hydrology Considerations in IMWP Guidelines

A major emphasis of the 'Technology' section of the Guidelines is on the use of remotely-sensed data and GIS. As the abstract from this section (reproduced below from DoLR, 2011, pp. 11-12) shows, there is a clear vision of using the latest technology available, but there is not much clarity on how watershed boundaries themselves are to be defined as there is no reference to hydrological assessments:

> Technology enables us, inter-alia, ***to strengthen program management and coordination, undertake activity-based project planning, formulate action plans,*** streamline sanctions and release of funds, create useful data bases, assess actual impacts of projects, ***make effective prioritizations,*** prepare sophisticated Detailed Project Reports (DPRs), document best practices and case studies and facilitate the free and seamless flow of information and data.
>
> Thus, the endeavor would be to incorporate strong technology inputs into the new vision of watershed programs. At the state and national levels, core GIS facilities, with spatial and non-spatial data, would be established and augmented with satellite imagery data received from National Remote Sensing Centre (NRSC), Indian Space Research Organization (ISRO) and Survey of India (SoI). ***All the GIS layers for various themes would be overlaid having a geo-referenced base layer up to the level of village***

boundaries, in the first instance. This core GIS data may be given controlled access/distribution over networks for local project planning. Application software for web-enabled integrated watershed development, spatial and non-spatial data standards and meta-data would also be worked out. ***Once such a knowledge base is in place, it would be possible to define watershed project boundaries with assignment of unique-identification (unique-id) to each project.*** It would also be possible to map treatment areas with respect to their respective administrative formations in terms of villages, blocks and districts.

Remote sensing data would be utilized for finalizing contour maps for assessment of runoff and for identifying structures best suited for location of projects. This would result in cost and time optimization in project implementation. Technology would also contribute immensely in assessing the actual impact of various programs in a given area. Due to the availability of latest remote sensing techniques, it is now possible to assess periodic changes in geo-hydrological potential, soil and crop cover, runoff etc in the project area.'

While the intentions to define watershed boundaries, assess runoff and identify locations for building (rainwater harvesting) structures are there in the Guidelines, there is not much guidance on how this is to be done.

Responsibility for the selection of watersheds as well as planning and implementation of interventions in these watersheds have been devolved to the state governments, albeit guided by the Common Guidelines and supported by the two key central government agencies, viz., the NRAA and the DoLR. Hydrology-based considerations figure in three parts of the project management cycle of IWMP projects implemented by state governments. These are discussed below in the context of the SLNA of the state of Gujarat (called the Gujarat State Watershed Management Agency or GSWMA):

- **Selection of watersheds:** Gujarat adopted the 13 criteria laid down by the DoLR Guidelines (DoLR, 2011) to select and prioritize its watershed development projects (Table 2.2).[6] Of these, only three are related to hydrology, viz., groundwater status (criterion 5), moisture index (criterion 6) and drinking water availability (criterion 8).

TABLE 2.2 CRITERIA FOR SELECTION AND PRIORITIZATION OF WATERSHED PROJECTS

Sl. No.	Criteria	Max Score	Ranges and Scores			
1	Poverty index (% of poor to population)	10	Above 80% (10)	80-50% (7.5)	50-20% (5)	Below 20% (2.5)
2	% of SC/ST population[7]	10	More than 40% (10)	20-40% (5)	Less than 20% (3)	-
3	Actual wages	5	Significantly lower than minimum wage (5)			
4	% of small and marginal farmers[8]	10	More than 80% (10)	50-80% (5)	Less than 50% (3)	
5	Groundwater status[9]	5	Over exploited (5)	Critical (3)	Sub-critical (2)	
6	Moisture index/DPAP/ DDP Block	15	-66.7 and below; DDP Block (15)	-33.3 to 66.6, DPAP Block (10)		
7	Area under rain-fed agriculture	15	More than 90% (15)	80-90% (10)	70-80% (5)	Below 70% (reject)

6 From GSWMA (2011), Annexure 1, pp. 47-48.

7. Scheduled Castes (SC) and Scheduled Tribes (ST).

8. Marginal farmers own or operate less than 1 hectare, small farmers, 1-2 hectares.

9. Development blocks (administrative units within a district) in India are defined in terms of four categories of groundwater problems: safe, semi-critical, critical and over-exploited.

Sl. No.	Criteria	Max Score	Ranges and Scores			
8	Drinking water	10	No source (10)	Problematic village (5)	Partially covered (5)	
9	Degraded land	15	Above 20% (15)	10-20% (10)	Less than 10% (5)	
10	Productivity potential of land	15	Lands with low production and productivity where productivity can be significantly enhanced with reasonable efforts (15)	Lands with moderate production and where productivity can be enhanced with reasonable efforts (10)	Lands with high production and where productivity can be marginally increased with reasonable efforts (5)	
11	Contiguity to another watershed that has been developed/treated	10	Contiguous to previously treated watershed and contiguity within the micro-watersheds of the project (10)	Contiguity within the project but non-contiguous to previously treated watershed (5)		
12	Cluster approach in the plains (more than one contiguous micro-watersheds in the project)	15	Above 6 micro-watersheds in the cluster (15)	4-6 micro-watersheds in the cluster (10)	2-4 micro-watersheds in the cluster (5)	
13	Cluster approach in the hills (more than one contiguous micro-watershed in the project)	15	Above 5 micro-watersheds in the cluster (15)	3-5 micro-watersheds in the cluster (10)	2-3 micro-watersheds in the cluster (5)	
Total		**150**	**150**	**90**	**41**	**2.5**

Information on a range of datasets (including geo-morphology, soil, slope, erosion, drainage, contours, geo-hydrology, concentration of poor and SC/ST populations), including some based on satellite imagery, was collected by the state remote sensing agency (the Bhaskaracharya Institute for Space Applications and Geo-informatics) and 'superimposed to get a composite picture of the priority areas' (GSWMA, 2011a, p. 17). These 'GIS based prioritized maps' prepared by BISAG for GSWMA were then used not only to create an 18-year State Perspective and Strategic Plan to guide phased watershed development in the state, but also given to District Watershed Development Units (DWDUs) for district planning.[10] It is then responsibility of the DWDUs to 'verify the prioritized maps on field and choose watersheds/ villages as projects on a cluster approach', where one cluster 'may include a number of watersheds/ villages totaling around 5000 hectares of land' and is called a 'project' (GSWMA, 2011a, p. 18).

- **Implementing a 'ridge to valley' approach:** The prioritization of watersheds to be taken up for the IWMP also uses a 'ridge to valley' approach in the sense that only upper areas were taken up for Batch 1 watersheds (starting in 2009-10), with areas of lower elevation being taken up in subsequent batches. Even while planning interventions in these upper catchment areas, potential downstream impacts, positive or negative, are not taken into consideration. The implicit assumption is therefore that the impact of such interventions is always positive, both locally (e.g., in terms of increased groundwater recharge, increased irrigated production and productivity and drinking water security) and for downstream communities (e.g., in terms of reduced sediment transfer and flood control).

10 While the Watershed Cell cum Data Centre (WCDC) is the generic agency defined in the Common Guidelines of the DoLR (see Table 2.1), the DWDU is the agency designated by the SLNA in Gujarat to coordinate IWMP activities at the district level.

- **Planning watershed management interventions:** The GSWMA also produced a Technical Manual for the IWMP (GSWMA, 2011b), which details the type of structures suitable for projects to be implemented in the three tiers of a watershed, along with drawings, photographs and guidance notes for field implementers. It begins with a fairly detailed discussion of hydrological issues, including measurement of rainfall, evaporation, evapo-transpiration, soil types, classification and erosion, drainage density, hydrographs, surface and subsurface runoff and methods of calculating runoff.

  Following the baseline survey, entry point activities, community mobilization and participatory planning processes, a watershed micro-plan is prepared and the coordinates of the proposed structures measured using a hand-held GPS unit (each DWDU has one) and depicted on a GIS map of the watershed. However, no survey is done of existing Rainwater Harvesting Structures (WHSs) and infrastructure used to access ground and surface water, such as open wells, check dams and community and farm ponds (built by other Departments such as Minor Irrigation, or under programs such as the MNREGS) or of bore wells and pumps – all of which influence the quantity of capturable runoff that new WHSs are being designed to harvest. Also, the baseline surveys and community stakeholder interactions do not discuss the pattern of rainfall and local understanding of water flows and priorities.

From these illustrations of the extent to which hydrological considerations are taken into account in the Common Guidelines at the national level and the Operational and Technical Manuals used to plan and prioritize watersheds and interventions by the state agencies, it is clear that the planning for IMWP projects is currently not based on a thorough hydrological assessment of the catchment. For instance, it is not one that normally takes into account the amount of surface and ground water that is available, the capturable runoff in normal, wet and dry years and, hence, the nature of interventions needed to allocate water across different parts of the catchment and also the water (demand and supply) management strategies needed to promote equitable and sustainable water use for the different stakeholders living and operating in different tiers of the catchment.

Implicit Hydrology-Related Assumptions of the IWMP

The lack of overt attention to hydrological issues in the design and (re-)formulations of the watershed development and management programs in India is partly due to certain implicit assumptions made in the approach to these programs:

- *There is a large amount of un-utilized water flowing out of the agricultural watersheds* (Kumar *et al.*, 2006 and 2008) during the wet season. The un-utilized water may be made available in dry periods, offering several potential benefits– increasing soil moisture for rain-fed agriculture, augmenting groundwater recharge and capturing runoff for storage for multiple productive uses or direct consumption[11] (Farrington *et al.*, 1999). In many catchments, there may be little or no un-utilized water during the monsoon season.
- *Comprehensive treatment will improve water availability, the soil moisture regime will reduce soil erosion, and even increase effective water availability for downstream communities during the lean season* – following from the earlier assumption that a large amount of runoff during the monsoon goes un-captured and eventually gets wasted as it joins the natural sink of sea, ocean or swamps.
- *In situ soil moisture conservation measures such as construction of bunds and terraces in the farm land, and contour bunds and trenches on common land* (forests, revenue wasteland and pastures) *do not take much water from the hydrological system,* and therefore, economic losses due to their adverse impacts are not taken cognizance of in the planning decisions (Batchelor *et al.,* 2003). The increased soil moisture storage is expected to increase the intensity of crop cultivation by farmers during the monsoon season and help protect new plantation in the common land – without considering the

11 In typical rural settings, the productive uses include water for irrigation, and consumptive uses include water for all domestic uses (drinking, washing, cleaning and personal hygiene and livestock drinking).

possibility that there may be downstream water systems like tanks and ponds which depend on this runoff for uses such as domestic needs, supplementary irrigation of crops and fisheries.

- *Increasing the vegetative cover in the upper catchments will reduce erosion and sediment load in the runoff, and increase base flows,* irrespective of the agro-ecology.
- *Improving the efficiency and/or productivity of water use frees up water for other water users or uses either locally or downstream.* There is increasing evidence that improving efficiency and/or productivity of water use can deliver significant benefits but freeing up water for other uses is rarely one of them.

These assumptions may not reflect reality in many cases. One reason is also partly due to the fact that the catchment is not addressed as a whole – thus obscuring downstream uses and users from the planning perspective of the upstream project.

Hydrological Realities of Watershed Development

Watershed development through programs such as the IWMP would have significant hydrological impacts both locally and downstream. Well-documented beneficial impacts include a localized increase in groundwater recharge (which can improve the productivity of irrigated agriculture and the security of drinking water supplies) reduced the magnitude of downstream flooding[12] and caused less sedimentation of downstream reservoirs. Watershed development programs can also cause significant reductions in the quantity of water flowing downstream through increased water use and loss via evapo-transpiration from expanded and intensified irrigated and rain-fed cropping and direct evaporation from the surface of Rainwater Harvesting (RWH) structures (Bouma *et al.,* 2011; Adhikari *et al.,* 2013; Kumar *et al.,* 2006; Glendenning and Vervoort, 2010). However, the reductions in downstream flow are often more significant in dry years (Kumar *et al.*, 2006 & 2008), an impact that will become significant with greater climate variability. Four specific impacts have also been noticed:

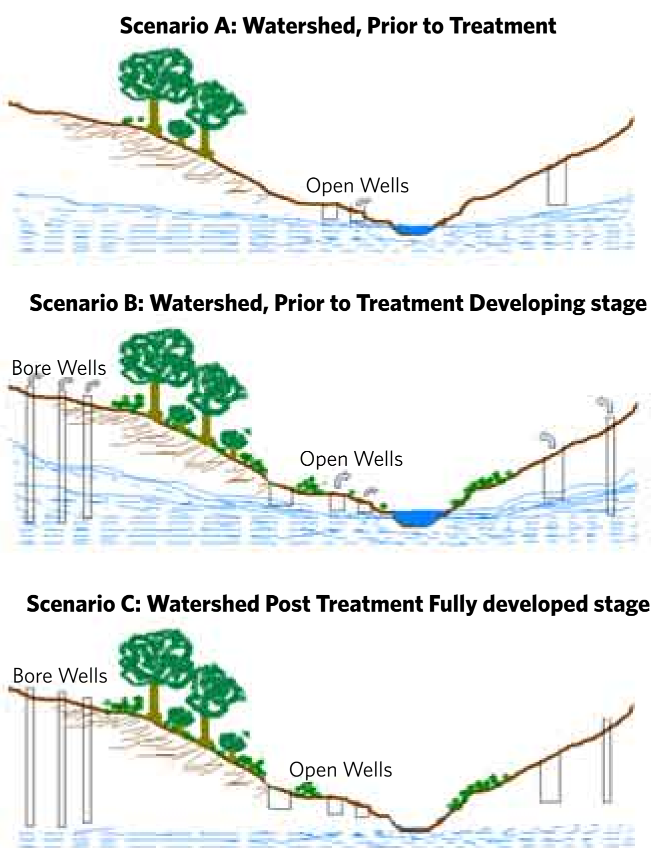
- **Decreased water flows to rivers and water bodies:** Nune *et al.,* (2012) analysed data for the Musi sub-basin in Andhra Pradesh and found a major decline in stream flow after implementation of watershed development. Kumar *et al.,* (2008) in their study of Ghelo river basin in Saurashtra in Gujarat found that after intensive water harvesting activities were initiated in 1997, the rainfall-runoff relationship of the basin altered, with less observed flows in the river for the same quantum of rainfall post-water harvesting intervention. Garg *et al.,* (2013) modeled the impact of watershed development in the 736 km^2 Osman Sagar catchment and predicted a 30-60% reduction in the inflows into the downstream Osman Sagar reservoir which is an important source of water for the city of Hyderabad.
- **Decreased water flows into community tanks:** In a study of the Gudalur community tank in Inchegiri taluka of Karnataka, Batchelor *et al.*, (2002) found that increases in water harvesting, groundwater extraction and groundwater-based irrigation reduced inflows into the community tank by 40% on average, with the decrease being greater in low rainfall years. Singh *et al.,* (2004) found in a related study that while the water harvested by water harvesting structures (WHSs) in the catchment of a community tank and in the tank itself was roughly 50:50 during normal years, it changed drastically to 75:25 during dry years with much more water being captured and used for irrigation in the upstream structures. As in most large community tanks in south India, this water is used by poorer community members, including the landless, for their livestock, brick and rope making activities and for washing clothes and vessels.
- **Limits to benefits:** Sharda *et al.,* (2006) measured groundwater recharge from RWH for two small catchments in Madhya Pradesh and found that higher rainfall amounts did not result in proportionally high recharge, as the structures had a limited capacity to induce recharge. Glendenning and Vervoort, (2011) in a study of the impact of watershed development on the Arvari catchment in Rajasthan found that RWH structures generally increased the sustainability of irrigated agriculture,

12 This is for small and medium floods, while for large damaging floods, watershed development delivers limited benefits and, in some cases, can exacerbate the damage caused.

but that the marginal benefit of each additional RWH structure was less than the preceding one. Also, Kumar *et al.,* (2006 & 2008) showed an increasing unit cost of harvesting of water (Rs/m^3 of water), at higher levels of development of the catchment: Above a certain limit additional structures did not increase groundwater recharge and only reduced downstream flows.

- **Lack of sustainable benefits from water harvesting:** Groundwater recharge is promoted within the catchment under watershed management as a 'positive value' on the assumption that will increase base flows, thereby making streams flowing in the lower catchment perennial through base-flows during the lean season. But, hardly any attention is paid to the fact that this activity is often followed by indiscriminate drilling and deepening of bore wells and open wells by farmers in the area, which ultimately leads to increased draft and threatening even the existing natural discharge of groundwater into streams and wetlands (see Figure 2.1).

FIGURE 2.1 STAGES OF GROUNDWATER DEVELOPMENT IN A TYPICAL TREATED WATERSHED



But there is virtually no control on groundwater abstraction planned under watershed management projects – as groundwater regulation is seen as the responsibility of another Department. Further, the community organizations formed in the watersheds have little or no role in either regulating land or water use or in allocating water amongst various uses.

Clearly, not taking into account both the existing levels of water harvesting and water use by different land uses in the watershed and potential impacts in downstream watersheds within the same catchment could lead not only to unintended negative consequences as well as a waste of resources if structures do not increase groundwater recharge as intended, and sustainably. Therefore patterns of land and water use and management need to be well planned. With a large number of different agro-ecological catchments, a country like India cannot afford general assumptions about catchment behavior. Guidelines on watershed management require answers to questions that include:

- How does the type of catchment land use and land use system influence the impact of increased vegetation cover on stream flows (including water quality), in different agro ecologies?
- How does the nature of vegetation (whether shallow-rooted grasses and shrubs, or deep rooted tress) determine the impact of increased vegetation cover on the consumptive use of water from the soil profile and groundwater system of the catchment?
- How will these impacts change across agro-ecologies?
- What is the hydraulic inter-dependence between groundwater and surface water in the catchment and, therefore, the impact of change in groundwater withdrawal on stream flows downstream?
- What is the fate of return flows from, for example, irrigation schemes and urban areas?
- What are underlying causes of water quality problems relating to natural contaminants (e.g. fluoride) and anthropogenic contaminants (e.g. from urban areas, as a result of agricultural intensification)?

Such knowledge is extremely important for guiding catchment management interventions as the sources of sedimentation can often be quite localized – such as newly constructed roads, stream-bank cultivation, and movement of livestock around, to or from a water point.

Given these kinds of potential issues with watershed programs in India, there is a critical need to develop a clearer understanding of catchment characteristics (drainage pattern, drainage area, type of soils and the slope), current land use in the catchment and the hydrological regime, before interventions are planned for changing these hydrological regimes.

CATCHMENT HYDROLOGY

The knowledge on the dynamics of interaction between a particular land use and land cover and water use in the upper parts of the catchment, and the hydrology and ecosystems of a given catchment can provide pointers on the way in which the former needs to be modified to produce social, economic and environmental outcomes that are acceptable to the catchment communities. But which land use or land cover- based intervention needs to be taken up, and to what extent they need to be changed to achieve the optimum outcomes (in terms of water yield, sediment load reduction, meeting water quality standards and reduction in soil loss etc.) can only be assessed using various models which simulate the hydrological and biophysical processes. Such models basically integrate those used for prediction of soil erosion from the catchment; crop growth; rainfall-runoff; sediment transport; and groundwater flow.

What is important to note is, that while altering land use and land cover and construction of vegetative bunds in the upper parts of the catchment could change the catchment yield along with soil loss, the withdrawal of either surface water or groundwater in the catchment to affect such changes could also cause variations in water yield received in the lower parts of the catchment. This in turn can bring about drastic ecological changes in those areas in terms of the nature and extent of vegetation that the river plains support. Hence, these models have to be used in an integrated way to understand the cumulative effects.

Insights from models and hydrological assessments can significantly improve the understanding of the catchment-wide impact of several key commonplace interventions, including afforestation, micro-irrigation and *in situ* soil and water conservation practices. As discussed below, some of these are quite nuanced and context-specific which make generalized assumptions difficult to sustain:

- **Biomass and groundwater infiltration and stream flows:** The traditional perception that forests increase water resources has long been questioned by the results of scientific forest hydrology since the early 20th century (e.g. Calder, 2002, IUFFRO, 2007). A large number of catchment experiments conducted all over the world clearly demonstrated that the deforestation of a catchment implies an increase of water yield from it and, conversely, the establishment of a forest cover implies a decrease of water yield (Sahin and Hall, 1996).[13]

Further, in arid and semi-arid regions, the increase in area under rain-fed crops in the catchment would have a negative impact on stream flows as a good share of the runoff generated from precipitation could be captured by the cultivated, bunded and/or terraced fields, which would in turn be taken from the soil profile by the standing crops as ET. The reduction in runoff could be disproportionately higher than the increase in recharge which occurs as a result of increased soil infiltration owing to larger vegetation cover, depending on the ET requirement of the crops (Kumar, 2010). In contrast, at least in some cases, increases in forest cover could have a lower impact on stream flows, as it will not capture the runoff, and use only the moisture in the soil profile or the vadose zone or shallow aquifer. An increase in tree cover would however have a much bigger impact on groundwater as the deep-rooted trees would suck water directly from the shallow aquifer or the vadose zone for meeting transpirative demands, while its effect on soil infiltration of rainwater may not be significant (Leblanc *et al.,* 2012).

- **Water savings from agriculture:** While several studies have shown that efficient irrigation technologies can improve efficiency and productivity of water use at the 'plot level' (through reduction in soil evaporation, runoff and deep percolation losses), deep percolation and

13 The application of this knowledge to designing sustainable water management practices, although necessary in water stressed regions, has been largely delayed because of difficulties inherent to the change of any scientific paradigm, the limited experience on the hydrological consequences of land cover changes in large territories, and the disconnect between policy and science (Falkenmark *et al.*, 2000; Calder, 2002).

runoff losses at the catchment scale may not be necessarily as large as that at the plot level (Wallace and Batchelor, 1997; Kumar and van Dam, 2009). Deep percolation or runoff at the field, farm, or village scales may be an important source of water for users further down the catchment and may also contribute to stream flow, reservoir storage and groundwater recharge. Therefore, field-level water savings that benefit individual farmers may only lead to 'notional' and not real water saving at the village, watershed or catchment scale.

Real water savings with efficient irrigation technologies can only come from reduction in soil (non-beneficial) evaporation and non-recoverable percolation. To what extent, the use of efficient irrigation technologies lead to real water saving, depends on factors such as distance between plants, the irrigation technology (whether drips, or sprinklers or mulching), climate, depth to water table and soil type. In shallow groundwater areas, with sub-humid or temperate climate, for closely spaced crops, the real water saving through a shift to efficient irrigation technologies such as drip irrigation would be negligible, as most of the deep percolation under traditional methods of irrigation would end up as recharge. Such savings could however be significant with this technology if the groundwater table is deep, the climate is semi-arid or arid, and crops are distantly spaced. Thus a poorly managed "hi-tech" system can be as wasteful and unproductive as poorly managed traditional systems.

- **Increased water use from water saving technologies:** This is a counter-intuitive finding that in areas where water scarcity limits farmers' ability to bring the entire cultivable land under irrigated production, the tendency of micro-irrigation system adopters has been to expand the area under irrigation using the saved water after installing the systems in their farms. If, in a given location, efficient irrigation technologies do not help to achieve real water saving (like in humid or sub-humid areas with shallow water table conditions), such a tendency can lead to farmers actually depleting more water in the form of consumptive use. In the other case, there may be no real water saving at the aggregate level (Howell, 2001); Allen, R. G. *et al.*, 1997); Molle and Turral, 2004 and Perry *et al.,* FAO, 2012).

There are several other examples of such detailed findings, including the following, all of which are discussed in greater detail in Annex 3:

- The relative effectiveness of field scale soil conservation measures *vis-a-vis* grass buffer strips and retention ponds in reducing soil loss and sediment yield (Verstraeten *et al.*, 2002).
- Rising groundwater levels and increase in soil salinity as a result of clearance of native vegetation for agricultural use in Murray Darling basin (Leblanc *et al.*, 2012).
- The effects of historical socio-economic developments and land use changes on river water quality in Scotland (Pollard *et al.*, 2001).
- The role of spatial and temporal patterns in rainfall and land use in the catchments, over and above aggregate rainfall, in explaining spatial and temporal variations in runoff occurring in the catchment in North West England (Orr and Carling, 2006).
- The negative impact of replacing paddy fields by forests on catchment yield, with just an opposite impact from replacement of forests by crop land, and positive impact of irrigated paddy on watershed hydrology in terms of quantum of flow in Chi river basin of Thailand (Homdee *et al.*, 2011).

These research findings not only suggest that assumptions based on observed reality at field or village or watershed scales may not hold true at the catchment scale but also that the specific features of every catchment must be understood through specific hydrological studies.

CATCHMENT ASSESSMENT AND MANAGEMENT PLANNING: INTERNATIONAL TRENDS

Watershed Development

There has been a shift in the international perspective on watershed management programs, based on experience so far (Table 2.0).

TABLE 2.0 SHIFT FROM 'PAST' TO 'NEXT' GENERATION WATERSHED MANAGEMENT PROJECTS

Past Generation	Next Generation
Integration of socio-economic issues within watershed management programs	Emphasis on watershed natural resource management as part of local socio-economic development processes
Focus on 'people's' or 'community' participation with an emphasis on bottom-up participatory planning	Focus on multi-stakeholder participation, linking social, technical and policy concerns in a pluralistic collaborative process
Rigid program design that overestimates central government's capacity to enforce policies and lacks adequate institutional/organizational arrangements at the local level. Short term planning and financing	Flexible program design that adjusts to local governance processes. Long-term planning and processes.
Implementation responsibility entrusted to 'heavy' institutions such as donor-assisted programs or government watershed authorities	Implementation responsibility entrusted to 'light' institutions such as watershed management fora, consortiums and associations, with programs and authorities playing a facilitating and subsidiary role
Focus on on-site, short-term effects. Small scale projects with little watershed or basin-level coordination	Focus on upstream-downstream linkages and long-term impacts. Local-level processes coordinated at the watershed or basin level.
Quick-and-dirty participatory assessment and evaluation (e.g., Participatory Rural Appraisal [PRA]) with little or no linkage to natural and sociological evidence	Dialogue between local and scientific knowledge in 'fairly-quick-fairly-clean' action research processes involving a variety of stakeholders
Belief that access, tenure and social conflicts in watersheds can be solved by technically sound interventions	Awareness that most access, tenure and social conflicts in watersheds are rooted in society and politics and should be managed through continuing negotiation

Integrated Catchment Management

Integrated Catchment Management (ICM) is a concept implemented in some of the developed countries and is capable of addressing some of these concerns – especially the issue of multiple stakeholders with different expectations and requirements. ICM envisages catchment-wide management of water resources, while ensuring sustainable, efficient and equitable water use within the catchment (Batchelor, 1999). Its main features are the following:

- **Recognizes inter-connectedness** between upper catchment and streams, groundwater and surface water, and catchment land use, and quality and quantity of runoff from the catchment. Therefore it helps plan interventions in such a way that they protect the hydrological system integrity of the large catchment (Mitchell, 1990).
- **Appreciates that there are competing uses of water and land within the catchment** and therefore water allocation is as important as augmenting water supplies or creating new sources of water, from the point of view of ensuring equity in water use.
- **Helps analyze trade-offs** in promoting each use in terms of its impacts on the values generated by the other uses (see Box 2.4).

BOX 2.4 CATCHMENT MANAGEMENT TRADE-OFFS

Improving the river water quality could be a social objective, as it would improve drinking water supply and human health outcomes. Getting adequate quantities of water for irrigation could be an economic objective, as it can help increase the income returns for the farmers in and outside the catchment who receive water from it for irrigation. While some of the land use interventions like reducing the intensity of agricultural land use or changing crop sequences in the catchment management could help meet the former, it can impact the latter adversely. Similarly increasing the forest cover in the catchment might help improve the catchment ecology with better soil cover, soil biota, improvements in micro climate and some benefits of reduction in occurrence of flash floods in situations of intense rainfall, it might lead to overall reduction in catchment yields, thereby adversely forfeiting the social and economic benefits from the use of water flowing downstream.

- **Recognizes the importance of efficient use of water** (including the moisture in the soil profile) as much as the *amount* of water available for utilization in the catchment.
- **Calls for participation of stakeholders** in catchment management (Batchelor, 1999).
- **Goes far beyond typical bio-physical and structural interventions** taken up to improve moisture regime in the soil profile, local water storage and water quality.

Catchment management planning is thus not about intensifying the use of water and land within the catchment for enhancing biomass production or increasing other water needs, but it is about regulating catchment land and water use in order to achieve overall enhancement of various functions which the catchment performs.

Institutional Models of Catchment Management

There are some instances where developed countries have implemented integrated catchment management programs through legal, institutional and policy approaches. The fundamental change brought about in water management in these countries through the adoption of the ICM approach has been organizing water resource management around hydrological boundaries. However, many ICM strategies have not been able to bring about improvements in resource management at the catchment scale, mainly due to lack of delivery mechanisms and enabling policies that generate the interest and trigger the participation of local institutions and communities (Batchelor, 1999). In certain cases, catchment management programs were also implemented effectively without legislative support, although, in such cases, the success of the initiatives was largely due to the involvement of community leaders and resource agencies (Johnson *et al.*, 1996).

Several institutional models for ICM have been tried around the world with varying degrees of success, beginning in Europe (Britain and France in the early 90s), though the most common among them being tried in developing countries is decentralized, community-based institutions for implementing watershed management programs at the level of micro catchment (Darghouth *et al.*, 2008). The nature and functions of these institutions vary from country to country and in a few instances from province to province, such as the following:[14]

- **France:** The two tier tradition of water management with SAGE (*Schemas d aménagement et de gestion des eaux*) and SADGE (*Schémasdirecteurs d'aménagementet degestion des eaux*), implemented through local management commissions and higher order River Committees, respectively.
- **European Union member states:** The River Basin Management Plans (BMPs) developed under the flagship legislation of the European Water Framework Directive.
- **Australia:** The Murray-Darling Basin Plan, which provides the management framework for a trans-boundary, river catchment level management of water resources in the Murray Darling Basin, encompassing four basin states, being implemented by the newly constituted MDB authority. In Western Australia**,** the Integrated Catchment Management Programme, enjoys legislative, policy, administrative and financial support since the early 1990s.
- **South Africa:** The Catchment Management Agencies (CMAs) that are created for ensuring poor people's access to water for domestic and productive purposes, being facilitated the Department of Water Affairs and Forestry (DWAF) under the National Water Act. While visionary and far-reaching in its implications, the Act has proved difficult to implement in practice.

In countries where ICM practices have been attempted, the need for catchment-wide management of land and water resources had mostly arisen in response to the prevailing or perceived future conflicts over land and water use so as to ensure water for environmental flows to prevent coastal salinity, augmenting lean season flows for ecology, and preservation of aquatic life and protection of water quality for drinking. The objectives for catchment management varied across countries

14 The cases of Australia, Britain, South Africa and France are further detailed in Annex 3 (based on Johnson *et al.*, 1996; Bellamy *et al.*, 2002; Buller, 1996; Batchelor, 1999; Cornell, 2012; EEB, 2010; Herrfahrdt-Pähle, 2010; Mitchell and Hollick, 1993; Schreiner and van Koppen, 2002).

and situations though. While in MDB of Australia, the objective was to limit the water abstraction from the catchment to sustainable diversion limits, in South Africa, the main objective was to ensure water access to the poor native communities for domestic and productive needs, as provided by the National Water Act of 1998. In France, the approach to catchment management has largely been a state-led institutional response to the failures or inconsistencies of pre-existing management and regulatory structure. In Western Australia, the objective was to coordinate the policies and activities of the existing agencies under the prevailing structure.

The major features of ICM programs that have shown positive results include the following (Batchelor, 1999; Darghouth *et al.,* 2008, Cornell, 2012):

- An overall natural resource management strategy that clearly defines the management objectives.
- A range of delivery mechanisms that enable these objectives to be achieved.
- A monitoring schedule that evaluates program performance.
- Decision-making and action that take place at the basin-wide, regional and local levels.
- Local communities' involvement, wherever possible, both in decision-making and in resulting activities.
- Mechanisms and policies that enable long-term support to programs of environmental recovery.
- Catchment management planning is a process, however, and not a one-time activity. Its outcomes are determined by who initiates and facilitates the process. Different countries have followed different processes, with varied results:
  - In the Murray-Darling Basin of Australia, which has a long history of catchment management, the activities of various catchment management agencies are to be now regulated through a Basin Plan, which is a legally enforceable document. Within the framework of action provided by the Basin Plan, the four basin states are expected to come out with their own plans for water diversions for competing uses and the environment.
  - In South Africa, under the National Water Act, the DWAF is to facilitate the process of setting up CMAs within each basin, statutory bodies for basin-wide management of water resources. The CMAs are expected to come out with their own technical proposals for managing their catchments with the larger goal of participatory basin management. But, till 2012, only two CMAs could become operational in the country.

Trade-offs in Catchment Management

There are no perfect solutions to address the legitimate but often different values and interests of communities relating to water within a catchment (Mitchell and Hollick, 1993), and trade-offs are necessary. To achieve the goal of sustainable water use, the catchment planning process has to overcome the resistance from the more established administrative and policy-making interests at various levels, which are targeted at the former (Buller, 1996).[15] It requires institutional reforms and policies for Water Demand Management (WDM) to create an enabling environment for efficient use of water (Batchelor, 1999; Kumar and van Dam, 2013; Molle and Turral, 2004), and to affect inter-sectoral allocation of water. But, any move towards an integrated approach will include some turbulent and difficult times and honest differences of opinion regarding the most appropriate way to proceed and to allocate scarce societal resources (Warner, 2006).

Catchment management decisions ought to be based on multiple objectives and criteria, which are social, economic, environmental and political, given the variety of uses and users of land and water in the catchments. Often, there could be strong trade-off between maximizing economic outcomes and meeting environmental and social goals, and vice versa. The utility functions for catchment management would be based

15 The essential knowledge of hydrological and ecological processes for scientific management of the catchments are often lacking in political action. Such a perspective is reflected, for instance, in India's 12th Five Year Plan document, which gives a thrust to local rainwater harvesting and groundwater recharge and use as a solution for growing water scarcity, without taking cognizance of the catchment hydrology, especially the linkages between upstream and downstream and groundwater-surface water interactions.

on all these, and making the right management choice is about minimizing the trade-offs. But to what extent this trade-off could be minimized depends on which stakeholder has the political influence or is powerful. The challenge is to ascertain the weightage to be given to each one of the criteria, depending on the needs and concerns of various stakeholders in the catchment.

However, even a discussion of trade-offs must follow a clear scientific understanding of the underlying hydrology. The first step towards ICM, therefore, is to develop a sound understanding the hydrology of the catchment and potential impacts of management interventions, for which modeling is perhaps the only tool available.

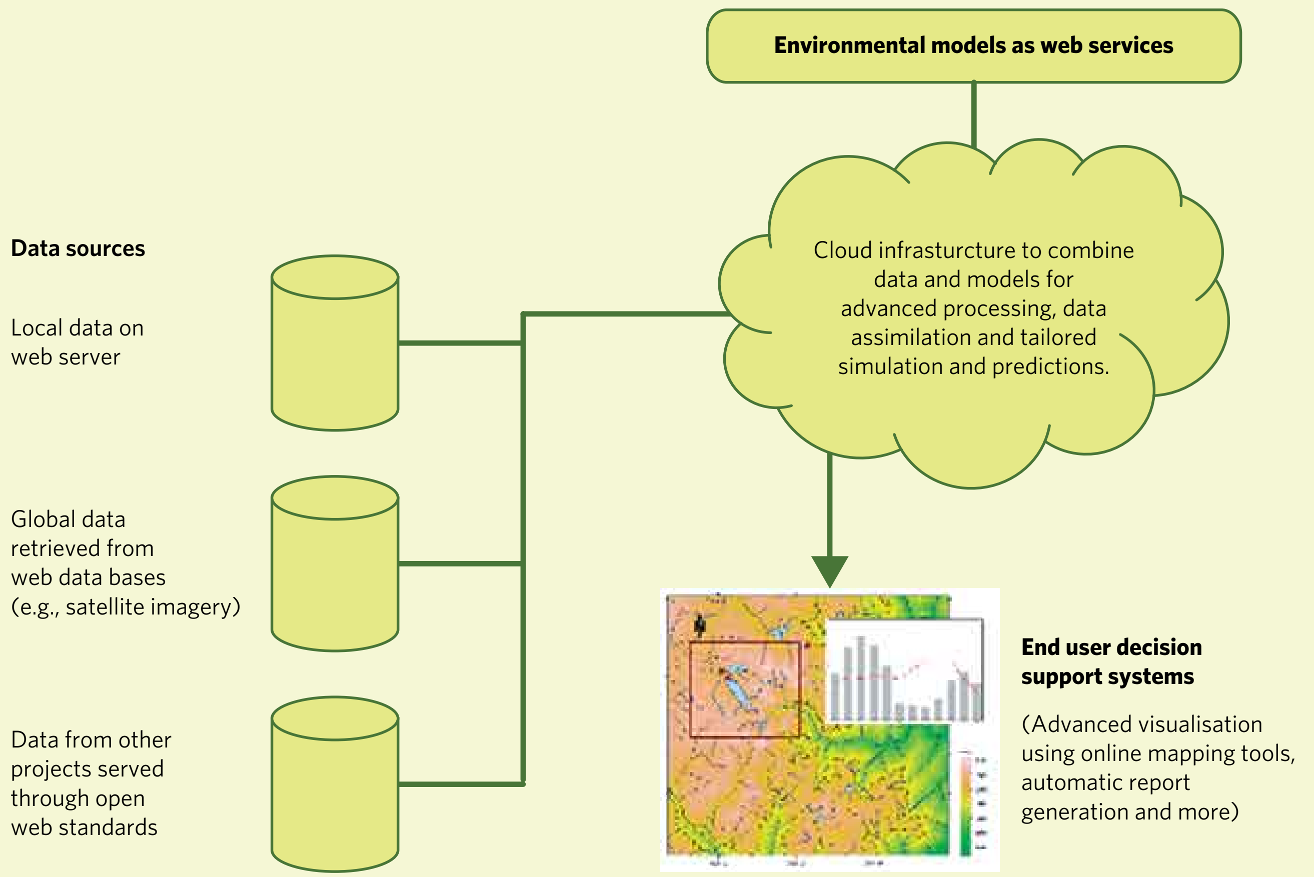
Modeling Catchment Hydrology

- ***Modeling tools exist for simulating the complex hydrological processes in catchments**,* which, if used correctly, have the potential to predict hydrological outcomes for projected changes in land use and land cover in terms of runoff, soil loss and sediment transport. They include 'integrated modeling tools which have a built-in rainfall-runoff model, crop simulation model, soil erosion model and sediment transport model. Models which incorporate economic outcomes of catchment management interventions into the hydrological and bio-physical models also exist, which can act as Decision Support Tools (DST) for integrated catchment management.
- ***Catchment management plans should offer a vision for the catchment and its communities for the future.*** Therefore, it is important that that they accept the rules and framework of actions broadly defined by such plans. Often, the communities are not really convinced about the influence of individual actions on catchment functions – goods and services provided by the catchments, like the impact of free grazing on natural regeneration of vegetation, catchment yield and quality of water or of agricultural practices on the quality of water in streams.
- ***Catchments cannot be managed merely on the basis of scientific knowledge of hydrological and ecological processes.*** There is a need to recognise the fact that individual actions of the community members are not governed by scientific practices that promote good catchment functioning, but other considerations. That only can foster the awareness of interdependencies between individual actions and catchment functioning and optimize the individual actions – for instance, the link between agricultural practices in the upper catchment and river water quality downstream. Facilitating the dialogue amongst stakeholder groups in the catchment, scientists and policy makers would help 'social learnings' wherein the experts and policy makers understand the rationale behind the individual actions like intensive use of fertilizers. Awareness of the interdependencies can be created through appropriate practical initiatives that provide a systemic awareness of the context in which the individual actions and catchment functions are positioned. That can help frame rational policies that ultimately work.
- ***There is no blueprint for catchment management:*** Technical experts, analysts and policy makers are realizing that there is no ready formula that can be applied, everywhere, for managing a catchment. There is, therefore, an increased emphasis (at least in some countries) on the value of "integrated, iterative and adaptive approaches" (e.g. IRC), "muddling through" (e.g. Andrews), "getting the basics right" (e.g. EU 2008), "good enough governance" (e.g. Grindle), "just-enough governance" (Fukuyama & Levy), "Learning Organizations" (IRC), "evidence planning and management" (Whitty & Dercon) and "institutional bricolage" (Cleaver). The move, clearly, is towards incremental learning based on feedback from the ground.
- ***Rapid advances in cyber technologies can be used to advantage:*** Technologies and concepts such as cloud-based information systems, modeling, remote-sensing, SMART-phone applications, eco-drones and citizen scientists, can allow the collection and use of rapid feedback. One such promising example is the virtual observatory (Box 2.1).

BOX 2.1 VIRTUAL OBSERVATORIES

Virtual observatories can link and integrate online: 1) Global, national and global information bases (containing both terrestrial and remotely-sensed biophysical and societal information); 2) Networks of environmental sensors; 3) Information collected by users of water services or by citizen scientists; and 4) Inter-connected web or cloud-based services or applications (Buytaert *et al.*, 2012).

Schematic of a virtual observatory of interconnected web services providing interactive information products and/or simulations



Potential benefits include

- More cost-effective and efficient access to biophysical and societal information for a specified domain.
- Active participation of local-level stakeholders and/or citizen scientists.
- Platform for stakeholders to share and access multi-sectoral, multi-scalar information.
- A possible alternative to existing uni-sectoral management information systems.
- Potential to blend real-time and historic information.
- A new innovation that could appeal to politicians and funding agencies.

Reasons to be cautious include

- New technology is not a panacea e.g. it will not overcome long-standing problems such as, lack of IT capacity, unwillingness to share information, lack of trust among some stakeholders and the tendency of some stakeholders to "cook" information.
- To be sustainable, virtual observatories will need an institutional home and a secure line of funding.
- Risk that uncertainties will not be tracked or quantified.
- Risk that the technology will not meet the needs of stakeholders and, as a result will end up being another water IT sector "white elephant".

- ***No alternative to larger-level planning:*** For consistency, however, watershed management planning and plans should be informed by, consistent with and nested within basin-level planning and plans**.** The Ten Golden Rules of Basin Planning (ADB, 2013) emphasize multi-level and nested planning starting at basin-level, using a planning approach that suits basin needs, with prioritized and phased activities, involving stakeholders on institutional platforms, and acknowledging that basin planning is inherently chaotic and requires an iterative and adaptive approach (Box 2.2).
- ***Hydrological modeling can help catchment management in several ways:*** The broader objectives of models and modeling include:
    - Providing analytical evidence to support decision-making e.g. for policy-making, for multi-scalar watershed management planning, to support integrated approaches.
    - Testing different hypotheses and new ideas across a range of conditions or scenarios.
    - Mitigating uncertainty, especially when used in conjunction with scenario-building.
    - Supporting inter-disciplinary lesson-learning e.g. by systematically combining scientific and local knowledge.
    - Identifying and assessing the scale and severity of externalities or trade-offs.
    - Assessing the resilience of strategies and plans to climate change and other sources of risk.
    - Assessing the resilience of land and water management strategies, e.g., to climate change.
    - Generating trustworthy information for areas that are not covered by hydrometric networks.
- ***Modeling is not a panacea and good models require time and effort to set up and run:*** While setting up and using models, the following needs to be considered:
    - Modeling is only as good as the understanding of the processes being modeled, the data and metadata that are available and/or used and the capacities of those involved in the process.
    - Modeling should be used to support decisions and not to make them.
    - It is rare for a register to be kept of small-scale watershed management interventions (e.g. size and location of check dams). It is even rarer for such an asset register to have up-to-date information on the condition or functionality of interventions.
    - In some cases, the process of modeling (and collective learning) is more important/successful than the modeling outputs.

BOX 2.2 TEN GOLDEN RULES OF BASIN PLANNING

1. Develop a comprehensive understanding of the entire system.
2. Plan and act, even without full knowledge.
3. Prioritize issues for current attention, and adopt a phased and iterative approach to the achievement of long-term goals.
4. Enable adaptation to changing circumstances.
5. Accept that basin planning is an inherently iterative and chaotic process.
6. Develop relevant and consistent thematic plans.
7. Address issues at the appropriate scale by nesting local plans under the basin plan.
8. Engage stakeholders with a view to strengthening institutional relationships.
9. Focus on implementation of the basin plan throughout.
10. Select the planning approach and methods to suit the basin needs.

- There will always be deficiencies/gaps in the data available for models. In addition to other benefits, structured dialogue of stakeholders and citizen scientists can be an effective means of filling these gaps.

❖ ***There are benefits to engaging with stakeholders during the modeling process.*** These include the following (FAO, 2014):

  - Key stakeholders play a role in identifying key questions and ensuring that outputs meet their needs.
  - Access to data and metadata is more likely.
  - Key stakeholders play a positive role in quality controlling input data and validating model outputs (i.e. checking that model outputs are consistent with local observations).
  - Key stakeholders may offer interesting insights during the interpretation of model outputs.
  - Key stakeholders are more likely to trust and have confidence in the modeling process and less likely to reject outputs or findings.
  - The modeling component and the wider watershed management planning process are less likely to fail.

❖ Ways to mitigate risks and uncertainties in watershed planning and management in water scarce areas include the following (ADB, 2013; EPA, 2008):

  - Identifying the main sources of risk and uncertainty (e.g. lack of good quality data, lack of understanding, prevalence of water-related myths) and take explicit steps to overcome or mitigate each of these sources.
  - Recognizing trade-offs between alternative political, economic, social and environmental objectives and between existing and potential future demands.
  - Carrying out scenario-based analysis and planning to address uncertainty in future development and climate, by assessing alternative hydro-economic scenarios.
  - Having cycles of adaptive planning and learning that update and improve plans as and when new information and evidence is produced by M&E systems.

❖ ***Water accounting and water auditing as part of an adaptive management process for watershed management*** (FAO, forthcoming) where:

  - *Water accounting* is the systematic study of the current status and future trends in water supply, demand, accessibility and use within a specified domain.
  - *Water auditing* places outcomes and findings from water accounting into a broader framework covering water governance, institutions, services delivery models, public and private expenditure, legislation, and the wider political economy.

CHAPTER-3

CATCHMENT ASSESSMENT AND MANAGEMENT PLANNING PILOT

OVERVIEW

This Section details the hydrological assessment, comprising the modeling and village-planning processes demonstrated in the pilot, the scenarios generated concerning potential local and downstream impacts and discussions of how such impacts can be addressed. The lessons from the pilot study and from international practice (discussed in the previous section), are used in the next Section to suggest an approach and methodology for wider application.

HYDROLOGICAL ASSESSMENT

Two broad and mutually-supportive methods can be used for hydrological assessments of catchments. The first is the use of conceptual (or perceptual) models based on hydrological principles for aggregate-level assessment of catchments, which does a one-time assessment for a given hydrological unit and for a given time frame. The second is the use of hydrological models to understand and simulate the hydrological processes in the catchment on a spatial and different time scales.

The fundamental difference between the 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, whereas simulation models are calibrated and validated to deal with the processes themselves, which are both time and space dependent. Simulation models can be run on various time scales (daily, weekly, monthly and annually) and for different scales (small watersheds, sub-basins, and the whole basin). Developing perceptual models is a very important step in a modeling process but it is not an alternative for a calibrated and validated hydrological model.

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, as also suggested in the Technical Group meeting of 15 November 2014, a good starting point for the modeling process. Following the choice of catchment and simulation model, the secondary and primary data collection is described, after which the findings from the perceptual model and the simulation model are discussed.

Choice of Catchment and Model

Choice of state

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. The main reasons for the choice of Gujarat were the following:

- 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 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 SLNA in Gujarat to be support and assist the pilot.

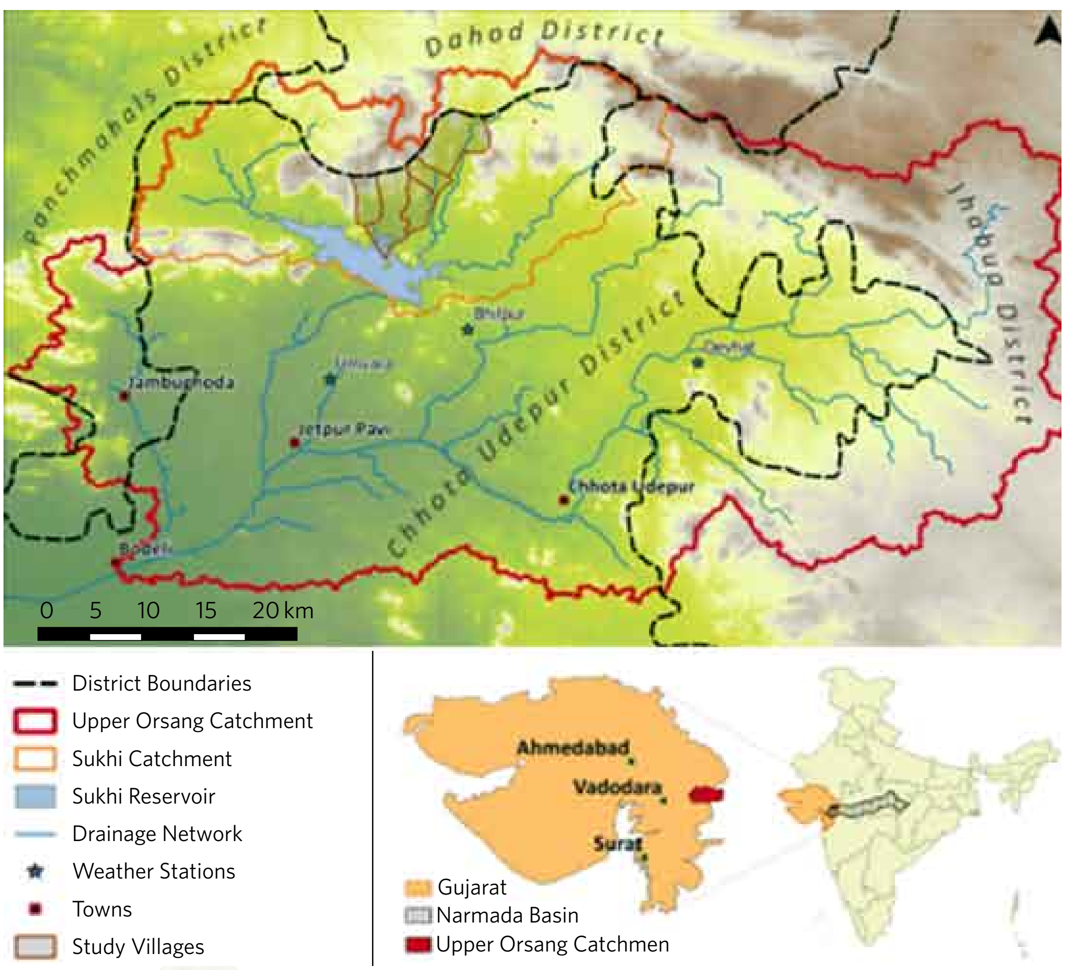
With introductions from the Water Resources Specialists at the World Bank, an exploratory visit was made to the State Water Data Centre (SWDC) in Gandhinagar, Gujarat, during which the Superintending Engineer in charge of the SWDC, and the Secretary, Department of Water Resources, Government of Gujarat, agreed to share the secondary data available with the SWDC.

Revisiting the initial catchment choice

The details of the study, its objectives and expected outputs, were presented to the GSWMA (the Gujarat SLNA) at a meeting in their office in Gandhinagar on 15 September, as well as the initial choice of the Upper Dhadhar catchment. But, apart from a large canal (from the Narmada river) running through the catchment of around 680 km^2, a key constraint pointed out by the GSWMA was that no IWMP projects were being implemented in even the areas upstream of the Narmada canal. The nearby catchment of the Sukhi river was potentially suitable, as it had the following characteristics (Figure 3.1):

- The Orsang river is a tributary of the Narmada river and the Sukhi is a tributary of the Orsang. The Sukhi catchment lies within the Orsang sub basin of the Narmada basin.

FIGURE 3.1 LOCATION OF THE SUKHI CATCHMENT



- The major part of the catchment is located 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.
- The catchment has an area of 393 km^{2,} which is mostly agricultural and forest land, and a significant part of the catchment falls within the Ratanmahal wildlife sanctuary.
- 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.
- Around 50 villages in the part of the catchment lying in Chhota Udeypur district have been selected by IWMP to undergo watershed development.

Locating individual IWMP watersheds

The 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 overlain 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 (Figure 3.2).

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 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

FIGURE 3.2 LOCATION OF IWMP WATERSHEDS IN THE SUKHI CATCHMENT

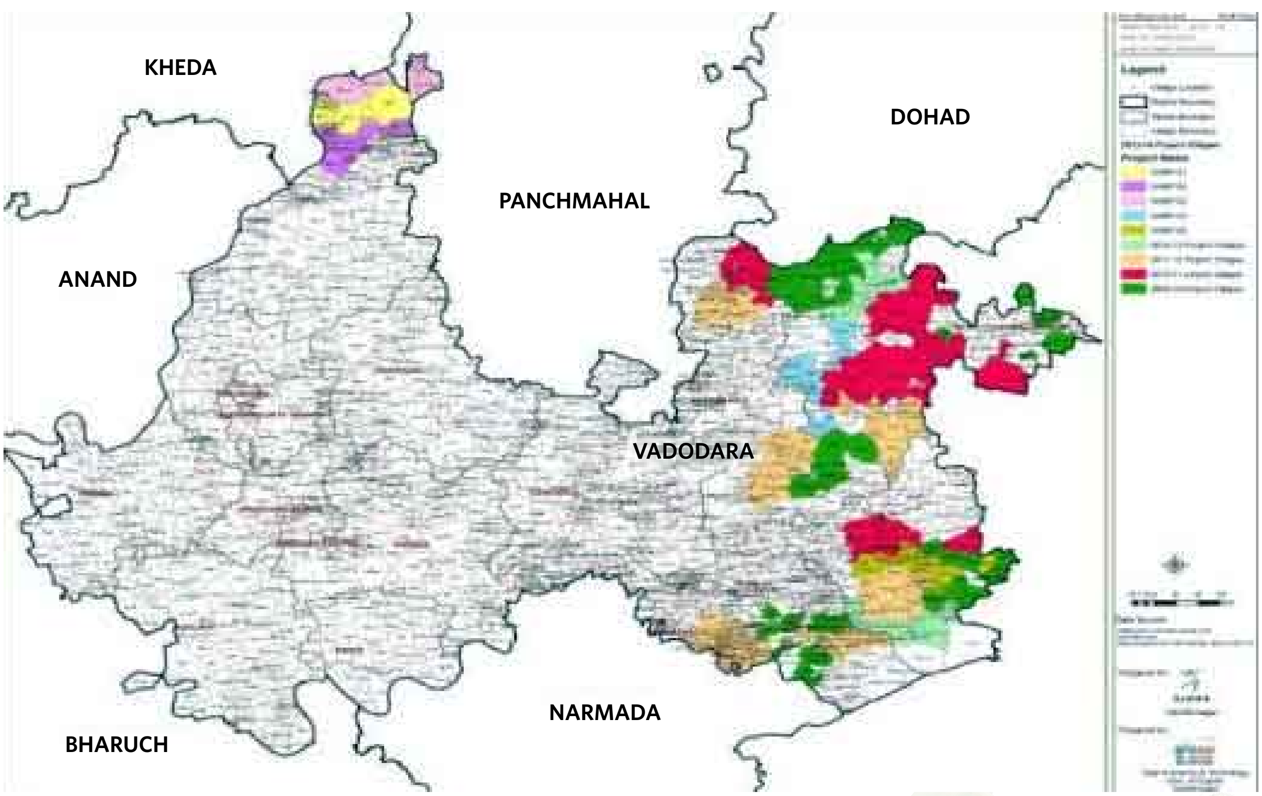
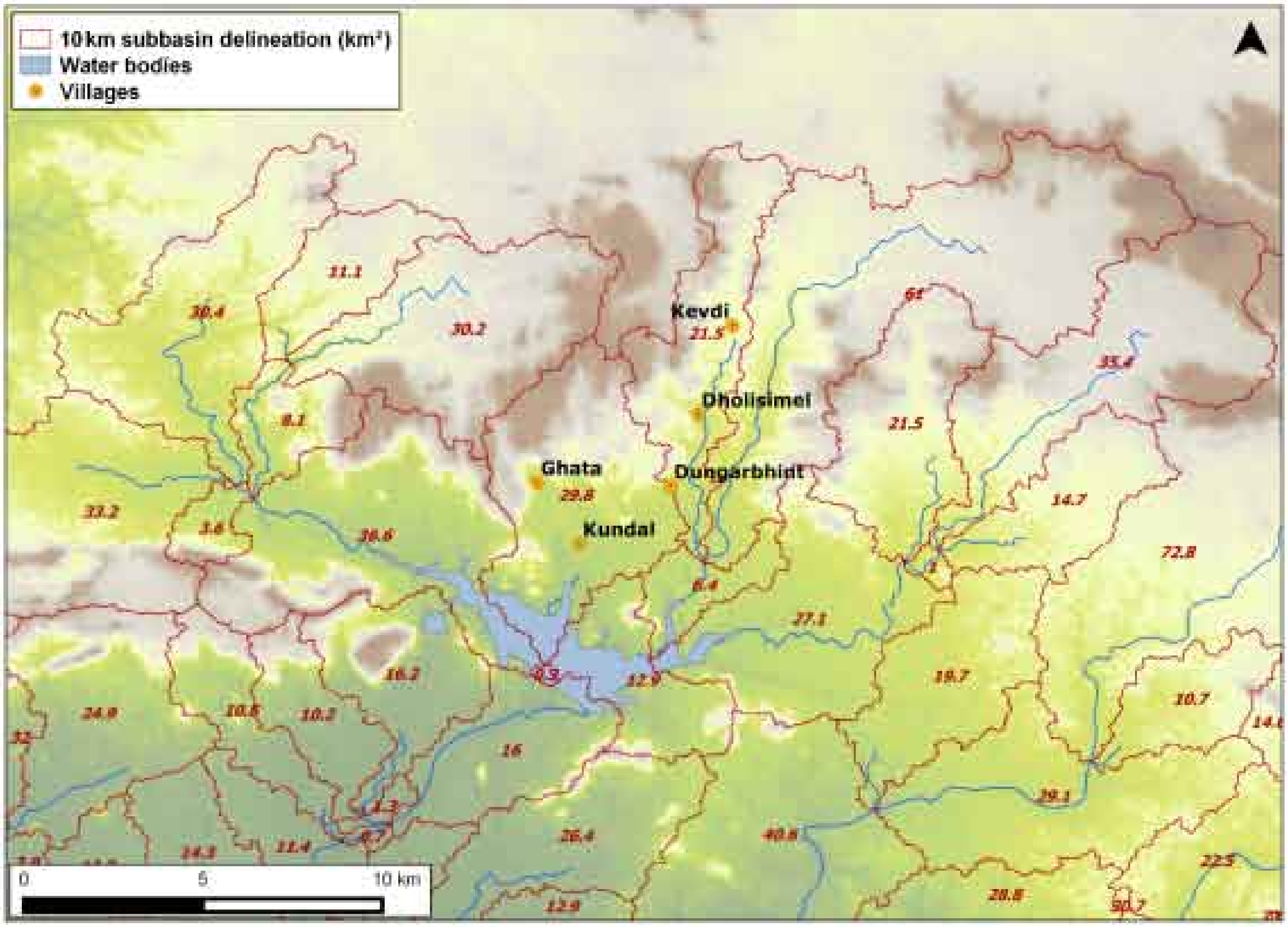


FIGURE 3.3 IWMP WATERSHEDS ABOVE SUKHI RESERVOIR (SWAT DELINEATION)



key criterion (sloping from 'ridge to valley') as locations for the choice of catchment.

With sub-basins delineated at 10 km these 5 villages cover the large majority of 2 sub-basins with Kevdi, Dholisimel, and Dungerbhint forming an upstream-downstream continuum within one 21.5 km^2 sub-basin (Figure 3.3). Another advantage of these villages is that the sub-basins lie almost completely within Chhota Udeypur district (Figure 3.1 above) 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.

Choice of model

The ease of setting up and using SWAT for selecting the catchment, as illustrated above, 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 confirmed that SWAT was a suitable model to study the impact of watershed development in India *(inter alia,* Mishra *et al.,* 2007; Glendenning *et al.,* 2012) due to a number of characteristics (see Box 3.1 for an overview of the model):[16]

- 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.

16 See the Section 5 of the Technical Note on SWAT Modeling in Annex 8 for a brief overview of studies carried out in India using SWAT.

BOX 3.1 KEY FEATURES OF SWAT (SOIL AND WATER ASSESSMENT TOOL)

- SWAT is a semi-distributed 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 when compared to ArcSWAT, useful online resources available can be accessed via these links. 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 this data is not always sufficient, especially for smaller catchments.
- It is possible to combine SWAT with other models such as MODFLOW and WEAP.

- An active on-line community that can provide useful support regarding all aspects of model use.
- It is a semi-distributed 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 sub-watersheds during model setup is flexible allowing SWAT to be applied at any scale from the plot level up to the continental.
- 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 modelling 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 modelling process and improve model outputs.
- There are a number of 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.[17]

Data Collection

Secondary data

During the same visit to Gujarat, the data inputs into SWAT were summarized and their various sources identified (Table 3.1), 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).

17 See the Technical Note on Modeling in Annex 4 for a detailed description of the SWAT model.

TABLE 3.1 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) Land use (Raster data or shape file) Soil type (Raster or shape file) Drainage Network (shape file) Village Cadastral Maps (Shape files) Shape files of village boundary and watersheds Canal network (shape file)	The website of the India Water Resources Information System (WARIS), Ministry of Water Resources National Remote Sensing Centre (NRSC) Hyderabad National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Bangalore	Orsang sub-basin	Gujarat State Watershed Management Agency (GSWMA) Bhaskar-Acharya Institute For Space Applications and Geo-Informatics (BISAG) Central Soil and Water Conservation Research and Training Institute (CSWCRTI) in Vasad, Gujarat	Orsang sub-basin
Meteorological data	Daily minimum and maximum Temperature Daily rainfall Daily sun-shine hours or Solar Radiation Daily average relative humidity Wind speed Daily pan evaporation	Indian Meteorological Department (IMD)	# Jetpur # Jambugam # Bhilpur # Chhota Udeypur # Bodeli # Jambughoda	Gujarat State Water Data Centre (SWDC) GSWMA	# Dhandhoda # Bhilpur # Jetpur Pavi # Devhat # Bodeli # Umarva
Hydrological and groundwater data	Daily river discharge Sediment Water quality Pre- and post- monsoon depth to groundwater level Estimated groundwater recharge	Central Water Commission (CWC)	# Bodeli # Chandwada (last site before Orsang meets Narmada)	SWDC	# Bodeli # Chhota Udeypur
		Central Ground Water Board (CGWB)	Observation sites at Pavi, Bodeli, Chhotaudepur, and Kevdi	GSWMA SWDC	Observation sites in Chhota Udeypur, Pavi Jetpur and Sankheda blocks
		CGWB	Different blocks in Vadodara district	GSWMA SWDC	Different blocks in Vadodara district
Reservoir Data	Water inflows 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	Central Design Organization (CDO) Gandhinagar	-	State Water Resources Department	Sukhi dam

A team member was dedicated to secondary data collection and worked for two months, from mid September to mid November, to collect all the required information. Data collection was not easy and was time-consuming, as the information had to be procured from different government agencies. This process is briefly described below:

- **Meteorological, hydrological and groundwater data:** The Gujarat State Water Data Centre (SWDC) provided most of the required information,[18] there were some gaps, especially in the meteorological data. For instance, rainfall data was available only for monsoon months while only data for sunshine hours was available and not for solar radiation. The Indian Meteorological Department (IMD) only had a few rain gauge stations in the selected catchment and none upstream of the Sukhi reservoir. The Central Water Commission (CWC) maintained the river gauging site at Bodeli on the Orsang river (the outlet point of the catchment) but no data was available for this site.
- **Sukhi reservoir data**: The Central Design Organization (CDO), Gandhinagar, had data collected at 15-day intervals, and even this was not complete. Following the suggestion of a CDO official, the District Panchayat Office in Vadodara was approached, who suggested the Divisional Irrigation Office at Bodeli. The Bodeli office was able to provide data for the Sukhi reservoir (on capacity, outflows, estimated inflows etc.) taken at 10-day intervals, etc.
- **Remotely-sensed satellite data:** Setting up of SWAT model need raster data (or 'shape' files) for the Digital Elevation Model (DEM), land use/land cover and soil type as a minimum requirement.
  - ***Shape files:*** While some information was available on the India WARIS website of the MoWR, downloading this data required permission from the MoWR. The GSWMA could only get this data from the state remote-sensing agency, the Bhaskaracharya Institute for Space Applications and Geo-Informatics (BISAG), but their request did not succeed initially as it was for a study and not for regular departmental operations. GSWMA was finally able to get the required shape files of watershed boundaries as received from BISAG.
  - ***DEM:*** The study team requested the National Remote Sensing Centre (NRSC), Hyderabad for the DEM and one of their scientists helped the team download it from the Bhuvan website (maintained by NRSC for DoLR).
  - ***Land use/Land cover:*** NRSC however could not directly provide the requested Land Use/Land Cover data, and suggested that a request be routed through GSWMA. Based on a formal request and undertaking by the Head of the GSWMA, the spatial data on land use and land cover was obtained from NRSC.
  - ***Soil type and soil profile:*** Initially the Central Soil and Water Conservation Research and Training Institute (CSWCRTI) in Vasad, Gujarat, and the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Bangalore were approached for spatial data on soil type and soil profile of the selected catchment but the data could not be procured. GSWMA was requested to get this information from BISAG and this was finally made available.

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.

18 As the State Water Data Centre is under the Department of Water Resources and the SLNA under the Department of Rural Development, and because this information was being requested for a study and not as part of official work of the SLNA, an official letter from the Water Resources Specialist at the World Bank, New Delhi office, had to be sent to SWDC and the Secretary of the Department to get the data.

TABLE 3.2 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
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 socio-economic, 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 of 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

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 catchment and the impact of these interventions on resource conservation and on livelihoods (including crop yields and returns). These five selected villages comprise seven different sub-watersheds as delineated by the SWAT model using global datasets.

The initial field visit by the team in mid-September 2014 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 DWDU staff and villagers revealed that the Gram Panchayats wanted more large check dams (seeing the benefits from the ones already constructed). Since there was little room left for more (large) structures in the flatter areas, they were planning to use funds under all 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 3.2).

A field team member was dedicated to this task and the primary data collection was completed in parallel with the secondary data collection, in two months from mid-September to mid-November 2014. The primary data collection from the five villages in a part of the Upper Sukhi Catchment 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.

Basic Analysis

The collected data were used not just as inputs into the modeling process but were also analyzed separately. The main findings are summarized below.[19]

Catchment Characteristics

Soils: The main soil types in the catchment are Haplusteps (Figure 3.3). 50% of the catchment area is Udic Haplusteps, 40% Lithic Haplusteps, and 8% Fluventic Haplusteps, while the rest consists of rocky areas. In terms of soil depth, 40% of the catchment has shallow soil (25-50 cm), 42% moderately deep soil (75-100 cm), and 15% very deep soils (150+ cm).

19 Further details are in the Technical Note on SWAT Modeling in Annex 8.

FIGURE 3.3 SOILS IN THE UPPER SUKHI CATCHMENT

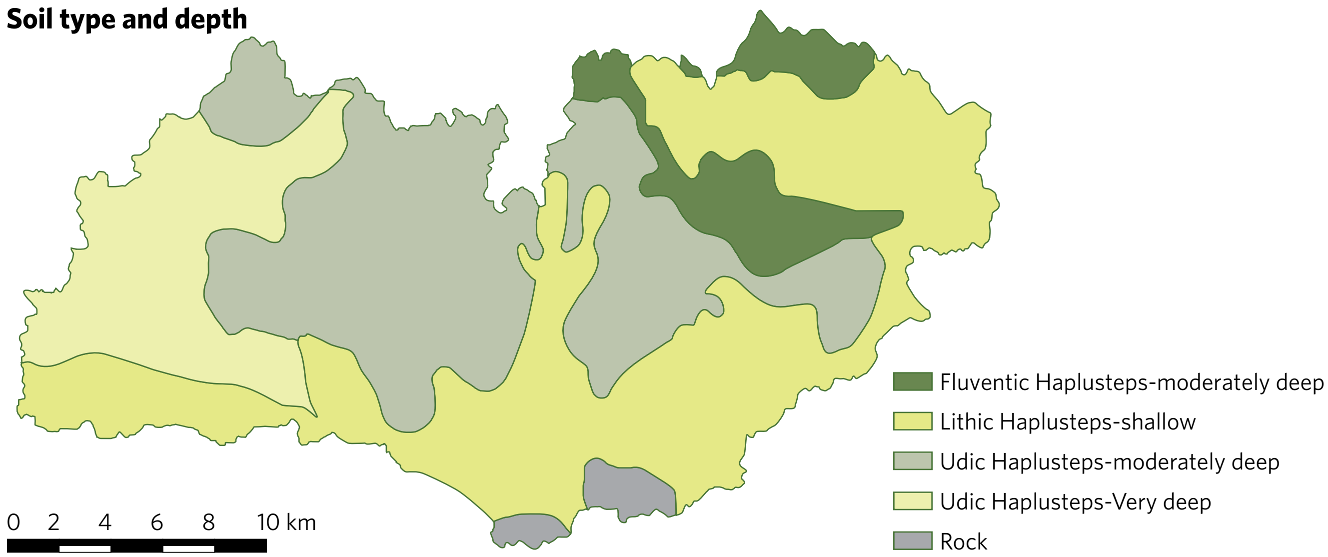
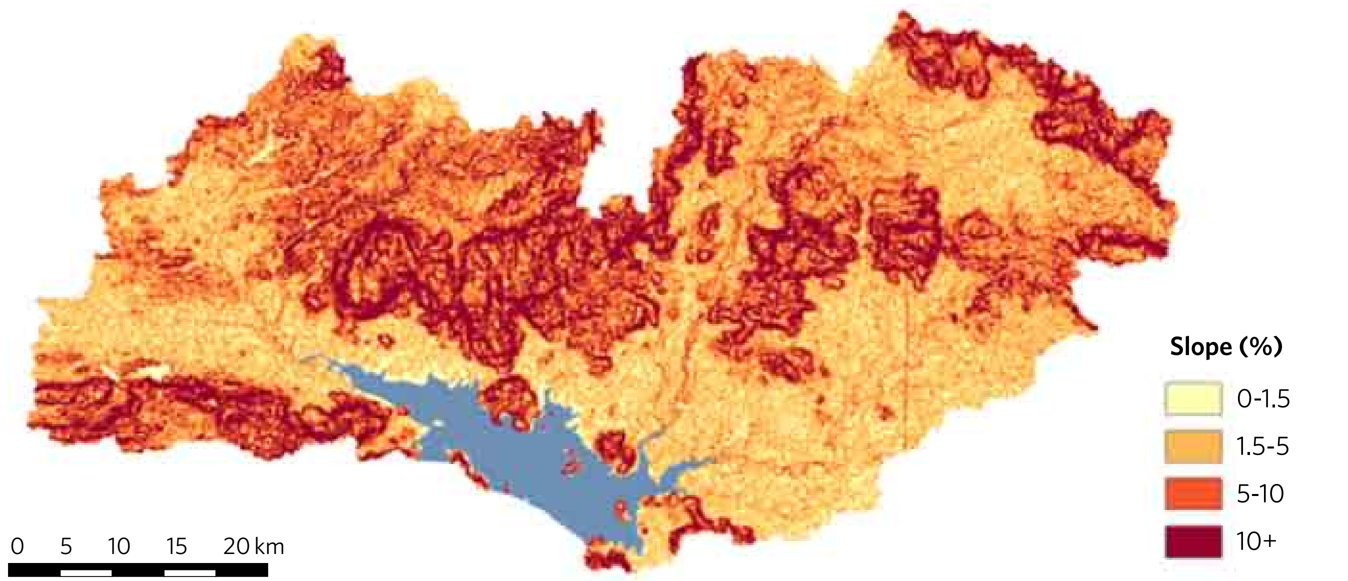


FIGURE 3.4 SLOPES IN THE UPPER SUKHI CATCHMENT



Slope: Elevation ranges from 82 to 460 meters, with the highest areas being located in the center, south-west and north-west of the catchment (Figure 3.4). Large parts of the catchment have steep topography: Around 20% of the catchment has slopes of greater than 10% and 25% of the area has slopes between 5 and 10%.

Rainfall: Average annual rainfall for the study period (1999-2013) was 1062 mm with a standard deviation of 386. Nearly all the rainfall occurs during the monsoon in the months of June, July, August and September. The majority rainfall occurs on days with more than 25 mm of rain (Figure 3.5). 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 RWH structures.

The rainfall in the catchment 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,

FIGURE 3.5 ANNUAL RAINFALL IN THE UPPER SUKHI CATCHMENT

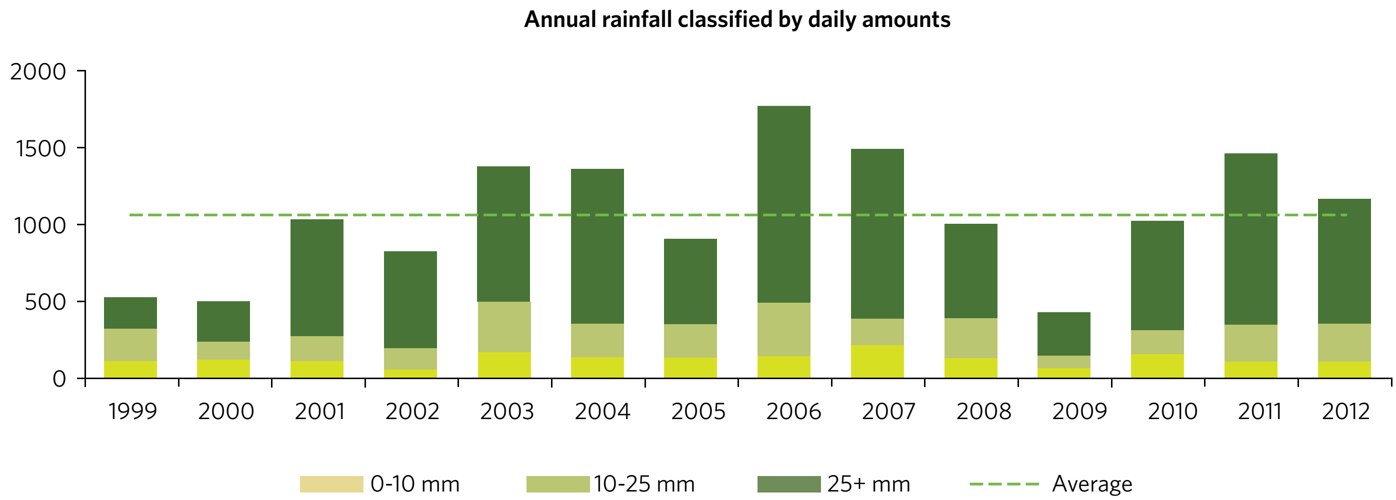
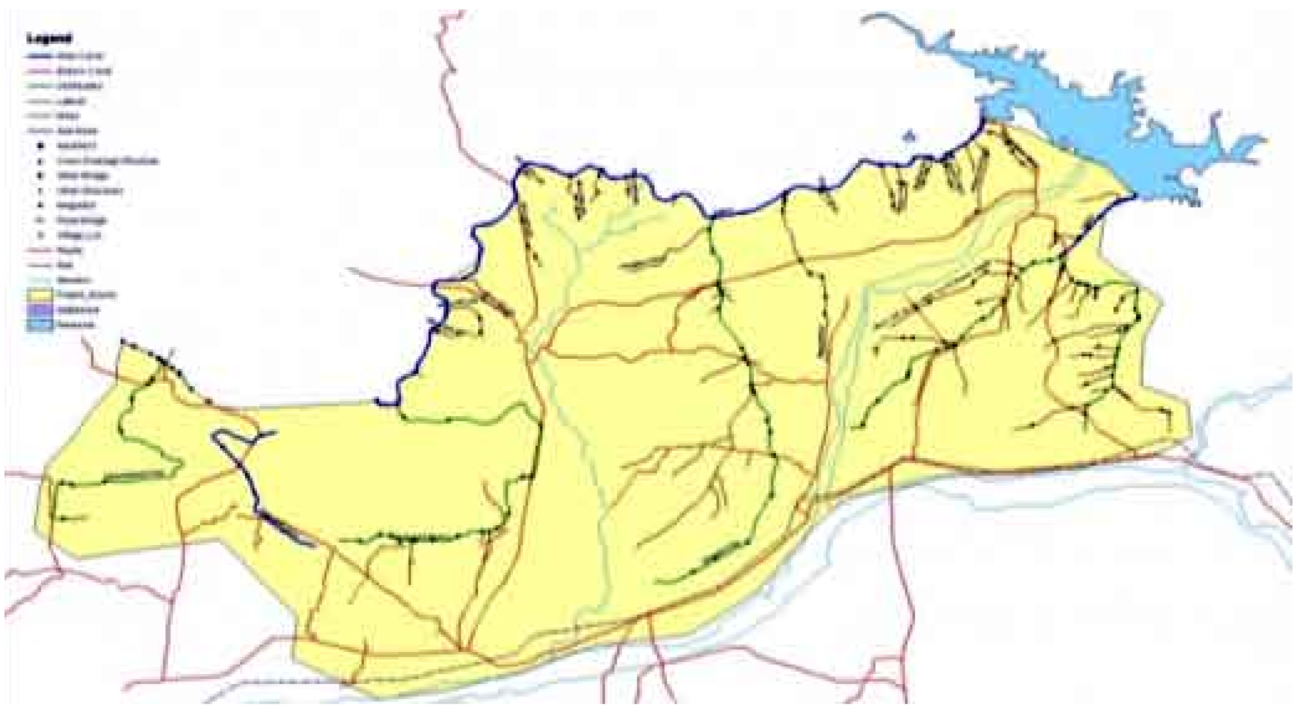


FIGURE 3.6 SUKHI RESERVOIR AND ITS IRRIGATION CANALS



Source: http://india- wris.nrsc.gov.in/wrpinfo/index.php?title=Sukhi_JI01042. Map prepared by NRSC.

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.

This variation impacts inflows into the Sukhi reservoir and, by extension, the water released for irrigation in downstream villages.

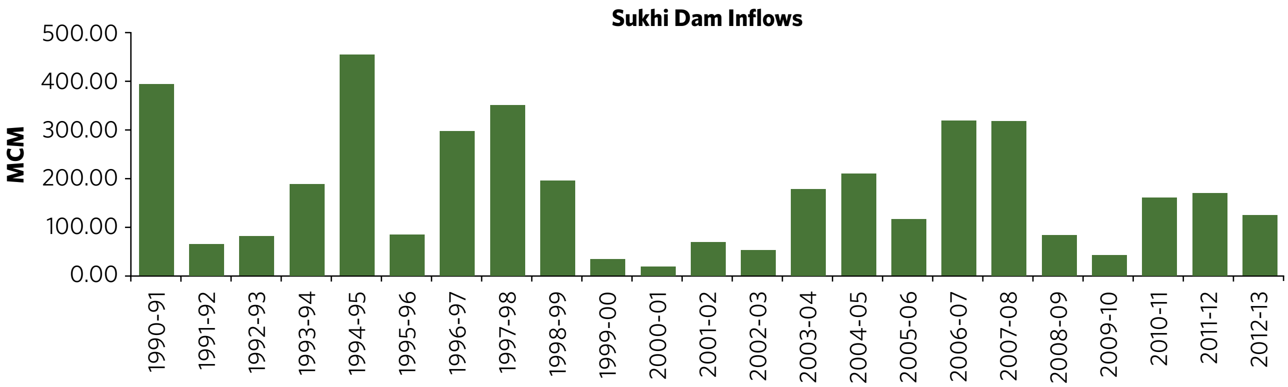
Sukhi Reservoir

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 km^2 when full. Built for irrigation, two canals flow downstream with a total command area of 31,532 hectares Landsat images show that the surface area of the Sukhi reservoir changes dramatically pre- and post-monsoon (Figure 3.7 and 3.8).

FIGURE 3.7 PRE-MONSOON SUKHI RESERVOIR LANDSAT IMAGE 20 MAY 2013

FIGURE 3.8 POST-MONSOON SUKHI RESERVOIR LANDSAT IMAGE 13 OCTOBER 2013

FIGURE 3.9 ANNUAL INFLOWS INTO SUKHI RESERVOIR



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) (Figure 3.9).

Village information

Elevation and topography: The five villages surveyed, Kevdi, Dholisimel, Dungarbhint, Kundal and Ghata, are situated towards the center of the Sukhi catchment and are contiguous, with Kevdi being the uppermost and Kundal and Ghata edging the Sukhi reservoir (Figure 3.1). The villages are characterized by large elevation ranges and steep topography (Table 3.3). 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 dominant land use and steeper areas (e.g., in Kevdi) that are mainly covered by forest.

TABLE 3.3 VILLAGE AREAS, POPULATION, ELEVATION AND SLOPE

	Kevdi	Dholisimel	Dungarbhint	Kundal	Ghata
Area (km²)	12.87	3.73	5.17	10.52	5.33
Population (2010)	1136	956	1326	1723	390
Minimum elevation (meters)	114	104	91	84	90
Maximum Elevation (meters)	292	275	202	279	321
Percentage of village area with slope between 0–5°	50	49	62	55	35
Percentage of village area with slope between 5–10°	26	31	21	25	25
Percentage of village area with slope greater than 10°	24	20	17	20	40

Land use: 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 stayed relatively stable through the study period.

Cropping patterns: The main crops include cotton, rice and maize during the monsoon *(Kharif)* season and maize during winter (*Rabi*) season (Figure 3.10).

The major change in cropping pattern over three periods, 2004-05, 2008-09 and 2012-13 (for which land use data was procured from NRSC) is a large shift from *Kharif* crops only to double crop agriculture – most evident for the two villages closest to the reservoir, Ghata and Kundal (Figure 3.11). While in 2004-05 the majority of agricultural land is *Kharif* crops only for all villages (apart from Ghata where the areas of double cropping and *Kharif* crops only agriculture are relatively similar), in 2008-09 and 2012-13 all the villages see a major shift to double cropping.

FIGURE 3.10 MAIN CROPPING PATTERNS IN THE FIVE VILLAGES

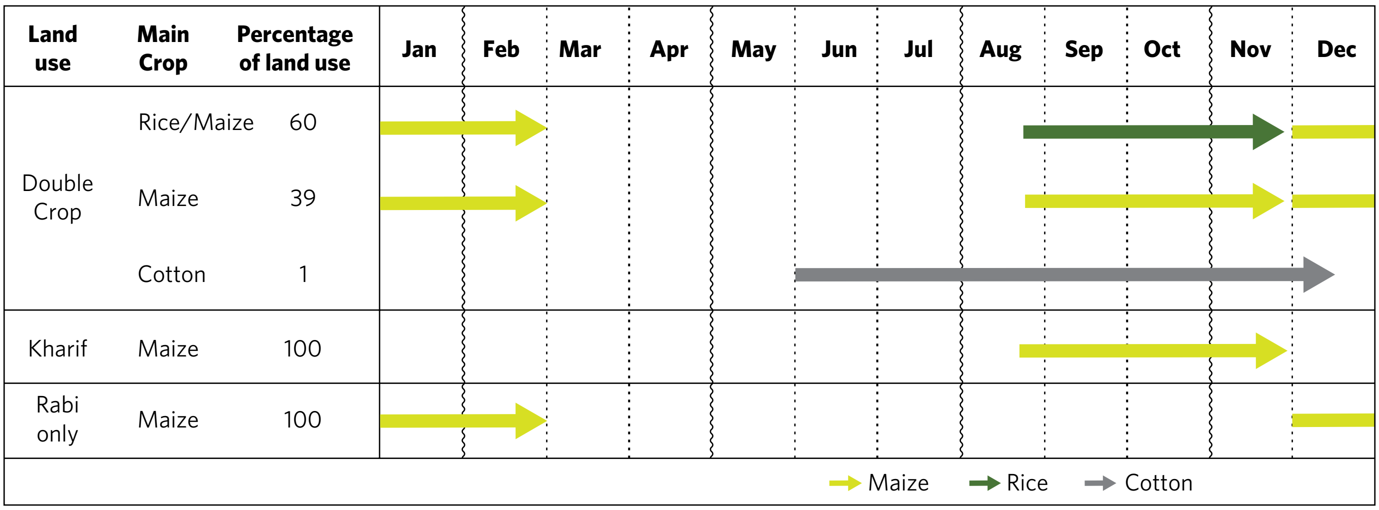
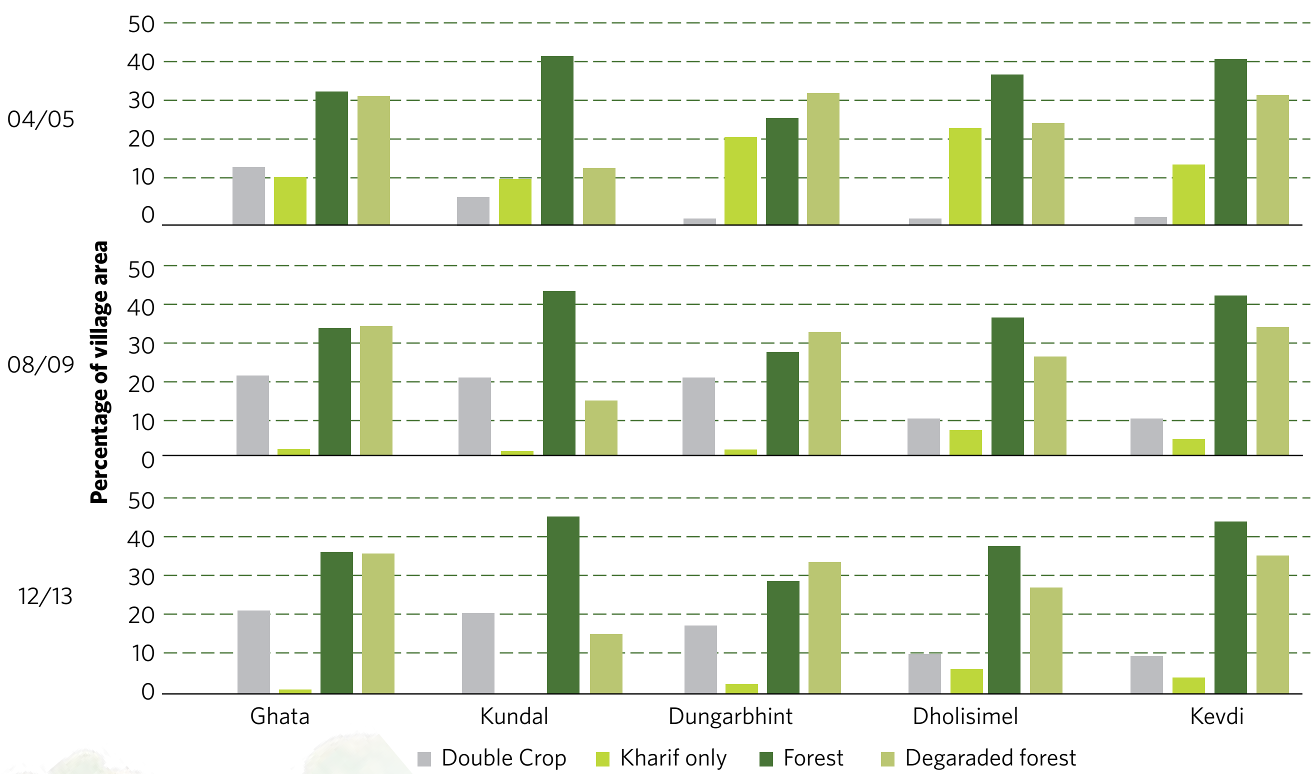


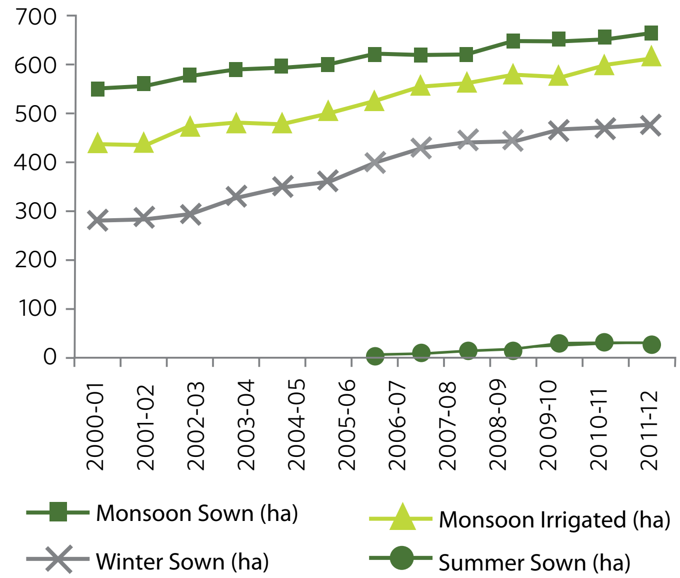
FIGURE 3.11 CHANGES IN CROPPING PATTERN IN THE FIVE VILLAGES



Village-level discussions and cropping data from local government sources (Figure 3.12) confirmed these 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 *Kharif* and *Rabi* seasons, replacing single-season cotton. Also, groundnut is a minor summer crop introduced in 2006-7 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.

FIGURE 3.12 SOWN AND IRRIGATED AREAS IN THE FIVE VILLAGES



Wells and rainwater harvesting structures: The village survey recorded the location of all RWHs and wells in the five villages, using a hand-held GPS device. For each, a range of attributes were collected including type, date of construction, condition, funding source, and cost.

Wells: There are 402 wells in total, of which 70% are dug wells and 30% bore wells, giving a well density of

FIGURE 3.13 WELL TYPES AND STATUS FOR THE FIVE SURVEYED VILLAGES

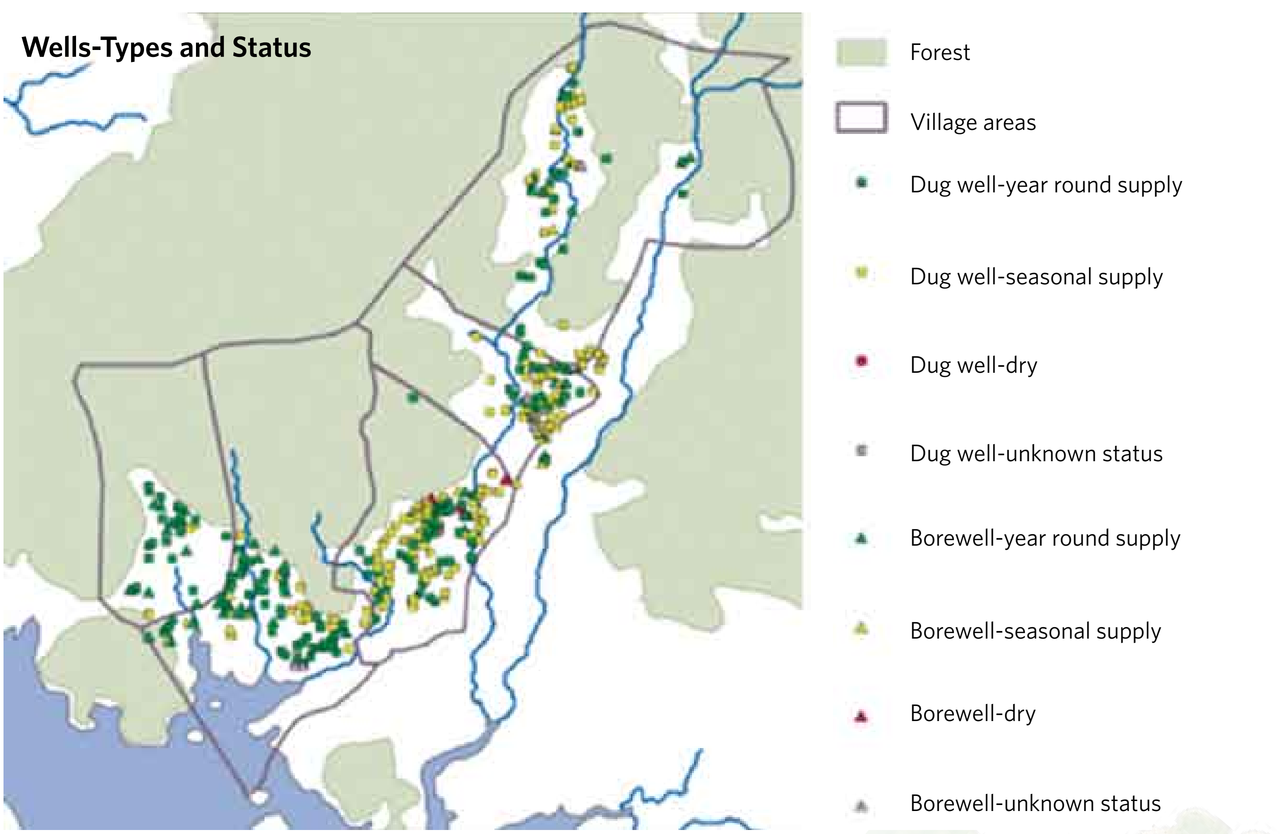
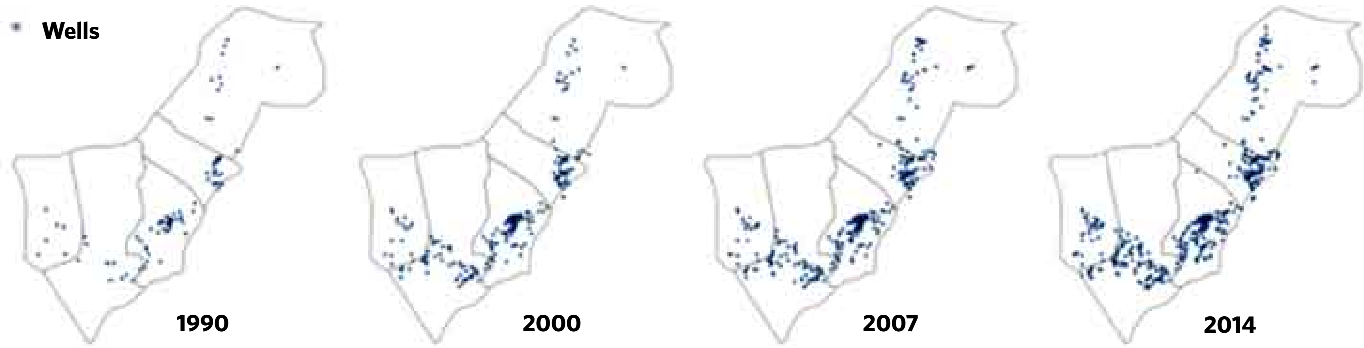


FIGURE 3.14: GROWTH OF WELLS IN THE FIVE VILLAGES, 1990 – 2014



roughly 10 per km^2 for the village areas. These wells, however, are heavily concentrated along the drainage channels and very few are located in the forested areas (Figure 3.13).

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 farther 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 (Figure 3.14).

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.

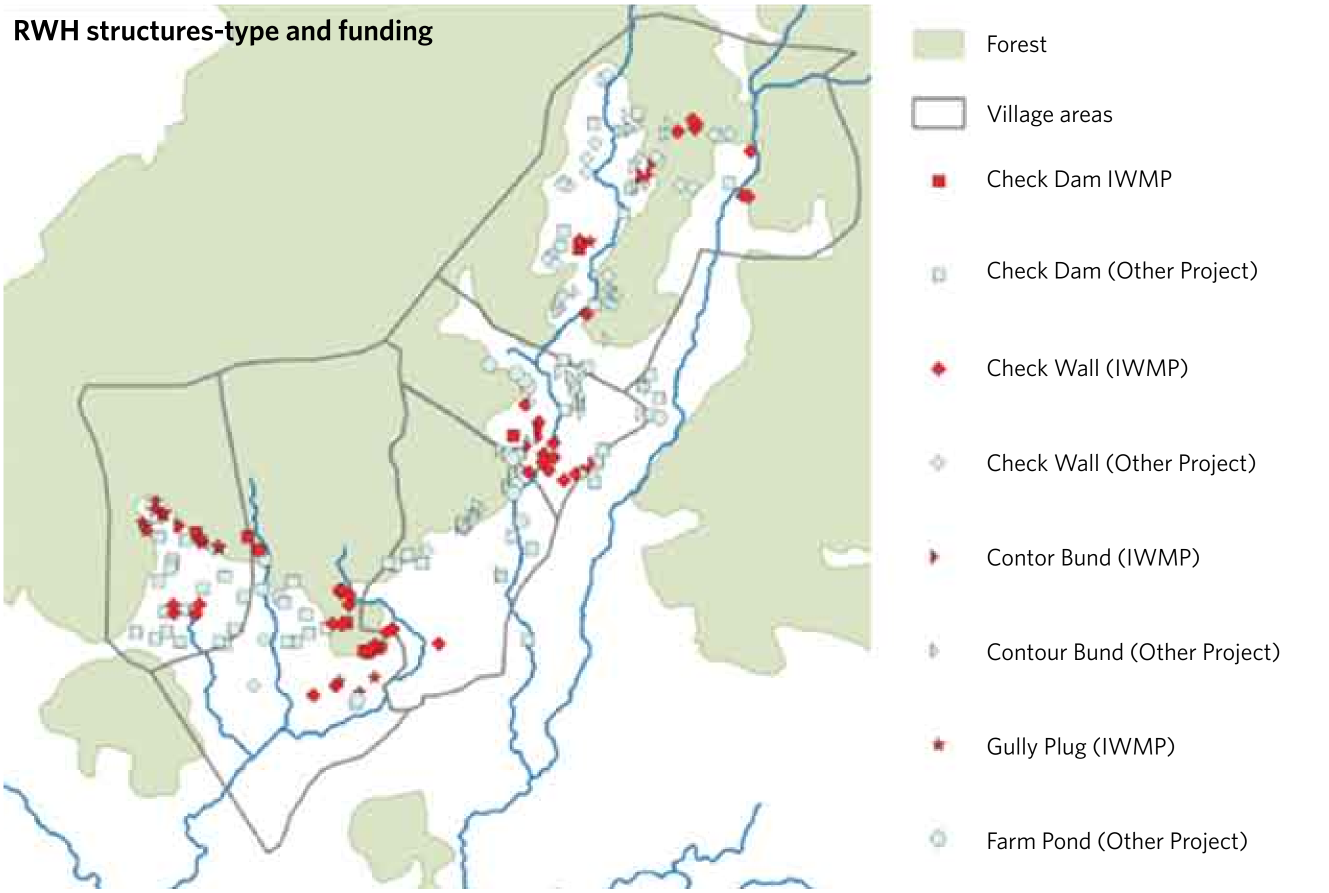
- **Water Harvesting Structures:** In total, the survey mapped 251 RWH structures in the five villages, of which 77 were funded by IWMP. Only 9 check dams, from a total of 72, were funded by IWMP, as the most optimal locations had already been used by the time the project started in 2009. No structures 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 (Table 3.4).
- 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 (Figure 3.15).

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

TABLE 3.4 RAINWATER HARVESTING STRUCTURES IN THE FIVE VILLAGES

Type of Structure	Total Number	Built by IWMP	Built by Other Projects
Check Dam	72	9	63
Check wall	72	40	32
Contour bund	71	11	60
Gully plug	17	17	0
Farm pond	11	0	11
Other	8	0	8
Total	**251**	**77**	**174**

FIGURE 3.15 LOCATION OF RAINWATER HARVESTING STRUCTURES IN THE FIVE VILLAGES



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 areas and the number of wells, indicating 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 (Figure 3.16).

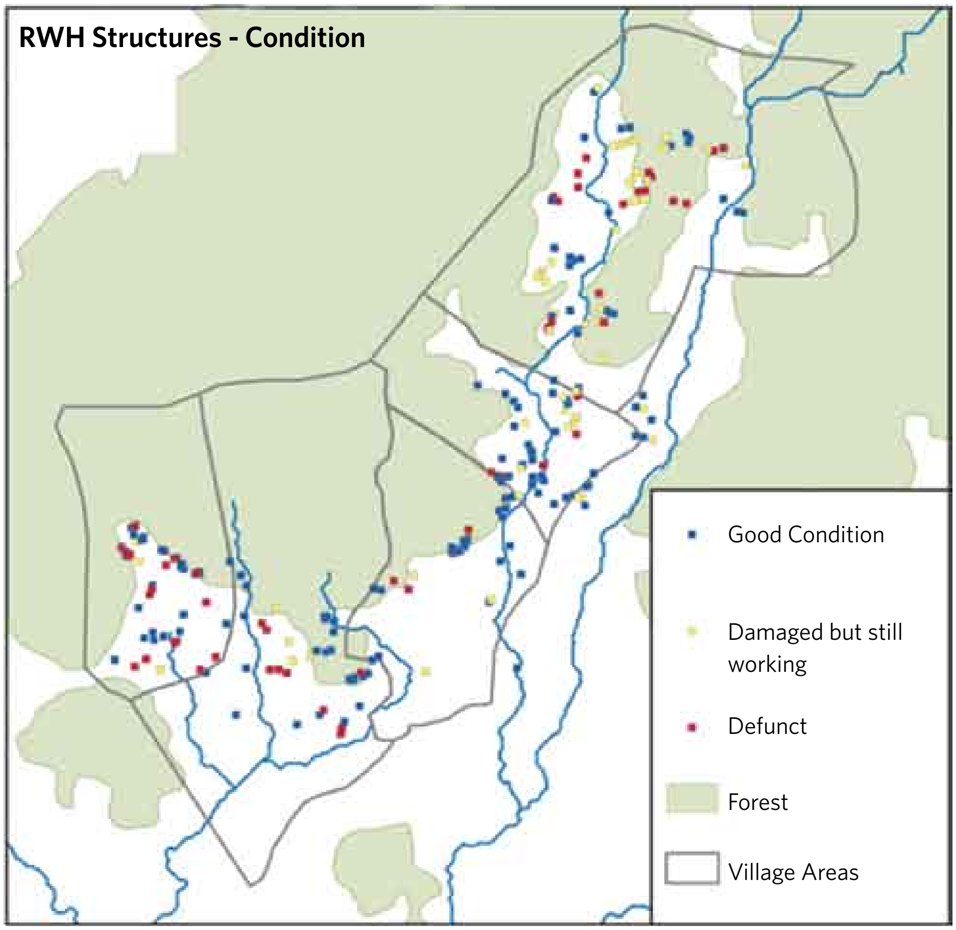
However the survey could not capture structures that were built earlier in the period but subsequently completely destroyed by floods. Kevdi village has the highest proportion of damaged and destroyed structures that can still be observed, and currently there is no check dam still standing on the main 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 (Figure 3.5) and the steep topography of the villages (Figure 3.4) support this observation.

Villagers' perception of water problems

The population of these five villages is largely tribal and poor.[20] Most households (78%) have agriculture as their main occupation while around 15% work as farm labour. Around 60% of farmers have marginal land holdings (less than 1 hectare) while 24% have small holdings (1-2 hectares). 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 Kuchch at the western tip of Gujarat and also to Mumbai.

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

FIGURE 3.16 STATUS OF WATER HARVESTING STRUCTURES IN THE FIVE VILLAGES



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

- **Summer months:** 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 of Kundal and Ghata are able to grow a summer groundnut crop.
- **Drought years**: 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.

Broad picture

The hilly and rocky Upper Sukhi Catchment 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 catchment 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 to supplement their livelihood after the monsoon *Kharif* crop.

Watershed management in this catchment has to take account of the following:

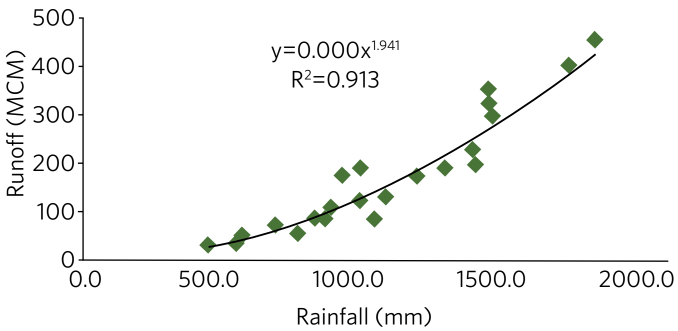
- The relative lack of treatment of the uppermost parts of the catchment which are forested, uninhabited, and directly under the control of the state Forest Department.
- A large number of structures already built on the (smaller) drainage lines, implying that there are few suitable sites left to build more 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 branches and boulders carried by the monsoon rainwater, and there is not much space in villages to build additional RWH structures.
- There are large variations in rainfall, evapo-transpiration and runoff across dry and wet years which affect inflows into the reservoir which, in turn, affect canal releases to downstream communities.

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

Perceptual Model of the Catchment

Three key aspects from the perceptual model, which informed the setting up of the simulation model, are discussed here (see Annex 8 for details): (1) the relationship between rainfall and runoff (2) estimates of evapo-transporation and (3) groundwater fluctuations.

FIGURE 3.17 RAINFALL-RUNOFF RELATIONSHIP FOR SUKHI CATCHMENT



The Rainfall-runoff relationship in the Sukhi Catchment

Virgin flows for the catchment, i.e., the runoff that would occur from the catchment in the event of no artificial impoundments, were first calculated for a 22-year period from 1991-92 to 2012-13. The estimated relationship between total annual rainfall and estimated total annual virgin flows (runoff) best fitted a power function (the 'goodness of fit' was indicated by the high R^2 value of 0.915 (Figure 3.17).[21]

A power function suggests that if rainfall increased by 1 unit, runoff would increase exponentially, i.e., by much more than 1 unit. The good fit of the regression indicates that the rainfall-runoff model is robust and can be used as an effective tool for prediction of virgin flows (runoff) from the catchment, for measured values of annual rainfall. It can also be used to generate stream flow scenarios, for droughts and abnormally wet years. However, the model predictions could be weaker, once the land use in the catchment undergoes significant changes during the period considered for the modeling.

Estimation of evapo-transpiration

Evapo-Transpiration (ET) is another key input into a simulation model, being the amount of water lost to the atmosphere due to evaporation and transpiration

21 Generally speaking, the R^2 value indicates the 'goodness of fit' of the posited relationship between independent and dependent variables and its value ranges between 1 for a perfect fit and 0 for no fit. More technically, the R^2 indicates the proportion of the variation in the observed values that are explained by the regression (line).

through flora such as grasses, crops, shrubs and trees. The greater the water lost through evaporation from water bodies and through the transpiration from biomass (grass, shrubs and trees) the lower the runoff, generally, and in this case, the inflows into the Sukhi reservoir.

Data on mean temperature and wind speed (from one of the three weather stations downstream from the Sukhi catchment) were used to estimate the Potential (or reference) Evapo-Transpiration (PET) using a simplified Penman-Monteith equation, a method that generally gives better results when used in the simulation model. This method also requires estimates of daily solar radiation, which was also obtained from sunshine hours (using a cumbersome manual calculation). The PET estimated for all days of the year for a 15-year period showed (1) large variations across the years – from as low as 2.5 mm per day during winter to 10.0 mm per day during summer months; (2) considerable variation in total PET from year to year (Figure 3.18).

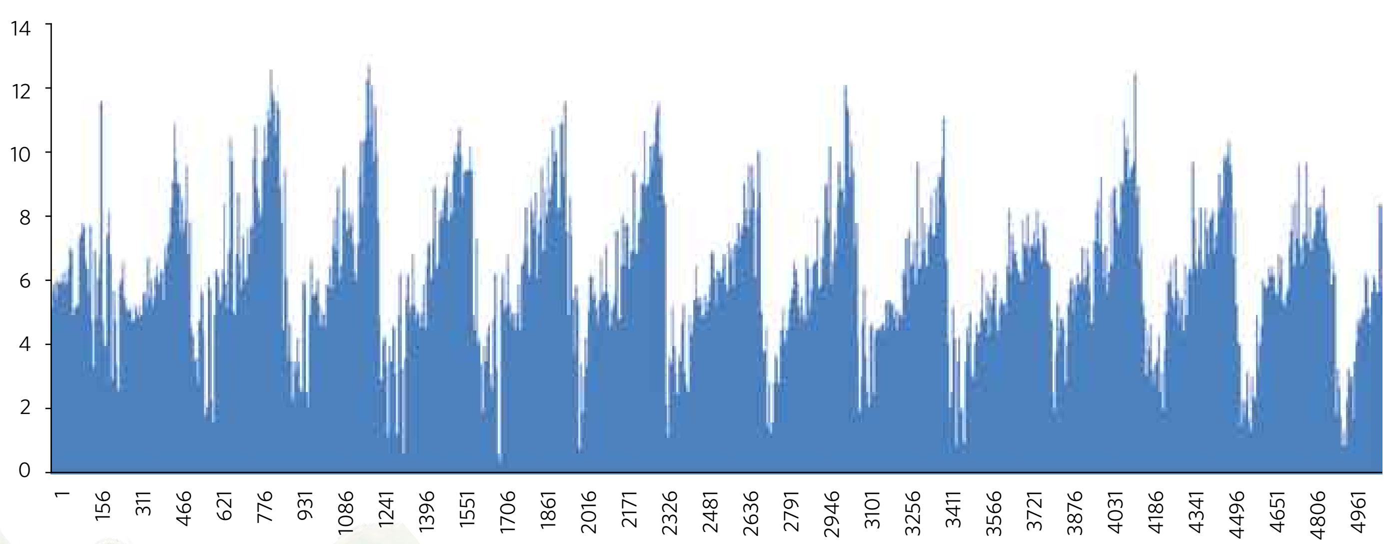
Groundwater flows in the catchment

The way in which the SWAT model handles groundwater is simplistic and, as mentioned earlier, the catchment selected was too small to get sufficient secondary data to run a supplementary groundwater model such as MODFLOW. The perceptual model, however, provided some insights that could be used to improve the simulation modeling using SWAT.

A key component of the hydrological behavior of a catchment is how groundwater storage changes over time, particularly with respect to rainfall. The main finding from 30-year data (1984 to 2013) on groundwater levels, pre-monsoon (May) and post-monsoon (October), for 18 locations in the catchment as well as from four observation wells selected for detailed analysis (in Ambala, Chhota Udepur, Ferkuwa and Kevdi) are the following:

- **There is significant inter-annual variability in 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 catchment gets discharged after the monsoon, in spite of the steep terrain.
- **Water level fluctuation is greater for very low rainfall than for abnormally high rainfall:** The four observation wells selected for detailed analysis (Ambala, Chhota Udepur, Ferkuwa and Kevdi) showed that the highest water level fluctuation was in a drought year (1987, when the values varied from 3.05 m to 0.47 m), and was much less in an abnormally wet year (1988, when the values varied from 6.37 m 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,

FIGURE 3.18 ESTIMATES OF DAILY POTENTIAL EVAPO-TRANSPIRATION IN THE SUKHI CATCHMENT, 1999-2012



which helps store extra water in the formation from the deep percolation.

- **The post-monsoon 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 post-monsoon 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 an increase in the number of wells and bore wells in the area and a presumable 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.

The option in SWAT to use expert knowledge to specify some parameters was used to incorporate these insights from the perceptual modeling.

Simulation Model of the Catchment

The aim of the hydrological assessment was not just to understand the key hydrological features of the catchment 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 catchment dynamics well can it (and should it) be used to generate scenarios of potential impacts.

Since past experience suggested that data collection would take time, the team decided to start the modeling using freely-available global datasets 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, showed how well the values predicted by the model matched the observed values of inflows into the Sukhi reservoir (see Box 3.2 for the basic steps in modeling, which are detailed in Annex 8).

The modeling approach was discussed with Prof. Ashwin Gosain of IIT Delhi on 7 November 2014 and Dr. Durga Rao of NRSC in Hyderabad on 12 November 2014 when the team was in Hyderabad (8-14 November 2014) to clean the data, finalize the approach and work on the modeling. The first set of results, using the global datasets and some national and state data, were presented at a Technical Meeting on 15 November 2014.

Model run with global datasets

The model set up in SWAT with global datasets (see Box 3.3) was 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 (Figure 3.19).

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 (Figures 3.20 and 3.21). (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).

BOX 3.2 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 is 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.

BOX 3.3 GLOBAL DATASETS USED

- Aster GDEM (30 meters) – 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 the 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 meter 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.

FIGURE 3.19 UPPER SUKHI CATCHMENT FROM GLOBAL DATA

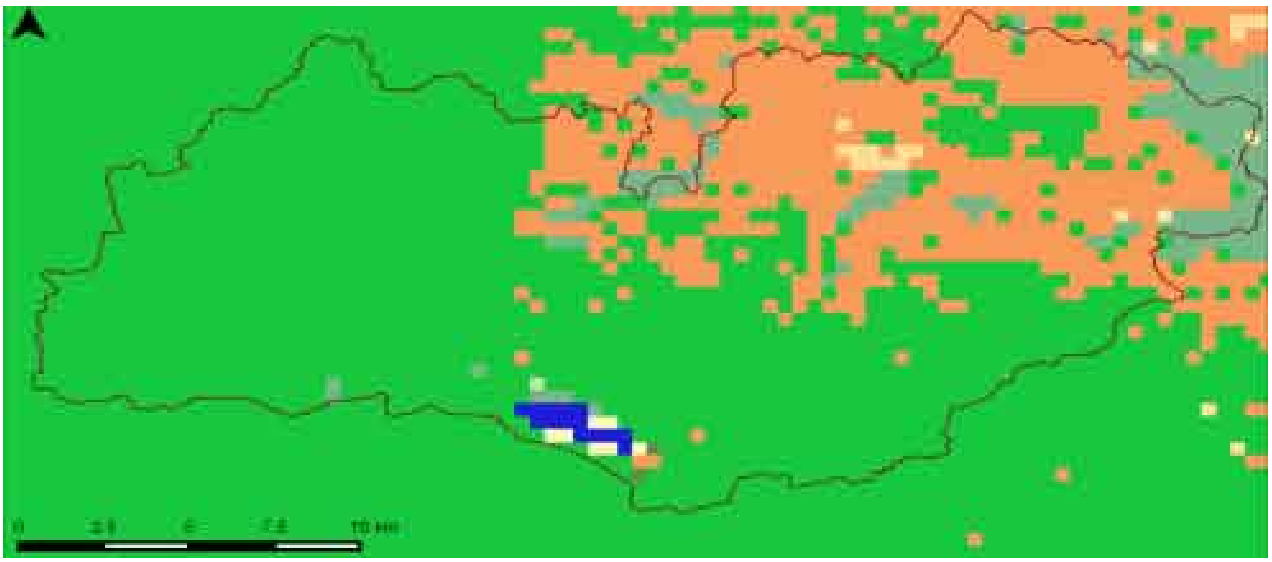


FIGURE 3.20 MONTHLY INFLOWS INTO THE SUKHI RESERVOIR, 1991-2012, GLOBAL DATA

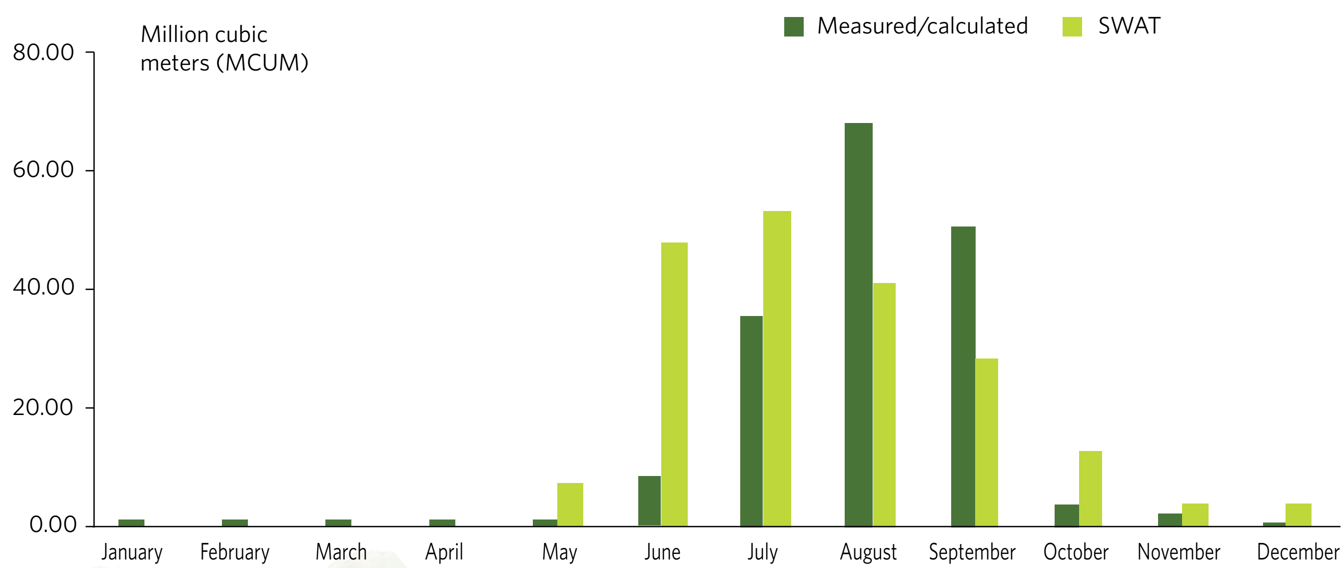
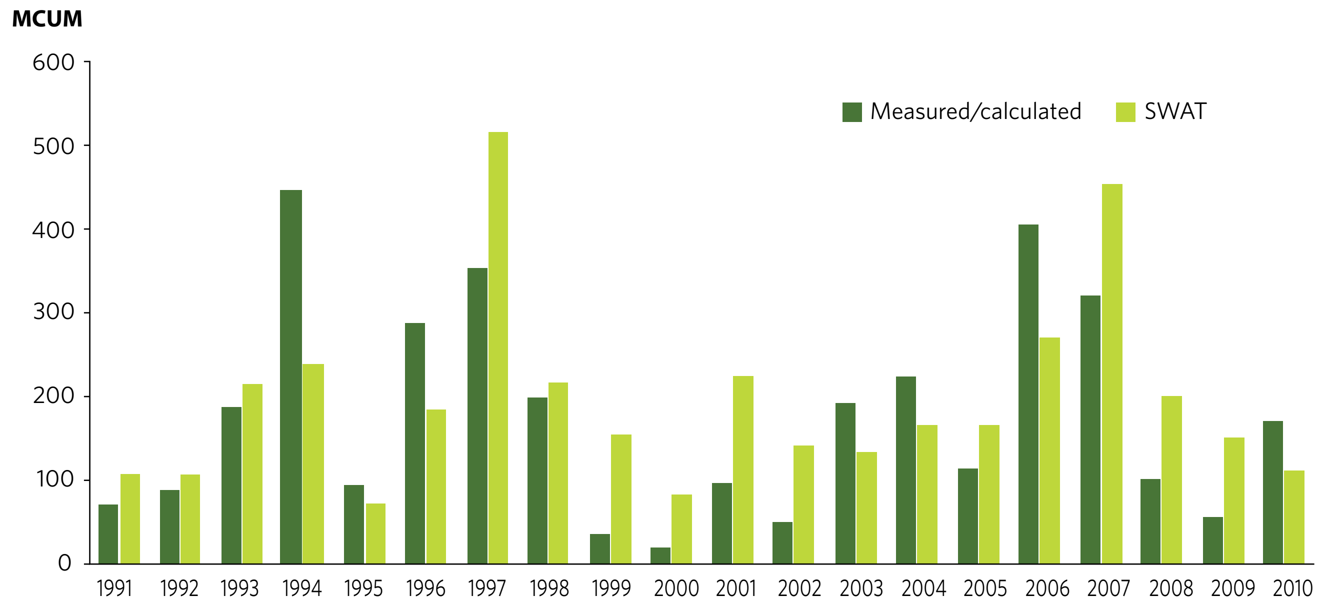


FIGURE 3.21 ANNUAL INFLOWS INTO THE SUKHI RESERVOIR, 1991-2012, GLOBAL DATA



Model Run with Improved Datasets

With the inclusion of some national and state data (32-meter 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 (Figures 3.22 and 3.23).

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 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 (Figures 3.24 and 3.25).

These findings were discussed at the Technical Meeting of 15 November 2015 (see Annex 6 for details) and the Study Team addressed as many of the suggestions made as possible[22] while continuing the modeling with improved datasets in the two weeks till end-November. The findings were presented at the National Workshop held at the World Bank office in New Delhi on 1-2 December 2015 (see Annex 7 for details).[23] During these two weeks, the Study Team also carried out a series of stakeholder meetings and discussions in the five study villages, culminating in a multi-stakeholder meeting in the Kevdi Eco-Lodge, Chhota Udeypur, attended by GSWMA staff from the state office in Gandhinagar, staff from the DWDU in Chhota Udeypur, officials from the Forest Department implementing the IWMP projects in the Upper Sukhi Catchment and representatives from the five villages chosen for detailed study. The findings of these stakeholder meetings were also presented in the National Workshop on 1-2 December and are discussed in the next sub-section.

Model final run

After replacing all the global data with national, state and local data, including those from the primary survey (see Box 3.4), the outputs from the final run of the model were much better.

22 See section 8 of the Technical Note on SWAT Modeling in Annex 4 for details of the assumptions and methods used to improve the model.

23 According to the original work plan, this was the last workshop planned for the study after which the outputs were to be written up and the Report submitted.

FIGURE 3.22 MONTHLY INFLOWS INTO THE SUKHI RESERVOIR, 1991-2012, IMPROVED DATA

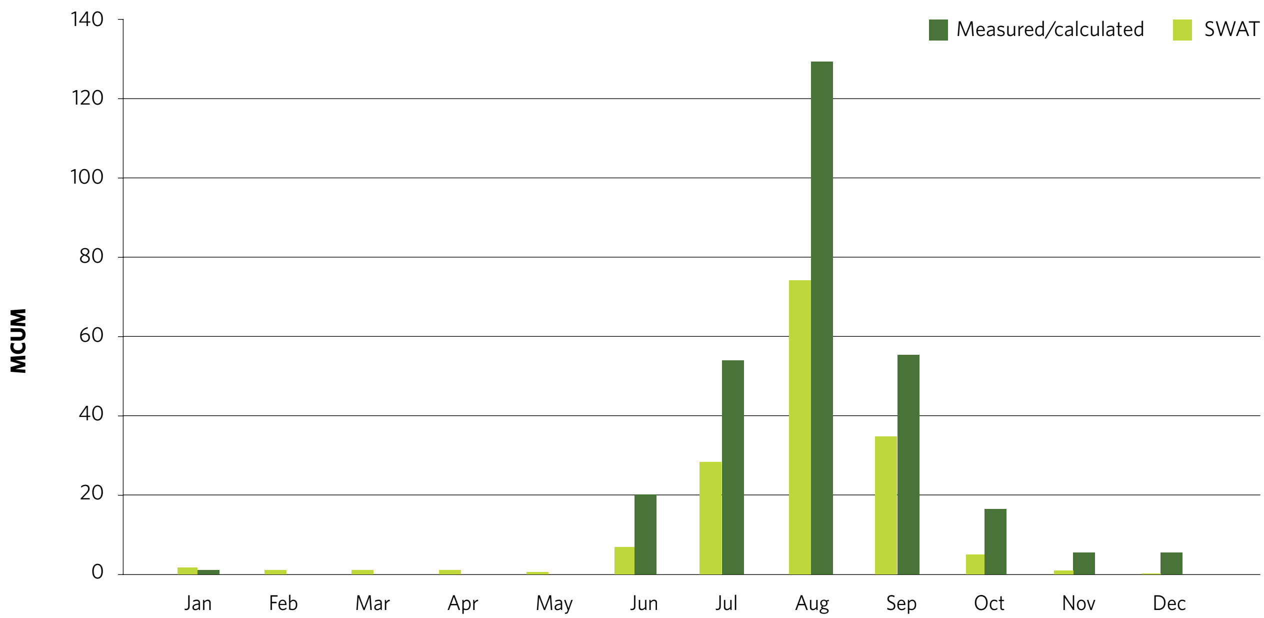
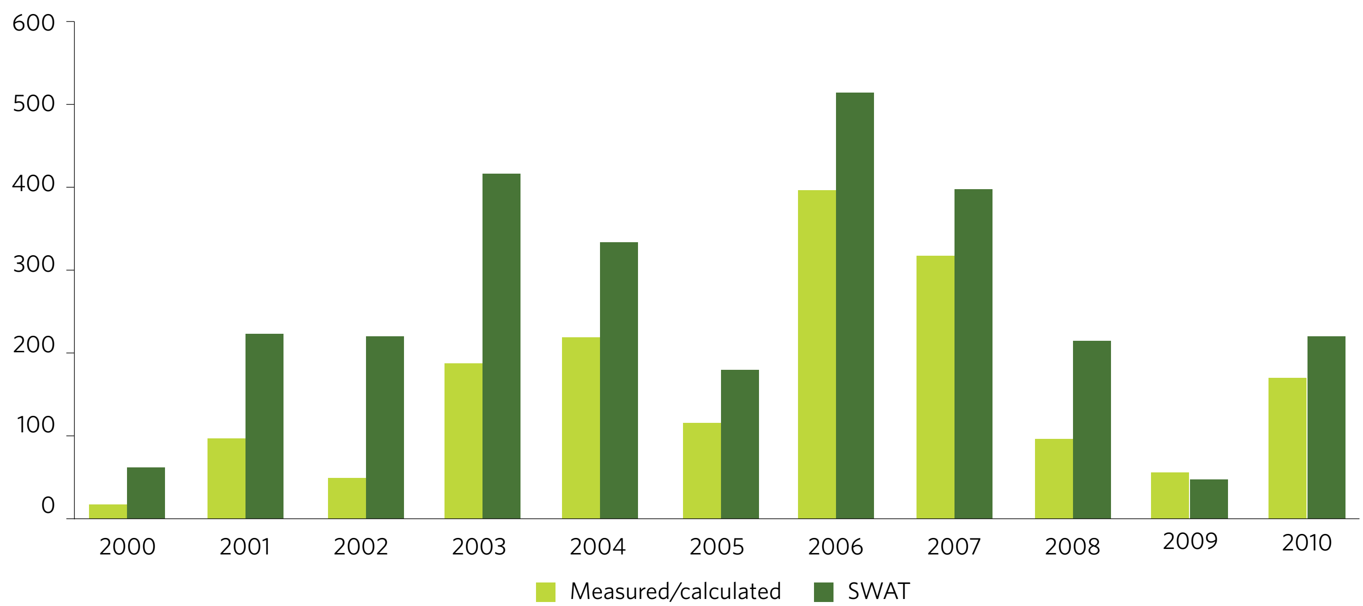


FIGURE 3.23 ANNUAL INFLOWS INTO THE SUKHI RESERVOIR, 1991-2012, IMPROVED DAT



The final results showed that the model simulation of monthly inflows into the Sukhi reservoir was a good match to the actual data (Figure 3.26).

The main results showed that the model captures the dynamics of the catchment quite well – as indicated both by excellent NSE and R^2 values and visual comparison of the observed and simulated reservoir inflows. 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 catchment and at lower elevations; (2) the observed reservoir inflow data used for calibration, which was not measured directly but calculated (by the Water Resources Department staff at the dam site) using a water balance equation and is 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

FIGURE 3.24 GOODNESS OF FIT OF THE MODEL FOR MONTHLY INFLOWS, GLOBAL AND IMPROVED DATA

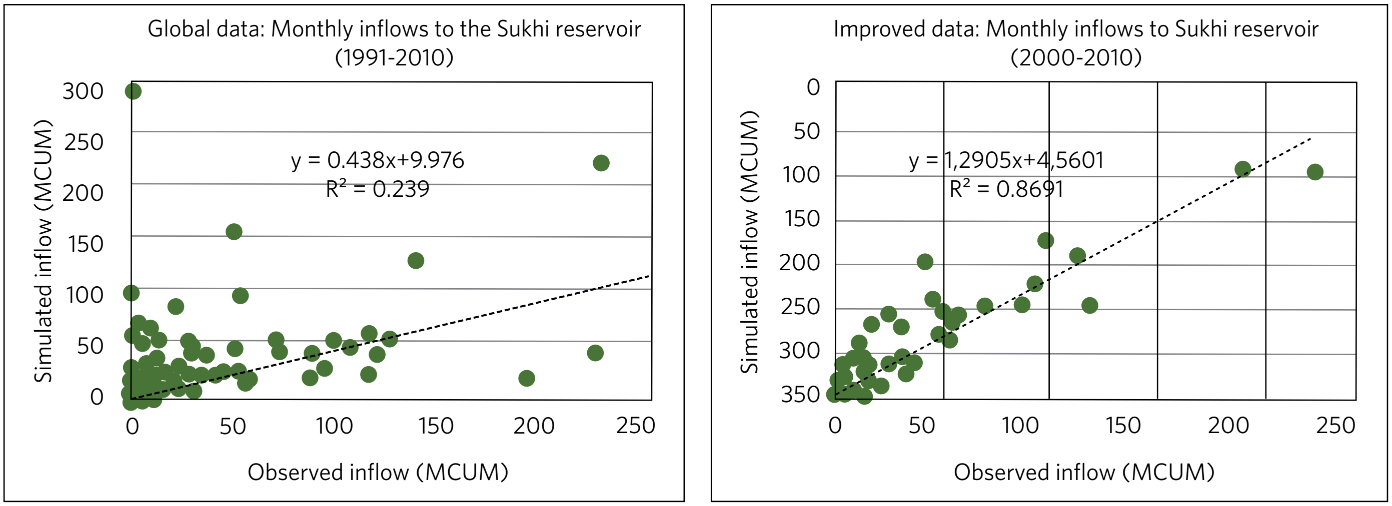
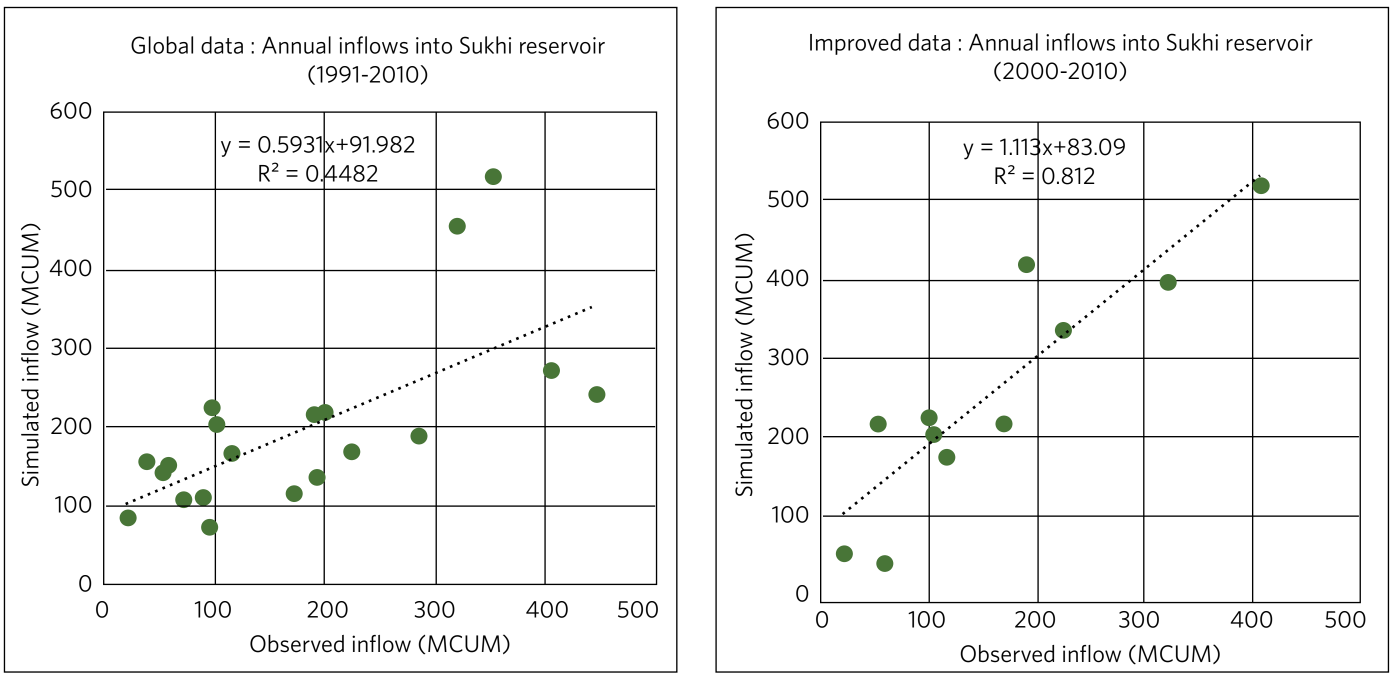


FIGURE 3.25 GOODNESS OF FIT OF THE MODEL FOR ANNUAL INFLOWS, GLOBAL AND IMPROVED DATA



BOX 3.4 MAIN DATA USED IN THE FINAL MODEL RUN

Digital Elevation Model (DEM): CartoDEM from NRSC with 30 meter 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.

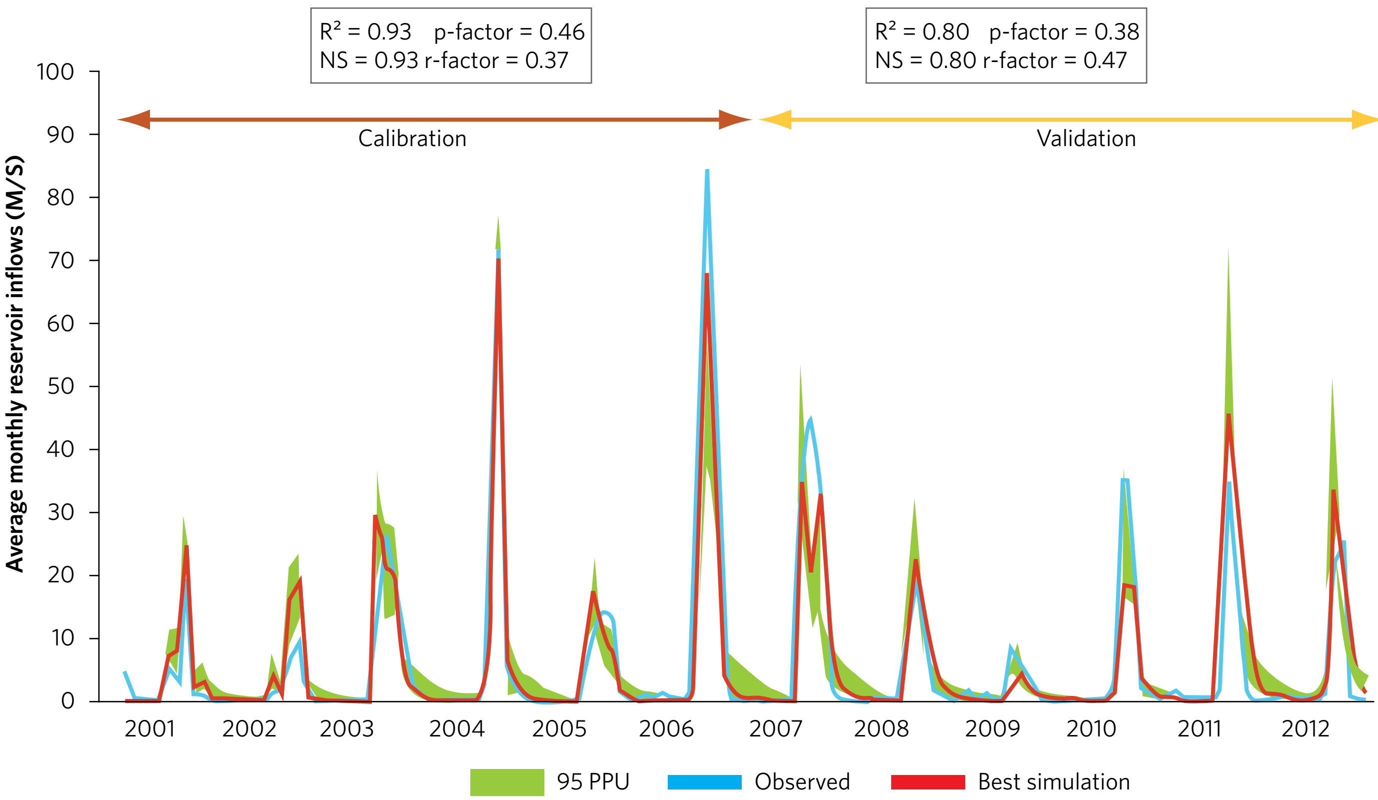
Climate data: Rainfall data from the three local weather stations nearest to the catchment and minimum and maximum temperatures, wind speed, solar radiation and relative humidity from one station (Dhandhodi).

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.

FIGURE 3.26 FINAL MODEL SIMULATIONS AND ACTUAL MONTHLY INFLOWS INTO SUKHI, 2000 – 2012



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 was however was adjudged ready for simulations, which are discussed further below.

Stakeholder Consultations

Interactions with stakeholders from the five villages were conducted, individually, and collectively, in the last two weeks of November by team members. At the multi-stakeholder meeting on 28 November 2014, chaired by the CEO, GSWMA, four key areas were discussed:

- *Community planning and co-management of water resources:* The basic idea was of *co-management of local water resources* by the village communities and the government.[24] The current practice is of government departments asking villagers to participate in various government development schemes (including MNREGS, drinking water supply schemes and the IWMP) by attending meetings, finding suitable locations for interventions and contributing labour, material and cash towards construction and maintenance. Instead, the co-management approach focuses on facilitating villagers to form their own plan for

24 This idea, contained the 2010 State Water Policy of Rajasthan, was further elaborated during the 3-day workshop in December 2013 in Jaipur, Rajasthan state, of representatives from five water-related government departments (the State Water Resources Planning Department (SWRPD), Water Resources Department (WRD), Public Health Engineering Department (PHED), Groundwater Department (GWD) and the *Panchayati Raj* and Rural Development Department (PR&RD) of the state of Rajasthan) and three training institutions (the Communication and Capacity Development Unit (CCDU) of the PHED, the Irrigation Management Training Institute (IMTI) of the WRD and the Indira Gandhi Panchayati Raj Sansthan (IGPRS) of the PR&RD, to finalize the Training Manual on Local-Level Integrated Water Resources Management (IWRM) under the European-Union State Partnership Programme (EU-SPP) in Rajasthan, which was finalized in May 2014 (EU-SPP, 2014).

water resource development and management to address the multiple-use water requirements (domestic water for humans and livestock and irrigation) of the village and asking government departments which of their schemes could help create the planned infrastructure.[25] The plan would also cover management of village water resources, thus allowing the inclusion of traditional knowledge of water management into the planning process.

- *Creating decentralized and flexible water storage in each village:* Given that the villagers had identified summer water shortages and problems during droughts, another issue discussed was ways to provide supplementary water for drinking, livestock and for *Rabi* irrigation (e.g., last 2 irrigations) in summer. An option discussed was the construction of flexible and decentralized storage (e.g., large or small traditional tanks like *talabs* and *tankhas*) in different parts of the village. An idea discussed– an outcome from the Rajasthan work – was to create supplementary underground storage tanks for each house, each of around 10,000 litres, two of which could provide drinking water for a family of 6 for 10 months. These, however, were not to include structures built on the main streams.
- *Minimal intervention on drainage lines:* Since most structures built in the past on the main streams had been broken by the high velocity of the monsoon streams, these were not considered useful investments any more. Instead, the idea given was to create supplementary storage *off the drainage line* but fed by diverting waters from the main stream during high rainfall years and periods. Such structures would also minimize the reductions in flows downstream into the Sukhi reservoir.
- *Water use productivity improvements:* An important intervention suggested was to improve water productivity (i.e., profit per unit of water), to counter potential reduction in water availability. Such interventions would include micro-irrigation and mulching, both of which would not only reduce the quantity of irrigation but could also reduce the non-consumptive use of water through evaporation from fields. Subsidized drip irrigation kits were already being promoted by the Gujarat Green Revolution Company (GGRC), while plastic mulch was being promoted (along with SRI paddy) in the World Bank supported IAMWARM project in Tamil Nadu.[26]

Local villagers were in general agreement with these ideas, pointing out that their older generations had wanted to build large *talabs* (traditional ponds) in the upstream areas to capture rainwater and recharge village wells. However, they also pointed out two key constraints to implementing these ideas:

- Upstream areas being under the control of the Forest Department, they were unable to get the required permission to build these RWH structures in the upper catchment.
- Land for creating decentralized storage was a problem, since the majority of the land holdings were small (less than 2 hectares) and few farmers could afford to spare the land required to build a *talab* on their lands. Also, very little common land was available in these villages as even the private fields had been cleared with difficulty and the boundary of the Forest Reserve ran alongside most the village boundaries.

Nevertheless, the CEO, GSWMA, requested the villagers to prepare village water plans and promised help from his team to support their efforts.

VILLAGE-LEVEL PLANNING

Concept

As discussed earlier, the idea of co-management with a decentralized village-level planning process was the

25 Village Development Plans were to be prepared by each village under a decentralized planning process initiated by the erstwhile Planning Commission of India, which were to be aggregated into Block Plans, District Plans and State Plans. However, a lack of capacity had led to these plans being prepared by consultants and senior bureaucrats (e.g., District Collectors) and not by the direct stakeholders. Nevertheless, an attempt was made to pilot a decentralized planning by the PR&RD in Rajasthan in October 2014. The Village Water Sub-Plan was to be part of the Village Development Plan.

26 There is, of course, the long term problem of the Jevons Paradox: If the micro-irrigation proves more profitable, it could increase net consumptive water use per unit area or per land holding – as farmers expand irrigated area to exploit this 'water saving' technology.

central concept of the demonstration. The implications of these plans on local and downstream water resources were to be included into the modeling as a distinct scenario to assess potential impacts. If these were found to have 'unacceptable' consequences for downstream communities (based on criteria that could be political, social, economic or environmental in nature), the plans were to be revised till they were found to be acceptable. The approach, thus, called for iterating between village-planning and checking the downstream impacts using the simulation model.

Expected Outputs

Although the preliminary modeling results showed that the catchment was 'water-surplus', the fact that the catchments are located within a 'closed' river basin meant that reductions in downstream flows had to be minimized (at least to maintain environmental flows). Within this context, key outcomes expected from the facilitated village-planning process were the following:

- **Improved capacity of the local community to create plans** to manage local water resources (especially storage to overcome summer scarcities and droughts), tap available government funding and create the required water infrastructure.
- **Creation of local storage with minimal intervention on drainage lines:** Create supplementary off-drainage line water storage to provide protective and/or supplementary irrigation (e.g., last two irrigations of the *Rabi* season) through flexible and decentralized storage options, including large or small *talabs* (traditional tanks), *tankhas*, etc., through a multi-annual Village Water Sub-Plan. The central concept was to capture and store water during high rainfall periods for use in the low rainfall periods – with minimal reduction of downstream flows. Options would include putting gates on check dams (which are kept open after storage is filled and during low rainfall periods) to minimize reductions in downstream flows.
- **Better drinking water security** by creating household-wise storage (i.e., *tankhas*) to store 15 months of drinking water for a six-member family. The logic was that this would take care of the 3 months of summer scarcity and also, in case the rains failed, the 12 months till the next rains.
- **Improved water productivity and land productivity:** Technical and economic options were to be provided to local communities to raise the profit per unit of water to offset any future reductions in water availability, especially downstream, due to a variety of possible reasons including increasing climate variability.

The village-planning process, however, did not proceed as planned and a revised approach had to be taken (see Box 3.6 for details) which focused on just the first three of the outputs expected.

Village Planning in Kevdi

The village planning exercise using this approach was carried out in Kevdi village and the implications for the water infrastructure detailed in the Village Plan (Figure 3.27). A noteworthy feature of the planning process was that, beyond the initial idea of having *talabs* (large ponds) in the forested upper part of the catchment (which proved impossible given the lack of permission from the Forest Department to construct structures on forest land), villagers had little idea of options beyond check dams and wells and could not appreciate or visualize other options.

Also, the other major component of the Village Plan, namely water demand management options could not be included as it required the active support and sustained field-presence of the local IWMP staff to work out the convergence with the Agriculture and other relevant Departments.

Thus, the village-planning demonstration focused on the water infrastructure, based on suggestions given by the study team and discussed with the villagers. The fact that this plan was not to be supported by implementation, even by the ongoing IWMP, was a shortcoming of the planning process. There was, however, interest from the villagers in findings solutions to their summer water shortages and drought water scarcities.

The main options for improved water infrastructure were the following:

BOX 3.6 DETAILS OF THE VILLAGE-PLANNING PROCESS FOLLOWED

Choice of demonstration site

In April 2015, the study team re-visited Kevdi with an innovative decentralized planning approach that had been successfully used in several countries to initiate community-level watershed planning. The approach essentially involved using Google Earth to show villagers their village, and encourage them to participate in marking their village boundaries, streams, water points, farmlands, forests and grazing lands – and to identify problems areas that were subsequently visited for more detailed assessments. This Transect Walk used hand-held GPS devices not only to mark water points and village streams and gullies (using the Track feature of a GPS unit) but also facilitated a detailed discussion of options to revive defunct wells, broken embankments and make improvements in the natural resource base. Once these improvements were identified, they were marked on Google Earth, along with details of the interventions proposed. Once discussed and approved by the Village Council (e.g., Gram Sabha) these are then added to the final Village Plan.

The main advantages of this innovative participatory planning approach are the following:

- Makes planning more inclusive for the community.
- Is the only option when maps and land records are difficult to procure.
- Also useful where maps may be available but detailed planning requires identifying water bodies and problem areas.
- Creates maps that can be used for implementation and monitoring.
- Uses existing methods: e.g., primary data collection using transects.

FIGURE 3.27 GOOGLE EARTH-BASED WATER PLANNING FOR KEVDI VILLAGE

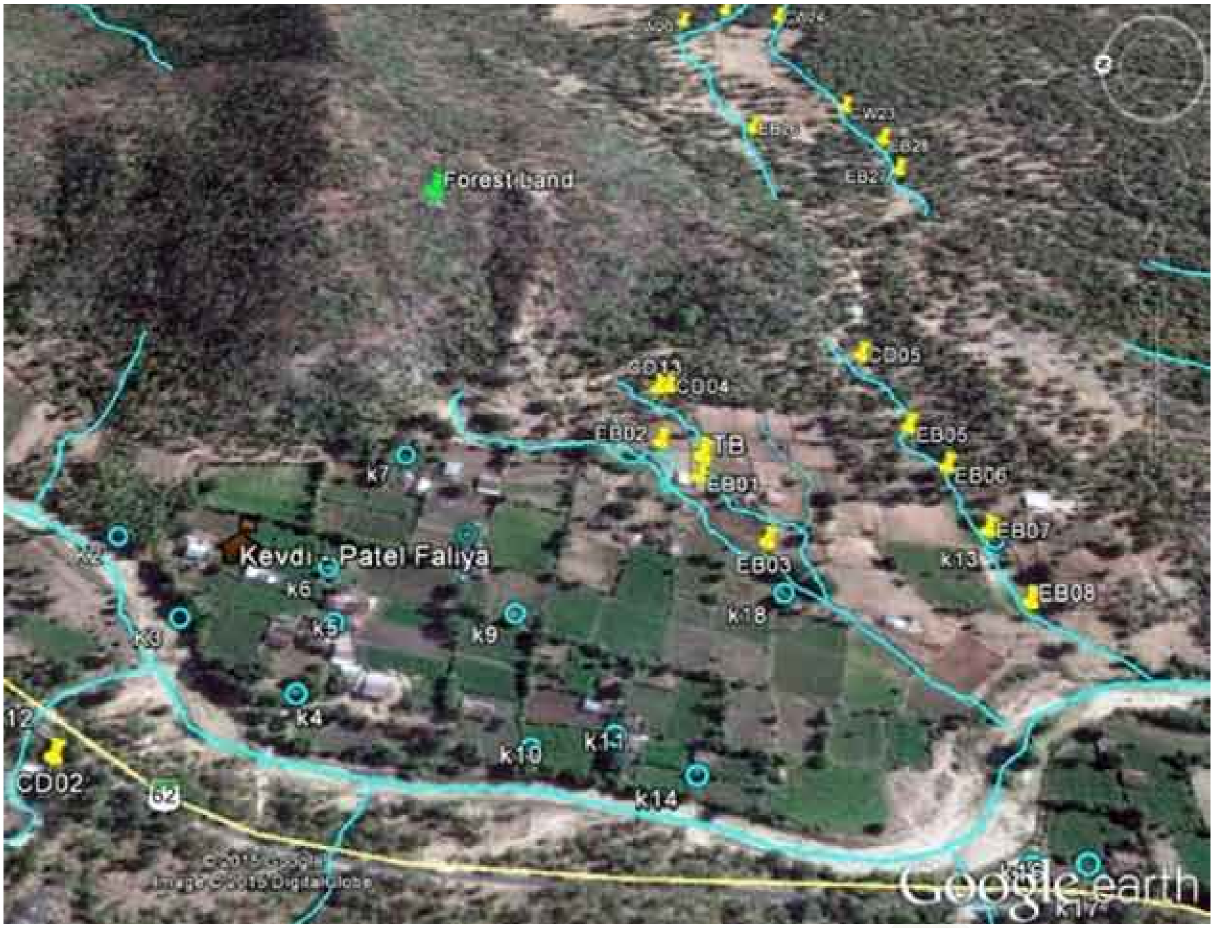


TABLE 3.7 PROPOSED WATER HARVESTING STRUCTURES FOR KEVDI VILLAGE

Structures	Type	Number of Structures						Unit Storage (cu.m)	Total Storage (cu.m)
		Total	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5		
Farm pond*	Storage	157	38	19	40	15	45	50	7850
Sub-surface tank*	Storage	01	01	-	-	-	-	500	500
Sub-surface dyke*	Storage and Recharge	15	-	-	-	-	-	750	11250
Water adsorption trench*	Recharge	2000	-	-	-	-	-	3	6000
Total		**-**	**-**	**-**	**-**	**-**	**-**	**-**	**25600**

* *Dimensions:* Farm pond: 4m x 4m x 3.2m; Sub-surface tank: 10m x 10m x 5m; sub-surface dyke: 15m x 1m x 50m; Water Adsorption Trench: 1m x 1m x 1m.

- **On the main streams:** *Bhoomigath Bandhara* (sub-surface dykes).
- **Inland:** Three options were discussed:
  - *(Farm) Ponds:* Lined to store water for protective irrigation and unlined to recharge nearby wells; protective stone plugs to prevent siltation of ponds.
  - *Earthen bunds:* repair of breaches in existing bunds on inland gullies, some of which have been deliberately breached by farmers, so as to cultivate in the moist soil upstream of these bunds.[27]
  - *(Rain-fed) Fields:* Lined farm ponds for protective irrigation. The rough calculation done with villagers was that a farm pond with the dimensions 4 m x 4 m x 3 m would create a storage of 48 cu.m, which would be sufficient for two irrigations of 3 cm for a 750 sq.m field (which is the dimension of an average field in the village).

The advantages of sub-surface dykes and tanks include the following:

- Low risk of damage from high velocity flows.
- Reduced evaporation losses.
- Lower cost of the structure.
- Water storage, being in a small area below the ground, has minimal impacts on standing crops or on water flowing in the main stream.

The total capacity of the proposed structures was around 25,600 cubic meters (Table 3.7).

Note that the additional storage created is relatively small and is only meant to provide *protective* irrigation (for the *Kharif* crop) and *supplementary* irrigation (for the *Rabi* crop) – and not to expand the area under *Rabi* or summer cultivation – although once created it is of course up to the individual farmer to use it any way they wish to. Note also, this focus on creating storage is therefore only a partial plan and has to be supplemented with advice on increasing water productivity through measures such as shifting to less water-using crops (or at least not shifting to a more water-intensive crop like cotton), micro-irrigation and plastic or biomass mulching, which are discussed in greater detail in Section 3.6 below.

The Kevdi plan for creating RWH structures was extrapolated to the other four villages in the catchment using the ratio of additional storage planned to total village area and this is discussed in the next section that presents the scenarios from the modeling.

ASSESSING DOWNSTREAM IMPACTS

Creating Scenarios

The development of model scenarios, generally speaking, enables an analysis of the potential impacts

27 The sides of these bunds have been breached by farmers to drain out the excess water that collects behind these bunds (while intact) and submerge the crops planted upstream of the bund.

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 trade-offs 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 3.5).

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

- *Changes in the levels of in situ and ex situ Rainwater Harvesting* (RWH) in the catchment.
- *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 catchment, and consider the important and uncertain impacts it may have downstream (see Box 3.5):

- **Importance:** These two factors are likely to have a big impact on the catchment in the future given the investments being made in watershed development by IWMP and other programs, as well as the expansion in the double-cropped area driven by population growth and the micro economic 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 catchment, there is significant uncertainty on the magnitude of this increase and the impact on downstream flows.

Two versions of the scenarios are presented, one for the catchment as a whole and the second for the five villages where detailed analysis was undertaken.

Catchment Scenarios

Scenario description

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

- **Scenario 1** models the catchment in the absence of the watershed development and the intensification of agriculture that has occurred over the last two decades. In other words, the catchment as it was prior to the start of the modeling period, when a major part of the agricultural land was used for *Kharif* crops only and there were very few large RWH structures. Although it is difficult to envisage a return to the pre-1999 situation in the catchment, Scenario 1 helps to illustrate the impact that agriculture and watershed development has already had on the hydrology of the catchment.
- **Scenario 2** models the opposite situation and represents a significant intensification of agriculture and watershed development as compared to current levels. This is the most

BOX 3.5 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 as 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).

TABLE 3.8 DESCRIPTION OF MODEL SCENARIOS

Scenarios		Description
Scenario 1	**a. No development**	This scenario models the catchment 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.
Scenario 2	**a. Intensification of agriculture and RWH**	This scenario represents the more likely future for the catchment: 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 catchments; and (2) an increase in double crop area from 30 to 40% of catchment 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 catchments.
	c. Intensification of agriculture	Increase in double crop area from 30% to 40% of catchment area but no change in reservoir capacity.

plausible future for the catchment, 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 3 parts:

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

The best simulation from the model calibration was used as the Baseline and the scenarios were evaluated for the period 2007 to 2012 (Table 3.8).[28]

General Scenario Results

The overall impacts of the scenarios as would be expected (Figure 3.28 and Table 3.9):

- Scenarios 1a, 1b and 1c, result in increases in inflow into the Sukhi reservoir while Scenarios 2a, 2b and 2c result in decreases.
- The combined impact of the two factors in Scenario 1a results in the largest increase in reservoir inflows.
- The combined influence of the two factors for Scenario 2a results in the largest decrease in inflows.
- The impact on watershed development on downstream flows is greatest in dry years – as the relative impacts of the scenarios are greatest in 2009, the driest year (inflows increase by 24% for Scenario 1a and decrease by 19% for Scenario 2a).

TABLE 3.9 PERCENTAGE CHANGE IN SUKHI RESERVOIR INFLOWS FOR SCENARIOS VIS-A-VIS BASELINE

Year	Scenarios					
	1a	1b	1c	2a	2b	2c
2007	**6.9**	0.3	6.6	**-6.3**	-4.5	-1.8
2008	**12.4**	0.7	11.9	**-9.7**	-6.4	-2.7
2009	**24.0**	3.9	21.0	**-16.9**	-15.1	0.5
2010	**13.0**	0.7	12.4	**-10.0**	-8.3	-1.1
2011	**7.3**	0.2	7.1	**-8.9**	-5.0	-3.3
2012	**8.5**	0.5	8.1	**-9.6**	-5.4	-3.4
Average	**9.5**	**0.5**	**9.0**	**-8.9**	**-5.9**	**-2.4**

28 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 then land use change would have had to be considered when evaluating scenario outputs.

FIGURE 3.28 ANNUAL INFLOWS INTO THE SUKHI RESERVOIR FOR THE SCENARIOS

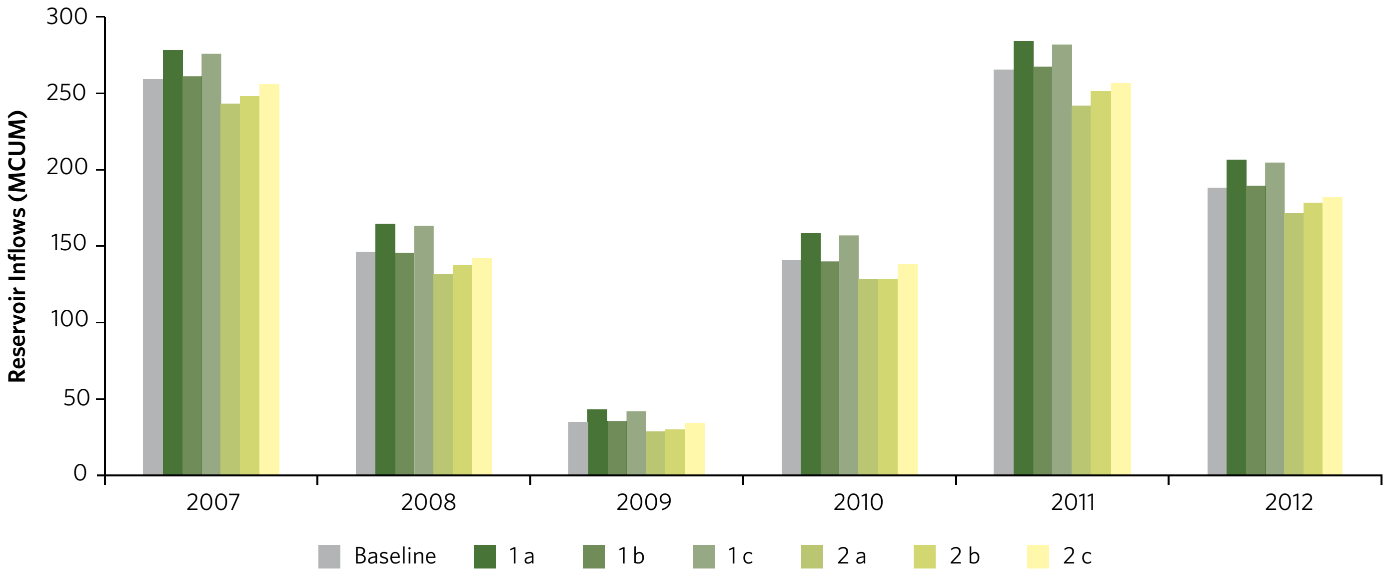


TABLE 3.10 WATER BALANCE COMPONENTS OF SCENARIOS AND BASELINE

All figures as percentage of rainfall

Years	Water Balance Components	Scenarios						Baseline
		1a	1b	1c	2a	2b	2c	
Dry Year (2009)	Evapo-transpiration	**77**	89	78	**99**	90	98	**90**
	Percolation	**38**	38	37	**43**	42	39	**39**
	RWH recharge	**0.0**	0.0	0.8	**2.5**	2.3	0.9	**0.9**
	Reservoir inflows	**24**	20	23	**16**	16	19	**19**
Wet Year (2011)	Evapo-transpiration	**26**	30	27	**33**	30	33	**30**
	Percolation	**46**	48	46	**52**	52	47	**49**
	RWH recharge	**0.0**	0.0	0.2	**0.8**	0.7	0.3	**0.2**
	Reservoir inflows	**48**	45	48	**41**	43	44	**45**
Average (07-12)	Evapo-transpiration	**36**	40	36	**43.6**	40.4	43.4	**40**
	Percolation	**40**	42	40	**46**	46	42	**43**
	RWH recharge	**0.0**	0.0	0.3	**1.1**	1.0	0.4	**0.4**
	Reservoir inflows	**45**	40	44	**37**	38	39	**40**

Detailed Scenario Results

Whether it is a dry year or a wet year also affects various water balance components – 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 (Table 3.10):

- **The driest year, 2009:** Changes in the double-cropped area have the largest impact on the amount of water lost as ET from the catchment with the impacts largest in 2009.

In this year ET for Scenarios 2a and 2c, in which the double-cropped area is increased to 40% of the catchment 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 catchment area, ET in 2009 is reduced to 77.4% of rainfall, more than 10% lower than the Baseline figure.

- **The wettest year, 2011:** The impact of the scenarios on ET is far less as a percentage of rainfall, although the absolute difference is similar.
- **Percolation rates:** 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 m^3 ha to 40 m^3 ha for Scenario 1a and an expansion of structures into the mainly forested sub-watersheds. Recharge from RWH structures in 2009 is double the average recharge as a percentage of rainfall.

Village Scenarios

Extracting village areas

While simulation models can create scenarios that enable insightful inferences to be drawn about the behavior of the catchment 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 catchment 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 catchment 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 sub-watersheds can be delineated at a user-specified resolution which allows results to be analyzed at local levels, even for large catchments. A trade-off is that models of large catchments with many sub-watersheds can substantially increase model runtime and make processing model outputs a time-consuming process. One solution, used by Notter *et al.,* (2012), is to vary the resolution of sub-watersheds across the catchment so that areas of interest are defined in more detail.

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 sub-watersheds 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. However, it was not possible to match the boundaries exactly, as neither the village boundaries nor the boundaries of the government delineated micro-watersheds matched the hydrological boundaries as defined by the DEM. Although watershed development under IWMP is meant to be planned for the government-delineated micro-watersheds, it appears that in the Sukhi catchment most of the planning was done using village areas.

The SWAT sub-watersheds overlain onto the areas of the five survey villages shows that the village areas cover parts of a number of different sub-watersheds but the majority of the areas are covered by nine (numbered) sub-watersheds (Figure 3.29).

The sub-watersheds shown in Figure 3.29 can be divided into three distinct groups based on their dominant land uses:

1. Sub-watersheds 13, 36, and 39 are nearly completely forested.
2. Sub-watersheds 22, 25, 51 and 55 are split between forest and agricultural land.
3. Sub-watersheds 43 and 53 have a mix of agricultural land, grassland, and degraded forest.

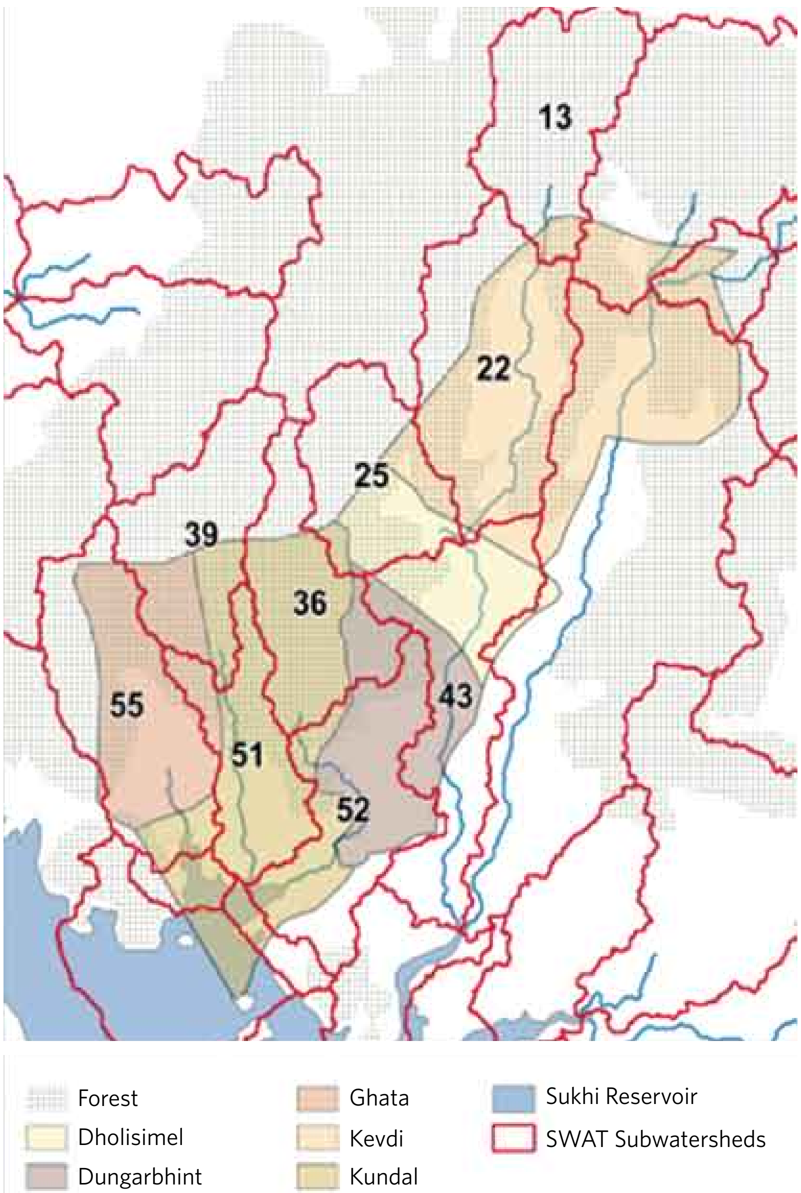
The land use of each sub-watershed has a large impact on its hydrology and therefore on the impact of the scenarios.

These nine sub-watersheds can be divided into 4 sub catchments, all of which drain directly into the Sukhi

TABLE 3.11 EXTRAPOLATION OF THE KEVDI VILLAGE DEMO PLAN TO THE OTHER SURVEY VILLAGES

	Ghata	Kundal	Dungarbhint	Dholisimel	Kevdi
Village area (ha)	533	1,052	517	373	1,287
Total agricultural area (ha)	121	231	104	62	179
Rabi area (ha)	114	228	95	38	127
Baseline RWH capacity (m^3)	7,995	15,780	7,755	5,595	19,305
Additional off-channel storage	14,911	28,791	13,341	8,490	26,164
Additional on-channel storage	8,602	16,455	7,425	4,429	12,719
Total extra storage (m^3)	19,116	36,567	16,500	9,842	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

FIGURE 3.29 SWAT SUB-CATCHMENTS COVERING THE FIVE SURVEY VILLAGES



Reservoir, making them a useful unit of analysis (Figure 3.30).[29]

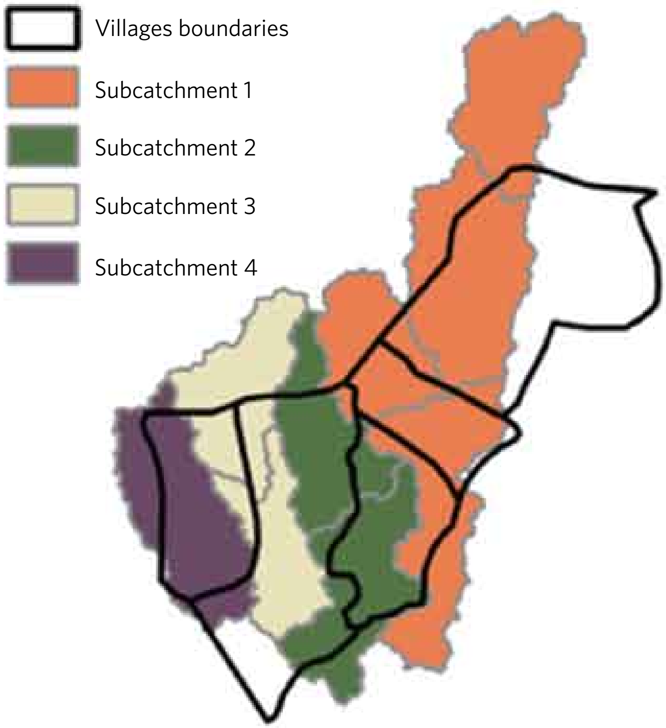
As discussed earlier, a detailed plan was developed for Kevdi village for RWH structures based on preliminary model findings, analysis of satellite images, and consultation with the local community, The main aim of the plan was to ensure that sufficient water was available for the whole *Rabi* irrigation, (as villagers reported that on a majority of farms located away from the river, 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 3.11). 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).

Scenario Description

The 40 m^3/ha figure applied in Scenario 2a earlier (to represent intensification of RWH), is slightly lower than the average of 42 m^3/ha

29 The only large area of the five villages that falls outside of the 9 sub-watersheds is the eastern half of Kevdi village, which covers a small part of a much larger sub-catchment. This illustrates the difficulties of using administrative units, such as village areas, when analyzing and planning hydrological interventions.

FIGURE 3.30 MICRO-CATCHMENTS COVERING THE FIVE SURVEYED VILLAGES



to investigate the impact of these plans at the local level (Table 3.12).

Note that for Scenario v2 and v3 reservoirs are also implemented in the forested sub-watersheds upstream of the villages (i.e., in sub-watersheds 13, 25, 36 and 39).[30]

Scenario Results: Water Balance Components

Extracting data on the water balance components for the nine sub-watersheds reveals differences to the Sukhi catchment as a whole for the Baseline, due to the differences in the proportions of the different land uses, topography, and soil characteristics (Table 3.13).

Table 3.13 also shows the following:

- **Evapo-transpiration** is lower than for the catchment as a whole; 30.8% compared to 40%. This is due to the large areas of forest and degraded forest in the nine sub-watersheds, which have lower ET than irrigated double-cropped areas, which make up a higher proportion of the rest of the catchment.

TABLE 3.12 DESCRIPTION OF VILLAGE SCENARIOS

Scenarios		Description
v1	No development	This scenario is identical to Scenario 1a and models the catchment 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 sub-watersheds covering the village areas based on the RWH capacity needed for each hectare of agricultural land (See Table o). The split between on- and off-channel storage for Kevdi village is also applied to all sub-watersheds. Reservoirs are also implemented in forested sub-watersheds 13, 25, 36 and 39, the sizes 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 sub-watershed and an associated increase in RWH capacity, calculated using the per hectare figure from the Kevdi village plan. The capacities of reservoirs in sub-watersheds 13, 25, 36 and 29 are doubled compared to scenario v2.

capacity of RWH structures calculated as a function of village area (Table 3.11). The capacity calculated is also higher than the figure of 40 m^3/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 sub-watersheds 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 catchment were adapted

- **Reservoir inflows** for the nine sub-watersheds are similar to those of the whole catchment for the baseline (as an average over the period): 40.5% compared to 40%. However the variations in inflows in 2009 and 2011, the driest and wettest

30 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 sub-watersheds is an effective way of representing the concentration of structures at the forest borders.

TABLE 3.13 WATER BALANCE COMPONENTS FOR VILLAGE SCENARIOS AS A PERCENTAGE OF ANNUAL RAINFALL

Year	Water Balance Component	Village Scenarios				Catchment Scenario Baseline
		v1	v2	v3	Baseline	
Dry Year (2009)	Evapo-transpiration	69.4	75.7	80.9	**75.1**	89.6
	Percolation	27.8	32.2	33.0	**28.9**	38.6
	RWH recharge	0	2.9	3.4	**1**	0.9
	Reservoir inflow	15.6	13.8	14.4	**14.8**	19.3
Wet Year (2011)	Evapo-transpiration	20.3	21.7	22.8	**21.7**	30.2
	Percolation	47	51.2	51	**48.1**	48.5
	RWH recharge	0	0.6	0.7	**0.2**	0.2
	Reservoir inflow	48.2	45.7	44.7	**47.6**	45.1
Average (2007-2012)	Evapo-transpiration	29	30.9	32.4	**30.8**	40.2
	Percolation	41.2	45.5	45.5	**42.3**	42.5
	RWH recharge	0	0.9	1.2	**0.3**	0.4
	Reservoir inflow	41.2	38.8	38.3	**40.5**	40

years, are more significant. For example reservoir inflow in 2009 under the Baseline scenario is only 15% of rainfall compared to 19% for the whole catchment.

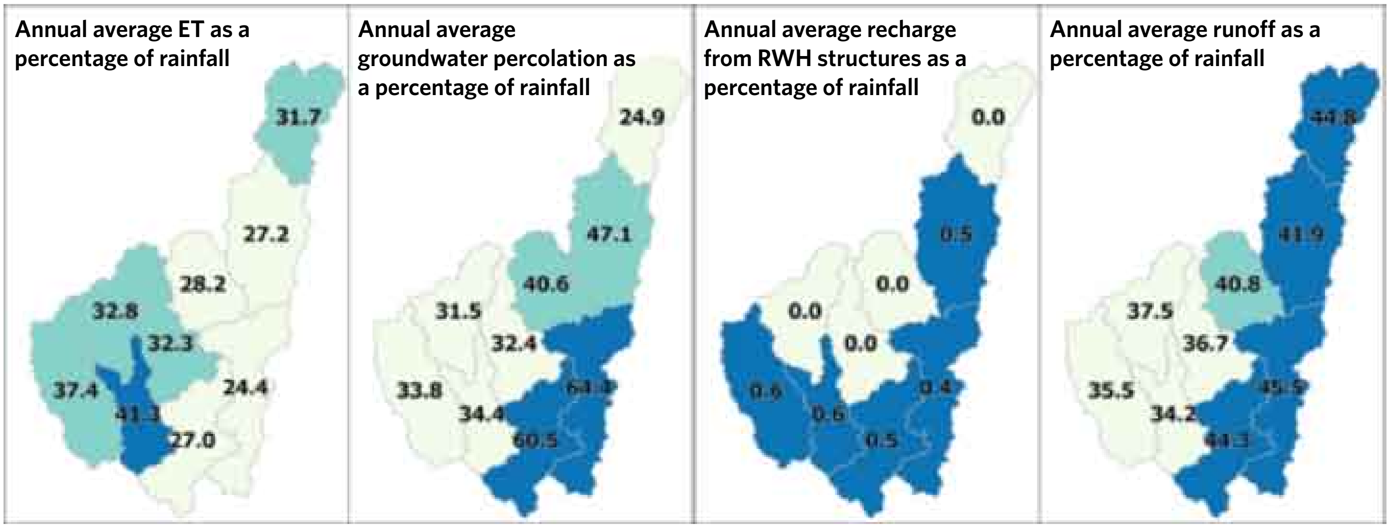
- **Percolation and (artificial) recharge from RWH** are similar to the figures for the whole catchment.
- **Scenario v1**, denoting a removal of RWH structures and the decrease in double-cropped area, sees only a small increase in average reservoir inflows: from 40.5% to 41.2% of rainfall. In comparison Scenario 1a, an identical scenario applied to the whole catchment, saw an increase from 40% to 43% of rainfall. This highlights the fact that the study villages are located in an area of the catchment that so far has seen relatively less intensive agricultural and hydrological development.
- **Scenarios v2 and v3,** as expected, result in decreases in reservoir inflows but the decrease is larger for Scenario v3 due to increase in double-cropped area and the larger increase in RWH capacity. 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.[31]

Scenario results for sub-catchments

A division is clear between sub-catchment 1 and sub-catchments 2, 3 and 4, excluding sub-watershed 52 which shows a response similar to

31 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 that in 2009, even with intensive RWH, enough groundwater would be available such that runoff resulting from irrigation would increase reservoir inflows. Deficiencies in the modeling of groundwater limits somewhat 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 could be an option for the Sukhi catchment but would obviously increase the amount of data and time needed to complete the modeling.

FIGURE 3.31 BASELINE WATER BALANCE COMPONENTS AS A PERCENTAGE OF RAINFALL



sub-catchment 1 (Figures 3.31 and 3.32). Sub-catchment 1 has high runoff and percolation while sub-catchments 2, 3 and 4 have higher ET. Topography and land use proportions are similar between the two areas, with soil depth likely to be the main factor causing the difference. Sub-catchments 1 and sub-watershed 52 are mainly covered by shallow soils, while sub-catchments 2, 3 and 4 have much deeper soils, which can store more water. As a result more water is available for plants and crops and hence more water is lost as ET.

The impact of the village scenarios varies across the sub-watersheds (Figure 3.32). The impact of Scenario v1, which is the removal of reservoirs and reduction in the area of double-cropped agriculture, has a greater impact in the downstream sub-watersheds that are more dominated by agriculture in comparison to the mainly forested sub-watershed upstream. Scenarios v2 and v3 show similar spatial impacts. Percolation and recharge from RWH structures is very similar for both scenarios. Scenario v3 has higher ET in the downstream sub-watersheds as a result of the increase in the area of double-cropped agriculture. This results in larger decreases in runoff in comparison to scenario v2.

Impact on yields

SWAT also models average crop yields and those in the nine sub-watersheds, for the period 2007 to 2012, compared well with those reported in the

FIGURE 3.32 CHANGE FROM BASELINE OF WATER BALANCE COMPONENTS FOR VILLAGE SCENARIOS

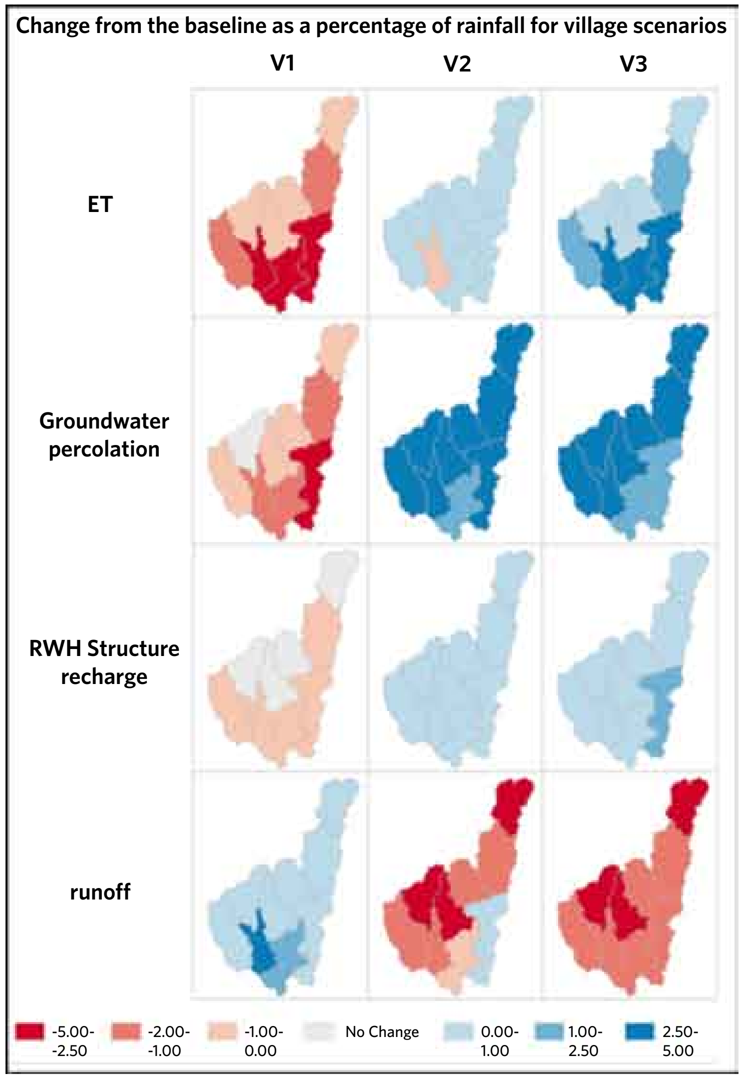
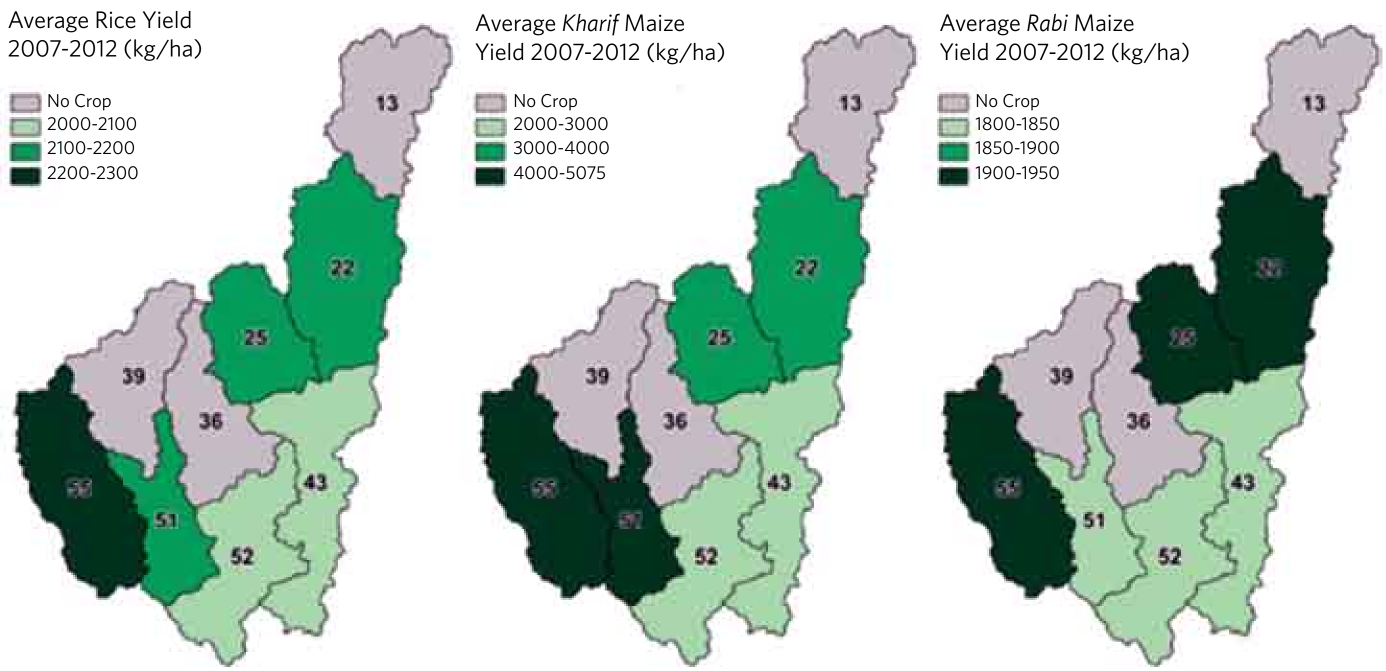


FIGURE 3.33 CROP YIELDS FOR THE SUB-WATERSHEDS COVERING THE SURVEY VILLAGES



primary village survey, with the exception of *Kharif* maize (Table 3.14).

Crop yields also vary across the different sub-watersheds (Figure 3.33). They generally are highest for sub-watersheds 55 and 51 which cover Ghata and Kundal villages, and the lowest sub-watersheds 43 and 52, which is similar to the primary survey findings. The low yields in sub-watersheds 43 and 52 can be partly due to the shallow lithic Haplusteps soils that cover the majority of the sub-watersheds. In comparison the soil in the other sub-watersheds is mainly moderately deep udic Haplusteps.[32]

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 sub-watersheds. 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.

32 Some variation in crop yields between sub-watersheds, and perhaps the differences between the model crop yields and those reported by the villages, can also be attributed to inconsistencies in the auto-irrigation function used in SWAT. In some HRUs with low yields, insufficient irrigation is applied, even when there is water available in the shallow aquifer. Developing manual irrigation schedules using data gathered from the villages would improve the model in this area.

TABLE 3.14 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

Concluding observations

Overall, the model helps to provide a solid hydrological foundation to the behavior of water in the catchment, 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 catchment. Such information is vital in planning for watershed management in the catchment and also in the prioritization of watersheds to be taken up for treatment.

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

- **Catchment inflows exceed outflows**: With 'catchment inflows' referring to rainfall falling over the catchment (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 availability 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. Population increases could further increase water demand even in average rainfall years.

- **Need alternative rainwater harvesting options:** The substantial rainwater 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 sub-surface tanks and dykes and farm ponds, which can provide the farmers the extra *Rabi* irrigation water that they mentioned as a major issue.

- **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 would mean not only options to reduce crop water use, such as shifting to less-water intensive crops, micro-irrigation (drip and sprinklers) and (plastic or organic) mulching to reduce evaporation from crop lands (and thus reduce the need to irrigate) but also options to raise agricultural profits, by reducing cultivation costs and increasing output prices.

- **Search for non-water based livelihoods:** 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 non-water-based livelihoods that are at least as profitable as migration could help to stem such stress migration.

ADDRESSING DOWNSTREAM IMPACTS

Classifying Catchments

The construction of infrastructure and changes in land use in upper catchment areas will impact the hydrology of the catchment and, more specifically, water flows to downstream areas. Hydrological assessments help to quantify these changes and to generate scenarios of possible future impacts of various interventions. Watershed management interventions will depend on the nature of these hydrological dynamics which, in turn, can be used to define the catchment. Based on their hydrological characteristics, a typology of catchments was developed to guide the nature of watershed interventions to be undertaken in each (Table 3.15). Each color-coded catchment type is explained further below.

Blue catchments

In *blue* catchments, the total catchment *inflow* (i.e., annual precipitation P) is far more than the *outflows*, comprising evaporation E and actual evapo-transpiration ETa, such that there is surface stream flow going out of the catchment (P > ETa + E). Also, the inflow is more than sufficient to meet existing annual water *demands* (P > PE + E) and, scenarios from modeling show that it will still have excess water, even after meeting any future increases in water demand (e.g., for expanding cultivation and for more domestic, livestock and other uses). Also, the available supply from various sources – i.e., the water tapped naturally or artificially from various sources (groundwater, surface runoff and soil moisture) to meet various consumptive uses) – are sufficient to meet the existing demands (S = PE + E). Such catchments are, and are likely to remain, 'open' (in a hydrological sense). Such watersheds are likely to be found in sparsely populated or uninhabited hilly areas, such as in the Himalayan foothill areas of Himachal Pradesh, Uttarakhand, Arunachal Pradesh and Kashmir.

TABLE 3.15 TYPOLOGY OF CATCHMENTS AND POSSIBLE MANAGEMENT OPTIONS

Inflows vs. Outflows	Supply vs. Demand	Inflows vs. Supply	Management *Strategy* and Options
Inflows far exceed outflows (P > ETa + E)	Entire demand met from supply (PE +E = S)	Inflow far exceeds supply	*All options to augment water-based livelihoods (e.g., RWH for cropping):* ■ Increase beneficial ET to meet future consumptive demands (through increased cropping, tree-planting, etc.) ■ Create RWH structures to increase soil infiltration and groundwater recharge (will reduce downstream flows)
Inflows exceed outflows (P > ETa + E)	Demand exceeds supply (PE + E > S)	Inflow exceeds supply	*Reduce excess of demand over supply* by creating RWH structures (will reduce downstream flows) *Augment downstream flows* by freeing water from agriculture through water productivity improvements (without increases in irrigated area) by: ■ Reducing non-beneficial evaporation ■ Reducing beneficial evapo-transpiration ■ Reducing non-recoverable deep percolation from irrigation
Inflows equal outflows (P = ETa + E)	Demand equals supply (PE+ E = S)	Entire inflow tapped No more renewable water available	*No RWH structures* (will only re-distribute the same water in the catchment by creating new losers and winners, a zero-sum game) *Augment downstream flows* by freeing water from agriculture through water productivity improvements (without increases in irrigated area), by: ■ Reducing non-beneficial evaporation ■ Reducing beneficial evapo-transpiration ■ Reducing non-recoverable deep percolation from irrigation *Prioritize and protect drinking water sources* *Promote non water-based livelihood options*
Inflows equal outflows (P = ETa + E)	Demand exceeds supply (PE + E > S)	Entire inflow tapped No more renewable water available	Reduce excess of demand over supply by: ■ Reducing non-beneficial evaporation ■ Reducing beneficial evapo-transpiration ■ Reducing non-recoverable deep percolation from irrigation *Prioritize and protect drinking water sources* *Promote non water-based livelihood options*
Outflows exceed inflows (ETa + E > P)	Demand met from unsustainable supply (PE + E = S)	Entire Inflow Tapped Deficit met through aquifer mining	*Reduce mining of aquifer by:* ■ Reducing non-beneficial evaporation ■ Reducing beneficial evapo-transpiration ■ Reducing non-recoverable deep percolation from irrigation *Prioritize and protect drinking water sources* *Promote non water-based livelihood options*

Note: ET a =Actual evapo-transpiration; E = evaporation (from water bodies and barren soil); PE = Potential Evapo-transpiration; P = catchment inflow (precipitation); S = water supplies.

Management options should be to reduce erosion and provide flood control, while increasing profit per unit of water for any local inhabitants.

Green catchments

In **green** catchments, current inflows exceed outflows (P > ET_a + E) and supply (P > S), but there are unmet demands for water, either current or in the future. Such additional water demands can be for expanding cultivated or irrigated area, intensifying cropping or expanding the tree cover, and hence the additional water is largely for meeting the evapo-transpirative demand of the new biomass. There could also be demands for increased livestock rearing or for the domestic and productive (small enterprise) needs of an expanding population, but these are usually much less than the water demand for increased biomass production. In such catchments, rainwater harvesting to develop the productivity of water resources or groundwater exploitation would help to meet water demands. Both would, of course, reduce surface and ground water flows out of the catchment.

Brown Catchments

In **brown** catchments, current inflow is more or less equal to the total consumptive water demand at present or future (P = PE + E) and all the inflow is tapped through various supply sources to meet the demands, such that there is no water flowing out of the catchment. The management strategy should be to free some water for downstream environmental flows. In rural watersheds, agriculture is the largest water-using sector and the only one that can free water for the environment through improvements in water productivity (i.e., more profit per unit of water). Options for improving water productivity are those that reduce catchment 'outflows' (ETa + E), comprising (1) *beneficial consumptive uses* – consumptive water use in irrigated crops (T) and consumptive use of water for rain-fed crops; (2) *non-beneficial consumptive uses* – evaporation from water bodies and moist soils in cultivated land; and (3) *deep percolation* through increased irrigation (especially flood irrigation). The main intervention options here are to increase the use of micro-irrigation and (plastic or organic) mulching and switching to less water-intensive crops. Encouraging price support and other policies for such products will help farmers adopt these measures, but training them in their optimal use and hand-holding till they master the new techniques are of equal (if not greater) importance. However, increases in the area under irrigation to utilize the water 'freed up' by interventions such as micro-irrigation, mulching and switching to less water-intensive crops, is the biggest challenges to realizing such water savings.

Protecting drinking water supplies (a primary need) through prioritization of needs (by authorizing reservations of water stored in irrigation tanks, for instance) and promoting non-water-based livelihoods are additional strategies that ought to be pursued in such catchments.

Orange Catchments

In **orange** catchments, the inflow falls short of the total consumptive water demand (P < PE + E), and all the inflows from various supply sources is tapped (P = S), with no water flowing out of the catchment (P=ETa+ E). The management strategy should therefore be to improve the productivity of water in agriculture (profit per unit of water), and to use any such water saved to release water for downstream ecological needs. An important addition, however, is to *not* build water storage and impounding structures as they will not improve the overall water balance in the catchment. Such RWH structures will only increase the water spread area (thereby increasing the chances of evaporation of the stored water) and redistribute existing water in storage structures across the catchments (those built in upper reaches will fill and reduce inflows into those downstream). Such catchments exist in many parts of semi- arid and arid India, including Karnataka, Andhra Pradesh, Maharashtra, Madhya Pradesh and Gujarat.

Red Catchments

In **red** catchments, total consumptive water use (i.e., outflow) is higher than the inflows (ETa + E > P) but the deficit is met through mining of groundwater so that supply equals demand (S = ET + E). Here, again, the strategies for orange catchments will apply but they are unlikely to eliminate or reverse groundwater mining – though they may help to reduce the extent. Such catchments are there in many parts of semi- arid and arid India, especially in Rajasthan.

Using Catchment Types

Classifying catchments as illustrated above can help determine management strategy and guide intervention planning, both in the upper and lower parts of the catchment. In the case of the Sukhi catchment, most of the sub-watersheds above the Sukhi reservoir are likely to be either Blue (especially the uninhabited forest areas) or Green (especially those including inhabited areas with agriculture), while those below could range from Green to Red. This will depend on further analysis of catchments farther downstream of the Sukhi reservoir. The classification will, however, assist the management strategy for even the five villages studied in the Upper Sukhi Catchment.

Three points to note concerning these classifications of catchments are the following:

- *Classifications* require inputs from hydrological modeling (to understand catchment inflows and outflows), from stakeholder discussions (to understand current and future water demands), and also from discussions with other government departments, to understand interventions planned by these agencies.

- *Classifications can apply to smaller units within a catchment,* such as sub-watersheds (as defined, for instance, by the SWAT model). Thus a single catchment can have a patchwork of colour-coded types within it.
- *Classifications can change* based on changes within the catchment (e.g., by other government programmes or departments), but any one government department or program (e.g., IWMP) may not be able to perceive the totality of these changes unless there is a central database logging all such watershed interventions.

Changes in Catchment Type

A catchment can move from Green to Brown if the consumptive water demand increases to touch the inflows and there is a proportional increase in supplies (by developing all water resources in the catchment) to meet this demand. This means either there will be increase in either or both ET and E. In this case, the outflows become equal to the inflows, with no water left in the catchment either in the form of renewable groundwater or runoff.

If further increases in demand for water are not met (due to the lack of water stocks), then the catchment would become an Orange catchment (as in some parts of hard rock peninsular India), and, if the excess demand is met through mining of groundwater, it would become a Red catchment (as in some parts of the Luni basin in Rajasthan).

Intervention Planning

Some details of the different types of interventions that can be considered for different catchment types are discussed below. Note that these are only illustrative and the actual type and nature of interventions are to be decided only after a detailed analysis of local conditions.[33]

- **Rainwater Harvesting Structures:** These are intervention options in Blue and Green catchments and possibly in Brown catchments. More RWH structures will increase evaporation in the catchment and reduce downstream flows. These impacts can be reduced to some extent by plastic-lining of structures (bottom and also top) provided these are financially viable, by building sub-surface structures or by putting gates in these structures to be kept open during high rainy season flows and closed towards the end of the rainy season (ensuring that water is impounded after it is released downstream).[34] These are therefore not recommended for Orange and Red catchments as they can create local re-distributions of water with the potential for conflict between new losers and winners within different parts of the catchment.
- **Micro Irrigation and Mulching:** These are possible options in Brown, Orange and Red catchments. Micro irrigation systems such as drips and sprinklers as well as plastic and organic mulching aim to reduce consumptive water use in irrigated crops. This reduction occurs through decreased evaporation from soil in fields (due to both micro-irrigation and mulching) and reductions in non-recoverable deep percolation (due to micro-irrigation).[35] Irrigated row crops for which a drip system can be used are: castor, cotton, fennel, groundnut, tomato, onion, maize, and fruit trees, plantation crops (coconut, etc.) and several of the vegetables for which the inter-plant spacing is more than one foot. The total area under irrigated

33 It is also to be noted that location, size and management of infrastructure is often as important as the type of infrastructure.

34 Some allowance may have to be made for sediment flows, in which case small embankments to trap the silt may be necessary. This is, however, a location-specific issue and such examples, as mentioned earlier, are only for illustrative purposes.

35 This reduction will have to be incorporated in the models (both SWAT and conceptual models) by changing the model parameters that compute soil evaporation and non-recoverable, deep percolation. But, at the same time, in the case of micro-irrigation, necessary modifications in the return flow fraction will have to be made in the model to take into account the fact that the deep percolation to shallow aquifer would be much less than that under traditional methods of irrigation, or even become zero. In order to apply water-saving technologies as a new intervention in the water balance models and to assess their impacts on overall water balance, it is important to know the physical impacts of these technologies in terms of real water saving, which comes from reduction in consumptive water use per unit of crop land. Such reduction can come from the following: 1] reduction in non-recoverable deep percolation; and 2] reduction in non-beneficial evaporation from the soil covered by canopy and barren soil (see Allen *et al.*, 1998; Kumar and van Dam, 2013).

crops which are amenable to micro-irrigation and mulching will need to be assessed.[36]

- **Mulching for Rainy Season Crops:** This is a possible option for Brown, Orange and Red catchments. Mulching in rain-fed crops could decrease water demand by reducing soil evaporation and increase the total water availability for meeting the transpirative demands from the soil profile, and reduce the need for supplementary irrigation.[37] Rain-fed row crops that are amenable to mulching and grown during the rainy season in the catchment will need to be identified.

- **Afforestation, Tree and Grass Plantation:** This can be an intervention option in Blue catchments, especially if the runoff from the catchment carries excessive sediments. While grasses will reduce erosion they may not increase ET and soil moisture storage as significantly as deep-rooted trees (though this is subject to the leaf area index and tree density; see Oliveira *et al.*, 2005). More importantly, unlike trees, grasses do not survive during the dry seasons in hot tropics, thereby bringing down the ET losses during the season to zero. More trees will, however, reduce downstream flows.[38]

36 As noted earlier, however, it is also true that with increasing profits per unit of water, farmers are likely to invest in expanding irrigated agriculture which could increase net consumptive use.

37 The actual impact in any particular location will depend on several location-specific factors including pests, labor requirements and relative costs.

38 Water to meet the ET demand of trees can come partly from precipitation 'interception', partly from the moisture in the active root zone, partly from the unsaturated zone underlying the soil, and partly also from shallow groundwater in the catchment. While the water demand of trees will reduce overall catchment yield (reduced runoff, reduced groundwater or both), the actual amount will depend on how the increased demand is being met from the hydrological system: If the deep soil strata (vadose zone) along with top soil contributes to ET of trees, then the impact will be on both groundwater system and runoff, whereas if shallow groundwater contributes to ET, then the most significant impact will be on base flows and groundwater. Higher the leaf area index, higher will be the transpiration (Hamilton and King, 1983; Oliveira *et al.*, 2005). On the other hand, litter cover on the forest floor increases infiltration rate of precipitation significantly (Hamilton and King, 2003). Nevertheless, the large canopy cover will have some effect on the micro climate in terms of increasing the humidity, reducing temperature and solar radiation. While all these factors would reduce ET rates for the vegetation per unit area, the third factor will also have a negative impact on the biomass outputs for crops due to the shade created by the tree cover.

Limits to Catchment Management in IWMP

While such typologies can guide the selection of management strategies and interventions for IWMP projects, such projects are clearly only one of many factors causing changes in the hydrology of the catchment. Apart from other government departments (such as the Departments of Water Resources, Agriculture and Forests, Highways) and programs (such as MNREGS, RKVY and BRGF), there is also a tremendous amount of private investment in bore well irrigation – all of which are rapidly changing the hydrology of these catchments.

The major limitation of the IWMP, however, is a much larger issue of convergence between different government departments and programs. However, the biggest constraint to catchment management in India, and possibly in other developing countries, is the lack of a regulatory framework for water, wherein all the different stakeholders (and their representative groups) can come together to discuss their various water requirements and reach agreements – even on 'caps' that dictate how much water is to be let down the main stream or river to the next set of communities in the catchment.[39]

Even in countries where this has been attempted, for instance through Integrated Catchment Management (ICM), there are several lessons to be learnt. At the very least it depends on finding the social and institutional framework that suit the local conditions and cultures the best, and it certainly does not mean simply importing an alternative system without analyzing whether it would suit the local context.

39 This is of course not easy and there are many reasons why regulatory frameworks fail or do not work well (Molle, 2007).

CHAPTER-4

LESSONS FOR HYDROLOGY-BASED WATERSHED MANAGEMENT

OVERVIEW

The basic lesson drawn from both the international experiences with Integrated Catchment Management (ICM) and the approach described in the previous chapter in the context of the IWMP, is the fundamental need for sound hydrological analysis, political-economy analysis and sustained stakeholder consultations to underpin decisions on management strategies.

The lessons from the practical application of the methodology for hydrological assessments for catchment management are discussed in the context of two situations: for application in a stand-alone watershed management project (e.g., externally-supported) and for a scaled-up multi-year government watershed management program involving several sites (e.g., the IWMP).

SINGLE WATERSHED MANAGEMENT PROJECTS

The basic steps for applying the methodology in a stand-alone watershed management project are (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 re-run the model to track changes in the catchment.

Selection of Project Area

The 'ridge-to-valley' approach is a good starting point, as in the case of the IWMP, but multi-scalar bio-physical analysis is now possible with the expansion of data availability. River basin maps and topology provide an overview of the various catchments in the basin, and the sub-catchments of each catchment.[40] Ideally, the highest point of the catchment or sub-catchment should be part of the intended treatment area of the project and the project should prioritize this area as the starting point for planning and interventions. Even if it is not so, as sometimes in the case of pre-selected 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 stand-alone site with no hydrological connections either upstream or downstream).

Even if selected, the hilly and forested upstream areas of catchments 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 micro-wave repeater stations) under the control of the Ministry of

40 Although 'catchment' and 'watershed' have been used interchangeably till this point in the Report, these terms are now being used as hydrological units, with a decrease in scale from basin to catchment to sub-catchment to watershed to sub-watersheds and micro-watersheds. Thus, a 'watershed management' project is assumed to refer to an area that is equal to or smaller than a sub-catchment.

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 catchment for the hydrological simulation modeling depends more the need for accuracy of model findings. Freely available global datasets and improved 'open source' software means that modeling can be done at any convenient scale, but generally speaking, the larger the catchment, the easier it is to find stream gauging points or reservoirs, and better the (simulation) model at simulating catchment hydrology. As demonstrated in Section 3, the area selected for project interventions can lie within this larger catchment selected for modeling.

Hydrological unit versus administrative boundary is an 'old chestnut' (e.g., Farrington *et al.,* (eds), 1999) and while it would be helpful for model predictions if the project area were determined by hydrological criteria (e.g., the sub-watersheds 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 Catchment) 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 at the upper reaches of the catchment in the project area, even though the entire catchment is not being taken up for treatment under the project. The modeling can provide catchment-level information and scenarios that can be used for planning interventions.

Hydrological Assessment

Reviews of earlier hydrological assessments and perceptual modeling are necessary first steps to a new or updated hydrological assessment. This essentially involves understanding the catchment, its dynamics and complexities, usually from experience with other similar catchments elsewhere. Collecting secondary information, trawling and mining the internet, and undertaking a drive-through or a fly-over the catchment are useful parts of this activity, and can be undertaken in any order that is convenient, but informal discussions with local stakeholders are usually a must, in order to add details of interest and to assimilate local information.

The choice of model is usually the starting point of 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 sub-watershed 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 catchment 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 model 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 datasets (on reservoirs and canal networks, soils, crop yields, weather, etc.) and (3) local information (on cropping seasons, crop durations, irrigation applications, the number, (geo-referenced) location and development timelines of wells and RWH structures, etc.). Thus while the model can be set up fairly easily using global datasets, 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 catchment 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.[41] 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 any 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 3, to assess the technical details of the modeling (e.g., the separation of the dataset for use in warm-up, calibration and validation, the setting of model parameters and the use of manual functions instead of automatic functions as in the case of SWAT).

Main model outputs are the basic water balance components of the catchment (including key features such as evapo-transpiration, groundwater percolation, recharge of aquifers and runoff outside the catchment), which can be used to classify the watersheds along with information from stakeholder interactions about demand and supply.

Understanding future catchment 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 catchment-wide baselines and scenarios are useful and necessary, the model can also be used to create scenarios for the project area in detail.

Iterative Village Planning

Although discussed under separate headings, the hydrological assessment and the village planning are part of the same mutually-supportive process and need to be undertaken synchronously and iteratively.

Village planning can be initiated as a part of the process of stakeholder consultations. Using information from the earlier stakeholder interactions and field visits, 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 catchment 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 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 or groundwater flows. At the minimum, discussions will have to be held with the village communities downstream to see if some part of the plan can be scaled down (to reduce such adverse impacts) or if they are willing to discuss these impacts with downstream communities to see how these 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 inter-basin transfers, dams, urban areas and ecological requirements in the selected catchment. These will require locally-relevant and

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

effective socio-political institutions and mechanisms to be set up and operate to resolve the trade-offs that are inevitable when downstream flows reduce.

Finalizing the village plan will require additional considerations: These include understanding the support required to promote non-water-based livelihoods and assess the strength and capability of local organizations (e.g., youth groups, women's groups, ex-servicemen, religious groups) and local government officials in order to plan for the capacity building of individuals and groups and the strengthening of local institutions. The 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 Plan but these are all aspects that are beyond the scope of this study. Also beyond the current scope is the issue of a multi-stakeholder basin-level plan which would appear to be the best way of explicitly recognizing the hydrological status of the catchment, identifying possible future trade-offs and addressing potential 'losers' in the business-as-usual process of development.

WATERSHED MANAGEMENT PROGRAMMES

Scaling up from a single (pilot) watershed management project to a watershed management program at a national or sub-national scale or implementing such a management program at scale can also benefit from the lessons of applying the approach and methodology detailed in Section 3 of this Report. The steps involved in doing so are basically the same as discussed earlier but there are certain differences, which are detailed below.

Selection and Prioritization of Watersheds

Use hydrological boundaries to define watersheds. In India, the watershed atlas defines macro-watersheds of 400 – 1000 square kilometers, which can be a good basis for the selection of the catchment for modeling, given that the chances of getting reliable data improves significantly at this scale. But since it is not clear whether these have been delineated using hydrological boundaries, it would be better to use a program like SWAT to define these boundaries.

Prioritizing watersheds is best done from upper reaches of catchments: As being done by the IWMP, starting with watersheds in the upper reaches and then moving progressively down to those in the lower reaches is a good approach, but needs to be done using hydrologically-defined boundaries, unlike current practice.

Hydrological Assessment

Modeling requires a cadre of competent hydrologists to service all project locations. Even if available, it is vital that they are put through a training program so that the approach taken to the modeling is similar and comparable. Ideally, all the modeling across the program should be overseen by an institution with expertise in modeling, although the approach and methodology (e.g., model choice, steps to be followed, iteration with stakeholder interactions, model outputs and scenarios) to be followed in the program should be agreed upon in advance and standardized. Ideally, the modeling should plan to analyze each upstream-downstream sequence of watersheds within the larger catchment, to inform stakeholder discussions in each sequence (or cascade).

It would be better to use the same model across the program: Although different sub-national units (e.g., SLNAs in the IWMP) could of course be given the freedom to use different models, better results and greater uniformity of quality may result from using the same model. Modifications can (and should) always be made based on local conditions (e.g., the addition of a groundwater model such as MODFLOW in catchments where groundwater aspects are critical to the water balance). Allocating sufficient time and resources to develop the modeling facilities and skills will critically affect the use of such models for watershed management and planning.

Model set-up will depend critically on the skill and experience of the modeler: Instituting hand-holding support from a centralized agency contracted to do so would help in the initial rounds of modeling to check the quality of modeling outputs.

Data collection should be standardized, in terms of data requirements and the sources and quality of datasets. A national government watershed management program should be able to provide modelers with access to the best possible country-specific data sets (e.g., DEM, soils, weather, reservoirs and canal networks, soils and crop yields). Providing access to such data officially through a national data portal will significantly reduce the time required to acquire the various datasets for the modeling and therefore to set up the model. There will still be a need to collect local information (e.g., on cropping seasons, crop durations, irrigation applications and the number, (geo-referenced) locations and development timelines of wells and RWH structures) through primary surveys, but these can also be standardized and applied through suitably trained field staff.

Model calibration and validation is best quality-checked by experts. How well the model is able to simulate catchment hydrology (based on both the 'goodness of fit' and the extent of uncertainty inherent in model predictions),[42] is best assessed by experts, preferably through the agency contracted to oversee the modeling process. Such a quality-check on the assumptions that went into detailing the model specifications (e.g., the use of manual instead of automatic functions in SWAT) and the data used (for the warm-up, calibration and validation) will help to ensure that the 'goodness of fit' is as close to ideal as possible and uncertainty is minimized.

Model outputs should also be quality-checked by experts. Basic outputs such as the basic water balance of the catchment (including key features such as evapo-transpiration, groundwater percolation, recharge of aquifers and runoff outside the catchment) will also have to be checked by the expert group to ensure that they are in consonance with both prior modeling results (e.g., published in international peer-reviewed journals) and expert opinion. Along with information from stakeholder interactions about water demand and supply (from the primary village surveys), these model outputs can be used to classify the catchment as per the types discussed earlier (Blue, Green, Brown, Orange and Red).

Creating future scenarios can also be standardized. Apart from certain basic scenarios, the expert agency could also decide to create additional scenarios based on the catchment in question. Interpretation of the catchment scenarios will also require oversight, at least initially, to ensure that good practice is followed (e.g., relating scenarios to a baseline produces more reliable results than taking the absolute values of scenario outputs). In addition to catchment-wide scenarios, the model should also be used to create scenarios for specific project areas.

Iterative Village Planning

Both, the hydrological assessment and the village planning, are to be undertaken synchronously and iteratively.

Village planning is to be done with inputs from the hydrological model. Although village planning is done in most watershed management projects, and often in a participatory mode, it is usually done without reference to outputs from a hydrological model. Field staff will, therefore, have to be trained in carrying out village planning, as a part of the process of stakeholder consultations, supplemented with model scenarios. In practical terms, this will mean moving beyond simple Focus Group Discussions (FGDs) as part of a Participatory Rural Appraisal (PRA) process to involving villagers in discussions of local catchment characteristics and problems, using maps based on remotely-sensed data. Tools to create interactive map-based discussions can range from the relatively cheap and simple Google Earth to more sophisticated maps using GIS layers on remotely-sensed data. The key issue, however, is to make the discussion interactive. Detailed planning will of course 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

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

drinking water for humans and livestock) using traditional knowledge and skills.[43]

Assessing plan implications using the model is an iterative next step. This step will also require special training and oversight from the expert group, at least in the initial stages. This will introduce into the model the key features of the Village Plans (including the total additional capacity of wells and RWH structures planned, the area of crops to be put under micro-irrigation and mulching, the area to be converted into double cropped area, new crop choices along with their irrigation regimes, duration and likely yields) to create a separate scenario to assess potential hydrological impacts in terms of the water balance components.

Addressing downstream impacts will be a critical part of the watershed management program. This can be based on the typology discussed earlier but focusing on stakeholder interactions with villagers in downstream areas. Wherever planned interventions are likely to have adverse downstream impacts, such as reductions in surface or groundwater flows, iterative discussions will have to be facilitated with representatives from downstream communities to see how these adverse impacts can be minimized. As these communities lower down are to be taken up sequentially for watershed management, the discussions with stakeholder groups can be started on issues such as water productivity enhancements (so that even reduced quantities of water may produce the same level of profit per unit area), prioritizing of drinking water for humans and livestock, and promoting non-water-based livelihoods (including, skill development and support for migrants).

An innovative aspect that would help build community cohesiveness would be to facilitate visits by the community benefiting directly from the project to downstream communities to help spread awareness about the benefits of these practices (based on their experiences through project interventions).

43 This was an approach (called 'gut-level planning') used in the early watershed management projects (1990 – 1995) of the Indo-German watershed management program started by the Social Centre in Aurangabad and later continued by the Water Organizations Trust (WOTR). It has, however, not been actively followed in later watershed management programs.

Sufficient time and resources (including staff being trained to facilitate these discussions) should be made available as communities will participate and invest in these discussions only if they feel the benefits outweigh the costs. Sustaining community involvement, however, will be a challenge. While some incentive will be available for downstream communities in terms of a future watershed management project, some sustained and consistent efforts will be needed to underpin long-term ownership of village plans and management. One possible option to avoid a falling-off of interest after the initial planning stage is to have either a financial commitment or a formalized agreement at the village-level. A possible co-payment option is for the government to pay for the infrastructure development, while monitoring and maintenance costs are shared by landowners and villagers in both upstream and downstream villages. In addition, a (stream flow) measurement-based monitoring system can be set up with to enforce long-term agreements on water allocation and sharing, similar to the setting up of discharge limits from upstream areas used in Australia. These possibilities, however, need further investigation and piloting.

LESSONS FOR IWMP

The hydrology-based approach and methodology for watershed management has several significant differences with the current approach (Table 4.1).

Policy and Other Supportive Actions

Increasing profits per unit of water as a strategy to manage rising water demand from agriculture requires supportive policy and program actions, such as price support policies (to promote less water-using crops – or at least to *not* promote more water-using crops), electricity pricing (which is a major driver of groundwater exploitation) and policies and laws to regulate groundwater use. Agricultural marketing remains a major concern, with high production not translating into high profits for many small and medium farmers, as are access to cheap institutional credit and better agricultural extension services to improve yields.

As the performance of national and state-level policies in India to provide top priority to drinking water needs

TABLE 4.1 DIFFERENCES WITH THE IWMP APPROACH AND METHODOLOGY

Issue	IMWP Approach	Revised Approach
Selection and prioritization of watersheds	Selection based on 13 criteria 'Ridge to valley' approach to prioritize selected watersheds, but without reference to hydrological boundaries Size of watersheds selected (5000 ha) but not based on hydrological units	Based on hydrological boundaries and prioritized using a 'ridge to valley' approach within these boundaries Sequence of watersheds selected from upstream to downstream till the outlets of sub-watersheds within the catchment Watersheds to be selected based on hydrological boundaries (e.g., sub-catchments and sub-watersheds)
Hydrological assessment	Not done	Perceptual and simulation modeling at catchment scale, possibly using large-scale macro-watersheds (e.g., 40,000-70,000 hectares), using information from secondary sources and stakeholder interactions
Village planning	Primary data collected using questionnaires and FGDs, as part of a PRA exercise, but only on existing RWH structures (but not geo-referenced) Planning usually finalized by technical experts with villagers asked to help with site selection Limited discussion of alternative options and no strategy to either raise water productivity or limit water demand (although micro-irrigation is promoted) No revisiting of village plans No discussions with downstream communities on approaches to tackle possible reductions in downstream flows	Primary data collected using questionnaires and FGDs, as part of a PRA exercise, directly aimed to collect (additional) information on hydrological aspects (e.g., geo-referenced information on wells and RWH structures and information on cropping patterns, crop durations, irrigation frequency, etc.) Village discussions informed by model outputs and scenarios Detailed planning of water supply augmenting options (including for different farmer fields and for water bodies) and water demand management options (including micro-irrigation, mulching and switching to less-water intensive crops) aimed at improving water productivity (i.e., profit per unit of water) Iteration of village plans using model scenarios to minimize downstream impacts Discussions with downstream communities on approaches to tackle possible reductions in downstream flows

has shown, it is not sufficient just to have policies: their implementation is just as important. This is where coordinated action across government departments is vital, and a good example has been set by the World Bank supported Irrigated Agriculture Modernization and Waterbodies Restoration and Management (IAMWARM) project of Tamil Nadu, where staff from seven government departments and an agricultural university formed local teams to work in project villages. A major factor in developing this cohesion was the innovative 'behavioral change' experiment carried out to raise the motivation and commitment of government staff.

In many cases, including the IWMP, such policy changes are not within the control of implementing departments, and inter-agency coordination (or 'convergence') is confined to IWMP staff facilitating farmers in project areas to access schemes from other departments (e.g., for drips and new varieties of seeds). As a result, IWMP projects do not facilitate better access to agricultural markets, credit, and non-water-based livelihoods, all of which are critical to improved watershed management. Even prioritization of drinking water is not seen as an area of work for the IWMP, as this is taken care of by a separate government department.

The hydrology-based approach and methodology discussed here may not progress far beyond an academic exercise in modeling if the IWMP (or any government national watershed management program) does not invest the time, effort and resources needed to raise (and use) the capacity of its staff for modeling and for facilitating stakeholder interactions, bring in (modeling) expertise and re-orient its activities to focus on improved watershed management outcomes.

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