EVALUATING THE IMPACTS OF RAINWATER HARVESTING (RWH) IN A CASE STUDY CATCHMENT: THE ARVARI RIVER, RAJASTHAN, INDIA

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A thesis submitted in fulfilment of the requirements of the degree of Doctor of Philosophy

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CERTIFICATION OF ORIGINALITY

I hereby certify that the substance of the material used in this study has not been submitted already for any degree and is not currently being submitted for any other degree and that to the best of my knowledge any help received in preparing this thesis, and all reference material used, have been acknowledged.

Claire Jean Glendenning
2009
ABSTRACT

In many areas of India, increasing groundwater use has led to depleted aquifers. Rainwater harvesting (RWH), the small scale collection and storage of runoff to augment groundwater stores, is seen as a solution to the deepening groundwater crisis in India. However while the social and economic gains of RWH have been highlighted, there has not yet been a thorough attempt to evaluate the impacts of RWH on larger catchment hydrological balances. The thesis here will endeavour to address this research gap through a case study of the 476 km$^2$ ungauged semi-arid Arvari River catchment in the state of Rajasthan. Over 366 RWH structures have been built in this catchment since 1985 by the community and the local non-government organisation (NGO), Tarun Bharat Sangh (TBS).

The local effects of RWH structures and general catchment characteristics were determined through field investigations during the monsoon seasons of 2007 and 2008. The analysis described large variability in both climatic patterns and recharge estimates. Potential recharge estimates from seven RWH storages, of three different sizes and in six landscape positions, were calculated using the water balance method, which were compared with recharge estimates from water level rises in twenty-nine dug wells using the water table fluctuation method. The average daily potential recharge from RWH structures is between 12 – 52 mm/day, while recharge reaching the groundwater was between 3 – 7 mm/day. The large difference between recharge estimates could be explained through soil storage, and a large lateral transmissivity in the aquifer. Approximately 7% of rainfall is recharged by RWH in the catchment, which is similar in
both the comparatively wet and dry years of the field analysis. This is because the
capacity of an individual structure to induce recharge is related to structure size and
capacity, catchment runoff characteristics and underlying geology. Due to the large
annual fluctuations in groundwater levels, the field study results suggest that RWH has a
large impact on the groundwater supply, and that there is a large lateral flow of
groundwater in the area.

The results inferred from the field analysis were then applied to a conceptual water
balance model to study catchment-scale impacts of RWH. An existing model was not
used because of the paucity of data, and the need to incorporate an effective
representation of RWH function and impact. The model works on a daily time step and
is divided into subbasins. Within the subbasin hydrological response units (HRUs)
describe the different land use/soil combinations associated with the Arvari River
catchment, including irrigated agriculture.

Sustainability indices, related to water from groundwater and rainfall for irrigated
agriculture demand, were used to compare scenarios of management simulated in the
conceptual model. The analysis shows that as RWH area increases, it reaches a limiting
capacity from where developing additional RWH area does not increase the benefit to
groundwater stores, but substantially reduces streamflow. This limiting capacity was also
seen at the local-scale, where cumulative potential recharge from an individual RWH
structure reaches a maximum daily recharge rate. These results could have important
implications for RWH development, but require further research. The analysis
highlighted the important link between irrigation area and RWH area. If the irrigation
area is increased at the optimal level of RWH, where the sustainability indices were
greatest, the resilience of the system actually decreased. Nevertheless RWH in a system
increased the overall sustainability of the water demand for irrigated agriculture,
compared to a system without RWH. Also RWH provided a slight buffer in the
groundwater store when drought occurred.
While RWH addresses the supply-side issues of groundwater operation, the institutions that form rules for groundwater use must also be considered, because of the link between irrigation area and RWH. The Arvari River Parliament, the community-based group in the case study area, was examined according to Ostrom’s factors for collective action. It was found that the major limitation for the effectiveness of this group was the minimal information available about the aquifer characteristics.
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This thesis is dedicated to my prerna, Vivek Umrao.
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1. INTRODUCTION

1.1. Motivation

Water is the most basic necessity for nature and humans. However, as human population increases, society is facing serious issues related to water quantity and quality. The global community now acknowledges a water crisis: the UN has declared 2005 – 2015 the decade of water and many of the Millennium Development Goals focus on water; Target 10 is to halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015 (UN Millennium Project 2005).

Groundwater is an important resource for humans. Globally groundwater provides 50% of current potable water supplies, 40% of the demand for self-supplied industry and 20% of irrigation water (Villholth 2006). In India, where 15% of the world’s population lives, groundwater accounts for over 80% of domestic water use in rural areas, and 55 – 60% of the Indian population (about 620 million people) is directly or indirectly dependent on groundwater for its livelihood. Since the increased use of groundwater in India, millions of people have been lifted out of poverty (Kemper 2007). Despite and because of the importance of groundwater, exploitation and degradation of groundwater supplies is a serious issue in India, and groundwater tables are rapidly falling in a number of states.
(Rodell, Velicogna et al. 2009). The search for feasible solutions for sustaining groundwater stores is therefore gaining considerable momentum, and rainwater harvesting (RWH) is encouraged as a possible solution.

Rainwater harvesting (RWH), a traditional catchment development tool in South Asia, collects and stores runoff that falls during the heavy downpours in the Indian monsoon season, allowing time for the stored water to recharge shallow groundwater aquifers. Despite the so-called ‘groundwater recharge movement’ in India, which has been promoting and reinvesting in RWH over the past three decades, there is a lack of systematic studies that have measured the hydrological impact of RWH structures and generated recharge on local and catchment-scale water balances. A number of studies have highlighted the possible negative impacts of RWH, which could be high unreliability in drought years and high negative externalities at higher degrees of catchment development (Kumar, Patel et al. 2008). Rainwater harvesting redistributes the available water resources across the catchment, by increasing the annual amount of catchment rainfall that is stored and becomes recharge, which could change other water balance components, including evaporation and streamflow, with possible trade-offs between upstream and downstream users, and users and the environment (Kumar, Ghosh et al. 2006). However these arguments are not confirmed by any empirical studies.

The purpose of this research is therefore to expand the knowledge of the impacts of RWH at the local and catchment-scales. This research seeks to understand the changes in the catchment water balance by first examining the local-scale impacts of RWH in a case study catchment of the Arvari River in the state of Rajasthan, India. A simple conceptual model is subsequently developed to extrapolate the results of the field work to the catchment-scale. This model makes it possible to investigate the interrelationships between RWH, irrigated agriculture and any possible impacts on catchment water balances that may occur under increasing areas of RWH. The major contribution from this study is a methodology to systematically examine the impact of RWH development in a catchment.
1.2.  Research Questions and Objectives

The principal question investigated in this thesis is:

*What are the hydrological impacts of RWH at the local and the catchment-scales?*

This research question will be broken down into two main parts. The first section considers the local-scale impacts of RWH for a case study catchment, the Arvari River, and the second section examines the catchment-scale impacts through the use of a water balance model. A final smaller section examines the institution in the study area catchment that manages groundwater use.

The hypotheses that are tested in the first section are:

- Recharge from RWH has a large local-scale effect on groundwater levels
- The magnitude of recharge from RWH is dependent on the annual rainfall

To test these hypotheses at the local-scale, research questions addressed included:

- How much rainfall is potentially recharged by an individual structure?
- Are there any differences or similarities in recharge behaviour between structures in a similar area or by structure type?
- How much potential recharge reaches the underlying aquifer?
- How effective is RWH in recharging groundwater?
- What is the zone of influence of RWH?
- What are the main hydrological processes that are influenced by RWH?
- What are the general climatic and landscape characteristics of the semi-arid case study catchment that might influence RWH?

The hypotheses that are tested in the second section are:

- Increased area of RWH decreases streamflow downstream
- Development of RWH increases the viability of irrigated agriculture
- At higher levels of RWH development in a catchment, the benefit is not as great as during the initial stages of RWH construction.

To address these hypotheses the research questions considered were:
• Is there an existing water balance model that can simulate all the relevant catchment hydrological processes related to RWH?
• Using a hydrological model, how does RWH impact the modelled catchment system?
• How effective is RWH in alleviating drought for groundwater irrigated agriculture?

Rainwater harvesting is a supply-side groundwater management tool, and therefore the institutions, which define access and conservation rules, are important to consider for sustainable groundwater management. In the final section of the thesis, the effectiveness of the catchment community institution in the case study catchment is investigated, and whether this institution addresses groundwater demand issues.

1.3. Outline of Thesis

The study consists of eight chapters. Following this Introduction, Chapter 2 reviews the current literature related to RWH in the world and more specifically in India. The major issues with groundwater in India are considered and RWH is defined. The gaps in the literature are identified and relate to the quantification of RWH impacts at the local-scale and catchment-scale. Groundwater institutions in India are also highlighted as an under researched area.

Chapter 3 gives a brief introduction to the study area catchment, the Arvari River, which was chosen for extensive field work in 2007 and 2008. The catchment is well known for its RWH work, with over 366 structures throughout the catchment. Like many catchments in India, RWH development was planned at the village-scale, with no larger catchment-scale plans. There is limited data available on aquifer characteristics, and no climate station in the catchment. The methodology for data collection is also described
and the analysis of the variation in catchment rainfall presented. The dominant land uses are explained and details of sampled soil profiles are given.

Field data collected in the monsoons of 2007 and 2008 in the Arvari River catchment are analysed in Chapter 4. The first part of the chapter examines the data from the RWH structures and calculates potential recharge from each monitored structure. These results are compared with the analysis of the response in groundwater levels from the monitored dug wells. High spatial and temporal variability is seen; a common feature of semi-arid regions, but some broad conclusions on local-scale RWH impacts can be inferred from this chapter. This information is needed to up-scale these impacts to a catchment-scale water balance model.

Chapter 5 develops a conceptual water balance model, which will be used to answer the catchment-scale research questions. The model is based on hydrological response units (HRUs), and includes the surface water – groundwater interactions, which are important in RWH function. Results of the simulation of different management scenarios in the model are then compared in Chapter 6 using sustainability indices. The impact of rainfall on RWH function is also examined.

Chapter 7 examines the Arvari River Parliament, a catchment group in the case study area, which has defined informal rules for water resource development and management. These rules are considered with regards to groundwater use, and whether the institution is effective in monitoring and enforcing groundwater extraction.

The final chapter presents the important implications of the results. Here, key findings are summarised, and implications are drawn from the study’s findings. The chapter also discusses limitations of the study, leading to avenues for further research.
2. A REVIEW OF RAINWATER HARVESTING (RWH) FOR GROUNDWATER RECHARGE

2.1. Introduction

Globally groundwater is an increasingly important natural resource, particularly in India where it accounts for more than 45% of the total irrigation supply (Kumar, Singh et al. 2005), and for about 9% of India’s GDP (Mudrakartha 2007). However this has not always been the case, in the last 50 years or so India has seen a huge boom in the use of groundwater. In 1960, tube wells numbered less than one million, which by 2000 had increased to an estimated 19 million (Shah, Deb Roy et al. 2003). This has had a large impact on small-holder farmers in India, because crops irrigated by groundwater are generally more productive than using surface water irrigation as groundwater requires little transport, can be accessed relatively easily and cheaply, is produced where it is needed and provides a relatively reliable source of water (Dhawan 1995). Evidence from India suggests that crop yield/m$^3$ on groundwater irrigated farms tends to be 1.2 – 3 times
higher than on surface water irrigated farms (Dhawan 1989). However three serious problems currently affect groundwater use in South Asia: depletion due to overdraft; water logging and salinisation; and pollution due to agricultural, industrial and other human activities (Shah, Deb Roy et al. 2003). In many parts of the country the water table is declining at the rate of 1 – 2 m/year (Singh and Singh 2002). The search for feasible solutions for alleviating groundwater shortages is therefore becoming urgent. One option being increasingly considered and implemented, is rainwater harvesting (RWH) (Agarwal and Narain 1997).

Different techniques of rainwater harvesting are found throughout the Middle East, Africa and South Asia. In many areas of India this method is important for groundwater recharge, because the major portion of the annual rainfall is received in around 100 hours of heavy monsoonal downpour, providing very little time for natural recharge to the aquifer due to rapid runoff. This technique has become even more relevant as more land has been deforested, increasing runoff. Rainwater harvesting stores monsoonal runoff, which then percolates to groundwater tables (Keller, Sakthivadivel et al. 2000). India has a long history of RWH and currently rising investment in RWH development. It is therefore increasingly important to quantify the hydrological impact of RWH structures. In particular, it is important to understand the downstream trade-offs in a larger catchment with RWH, because of possible changes in the catchment water balance and changes between blue and green water (Falkenmark 2003).

While RWH addresses supply issues related to groundwater, the management of groundwater demand is through institutions. Institutions affect the access, operation and monitoring of a resource through defined rules. Historically natural resources were common property in India, but under present legislation groundwater rights are privatised. This has lead to property rights issues and over-extraction of groundwater, for example the Coca Cola case in India, where the industrial use of groundwater has caused water levels to decline in neighbouring small-holder farms (Gronwall 2006). In developing countries community-based common property resource management is a viable alternative to state or private property rights (Saleth 2005). A key question is
whether such community institutions would be effective in management of the groundwater resource.

2.2. Rainwater harvesting (RWH)

Rainwater harvesting involves using small-scale structures to collect runoff for either supplemental irrigation, as is most common in Africa (Ngigi, Savenije et al. 2007), or for groundwater recharge, as is typical in many regions of India (Kumar, Ghosh et al. 2006). Although literature highlights RWH as an efficient cost-effective method of replenishing aquifers, the few studies that have quantified RWH impacts have generally done so at local, small-scale catchments and have not considered larger catchment hydrological impacts, such as downstream trade-offs or surface water – groundwater interactions, where use of one type affects the availability of the other (Badiger, Sakthivadivel et al. 2002; Sharda, Kurothe et al. 2006).

2.2.1. Groundwater Use and Problems in India

Eighty percent of global groundwater use occurs in Bangladesh, China, India, Iran, Pakistan and the US (Shah, Burke et al. 2007), with India being the largest groundwater irrigator in the world (Shah, Singh et al. 2006). In India and China combined, 1 – 1.2 billion poor small-holder farmers are supported by groundwater (Shah, Burke et al. 2007). This is because groundwater irrigation tends to be less biased against the poor than large scale surface water irrigation projects (Deb Roy and Shah 2002). Groundwater is easily accessible and can be developed quickly by farmers or small groups, and can be reliable and flexible in time and space. In India groundwater-based irrigation covers a greater area than the established canal irrigated systems, which were set up largely by the colonial government in the late 19th century (Sakthivadivel 2007; Shah 2007a). Groundwater also has the advantage of having less evaporation than surface dams and canals (Keller, Sakthivadivel et al. 2000).
In India, the advance of technology from shallow wells with animal pulling and human labour, to diesel pumps and electricity has greatly impacted the amount of groundwater extraction since independence in 1947 (Shah, Singh et al. 2006). While exponential groundwater use over the past few decades has improved livelihoods by allowing more stability for cropping, there are increasingly serious issues with aquifer depletion (Shah, Burke et al. 2007). This is partly due to electricity subsidies by state-owned electricity services to farmers, which has encouraged over extraction of groundwater (Radhakrishna 2003; Narasimhan 2005; Subash Chandra 2005). But there is also a serious lack of proper planning and management of groundwater extraction, with little regulation and enforcement (Radhakrishna 2003; Datta 2005; Subash Chandra 2005). Groundwater is largely a private informal sector, where each well owner regulates their own use; public agencies do not play a direct role in groundwater management. Effective institutional arrangements to manage groundwater have not yet been developed, which means that use of groundwater still remains unchecked (Villholth and Giordano 2007; Shah 2007b) (this will be explored in more detail in Section 2.4). With the increasing severity of extreme events such as droughts and floods predicted over the next 20 years, and increasing population pressures, groundwater management will become even more important to address (Pandey, Gupta et al. 2003; Gupta and Deshpande 2004; Ramesh and Yadava 2005).

Currently the response to groundwater depletion has focussed on supply-side management of groundwater rather than demand-side. In India a massive integrated catchment development program provides public resources to local communities for catchment development works, including constructing rainwater harvesting (RWH) structures (Hope 2007; Shah 2007a). Based on trends during the 1990’s, there has been a progressive shift of budgetary allocations from irrigation development to RWH (Shah 2007a). Methods to recharge aquifers, including RWH (sometimes referred to as artificial recharge), have become so widespread in India over the last two to three decades that it is now referred to as ‘a groundwater movement’ or ‘artificial recharge movement’ (Sakthivadivel 2007; Sakthivadivel 2008). However one of the difficulties of
such a movement is the lack of documentation of the impacts of these projects on groundwater, and any upstream-downstream trade-offs (Hope 2007; Sakthivadivel 2008). The reliance and depletion of groundwater in India has meant investment in RWH, to augment groundwater stores, has occurred rapidly without any hydrological assessment (Kumar, Ghosh et al. 2006). Consequently, the use of RWH and its impacts must be more fully understood to allow its potential benefits and impacts to be realised.

### 2.2.2. What is Rainwater harvesting (RWH)?

Some of the literature describes RWH for groundwater recharge as artificial recharge (Bouwer 2002). However in much of the literature, RWH is considered part of ‘managed aquifer recharge’, which also includes artificial recharge, enhanced recharge, water banking and sustainable underground storage (Dillon 2005; Gale 2005). Managed aquifer recharge is defined as the ‘planned, human activity of augmenting the amount of groundwater available through works designed to increase the natural replenishment or percolation of surface waters into the groundwater aquifers, resulting in the corresponding increase in the amount of groundwater available for abstraction’ (IETC 1998).

Rainwater harvesting encompasses methods to induce, collect, conserve, and store runoff from various sources and purposes, by linking a runoff-producing area with a separate runoff-receiving area (Boers and Benasher 1982; Rockstrom 2000; Young, Gowing et al. 2002) (Figure 2-1). Methods of RWH have three common characteristics (Boers and Benasher 1982):

1. They depend upon small-scale capture of local water. RWH does not include storing river water in large reservoirs or the mining of groundwater.

2. They can be applied in arid and semi-arid regions, where runoff has an intermittent character and rainfall is highly variable, so drought and flood hazards to agriculture are significant. In these areas storage of water is important. This means RWH is viable in areas with annual rainfall as low as 300 mm (Kutch
1. Rainwater harvesting is a relatively small-scale operation in terms of catchment area, volume of storage, and capital investment. The scale of RWH can range from household to field or small catchment (Ngigi 2003). Mbilinyi, Tumbo et al. (2005) based RWH on the size of the runoff-producing area. These include:

- On-farm, within-field systems or in situ. Rainfall is captured where it falls, to conserve water and prevent runoff from cropped areas and prolong the time for infiltration (Vohland and Barry 2009).
- Micro-catchment system, where there is a distinct division between the runoff-generating catchment area and a cultivated basin or storage area where the runoff is concentrated and stored (Gowing, Mahoo et al. 1999). In micro-catchment water harvesting, the percentage of runoff increases with decreasing catchment size due to reduced infiltration losses. Small watersheds can produce runoff of about 10 – 15% of annual rainfall (Boers and Benasher 1982).
- Macro-catchment RWH which has a large catchment area than micro-catchment systems.

Figure 2-1: Schematic representation of RWH function for groundwater recharge
From as early as 4500 BC, RWH has been practised in various parts of the world (Verma and Tiwari 1995), and is most commonly found in developing countries due to its decentralised, low cost and local-scale aspects (Ngigi 2003). Indigenous RWH systems, such as jessour and meskat in Tunisia (Schiettecatte, Ouessar et al. 2005), tabia in Libya, cisterns in north Egypt, hafaer in Jordan, Syria and Sudan, underground cisterns (aljibes) in Spain (Van Wesemael, Poesen et al. 1998) and many other techniques are still in use (Oweis, Hachum et al. 1999). Irrigation reservoirs or tanks have been in existence for more than 2000 years in Sri Lanka (Matsuno, Tasumi et al. 2003).

In India RWH also has a long history, practised for at least the last 1000 years and based on traditional knowledge and collaboration between communities with local kings (Agarwal and Narain 1997; Shah 2001; Pandey, Gupta et al. 2003; Sakthivadivel 2007). Traditional RWH systems were even practised in the Indus valley (3000 BC – 1500 BC) (Grey and Sharma 2005). Techniques of RWH have been noted in ancient texts, such as the Rigveda (1500 BC) and the Atharva Veda (800 BC) (Agarwal and Narain 1997). According to a historical study by Pandey, Gupta et al. (2003), abrupt climate fluctuations heightened construction efforts of RWH structures across regions in prehistoric and early historic societies. Despite the traditional use of RWH, it became neglected from the time of British rule (Radhakrishna 2003). With Indian independence, the state became the major provider of water, replacing communities and households as the primary units for provision and management of water (Agarwal and Narain 1999). But in the last few decades, RWH has seen a strong revival due to groundwater depletion, involving the participation of communities, government and non-government organizations (NGOs). It has been estimated that in India today, almost 1.5 million traditional village tanks, ponds and earthen embankments harvest rainwater in 660 000 villages (Pandey, Gupta et al. 2003).

In India one of the main purposes of RWH is to store runoff to recharge shallow groundwater aquifers (Agarwal and Narain 1997). This technique developed as a result of the pattern of monsoonal rainfall in June to September of each year, but methods are highly location specific (Verma and Tiwari 1995). The normal duration of the monsoon
in India is about 100 – 120 days and the Indian plains receive about 80% of annual rainfall during this time (Kumar, Singh et al. 2005; Ramesh and Yadava 2005). As a result of high intensity rainfall in such a short period of time, RWH stores runoff that could otherwise continue downstream. Because RWH has a small storage capacity, it responds quickly to rainfall-runoff compared to larger dams. Depending on the geology, stored water can percolate into the underlying groundwater table (Figure 2-2). The groundwater is subsequently used for irrigation, and domestic purposes via dug wells or tube wells. A disadvantage of RWH is that open storages are often subject to high evaporation losses, due to high surface area to volume ratios (Neumann, MacDonald et al. 2004). But storage in aquifers has the advantage of essentially zero evaporation (Bouwer 2002). Rainwater harvesting also tends to lead to increased crop production intensities and greater crop yield, because rises in the water table mean better accessibility and yields of groundwater (Keller, Sakthivadivel et al. 2000).

![Figure 2-2: Example of a RWH structure known as an Anicut in Rajasthan, India. At the end of the monsoon in September the structure is full. Three months later the storage is almost empty, through evaporative loss, lateral subsurface flow and recharge.](image)

2.2.3. Previous Studies Measuring the Impact of RWH

Until recently RWH was seen as a totally benign technology (Batchelor, Rama Mohan Rao et al. 2003). This is because the impact of an individual dam was considered relatively small. However the cumulative impact of RWH, which are essentially small farm dams, on streamflows could be significant (Calder, Gosain et al. 2006). Additionally, as groundwater increases, land use changes and favours more irrigated
agriculture (Sharma 2002). The need to quantify the overall impact of RWH in a catchment is important, because it can cause unintended impacts such as inequitable sharing of water between upstream and downstream users (Batchelor, Singh et al. 2002). Nevertheless there are very few published studies that have accurately quantified the nature and magnitude of these impacts in India, with most being mainly site-specific and descriptive (Kumar, Ghosh et al. 2006; Sakthivadivel 2008). In addition the studies relate mainly to RWH storage, but there is lack of research on recharge or streamflow impacts.

A number of studies have examined the amount of runoff that can be captured by RWH, i.e. runoff potential, to prioritise catchments for RWH development. Many studies encouraged the use of satellite images and GIS to estimate runoff potential of studied catchments (Sharma, Kiran et al. 2001; Anbazhagan, Ramasamy et al. 2005; Sekar and Randhir 2007). Gupta et al (1997) used the curve number (CN) method with GIS to estimate runoff potential in a semi-arid catchment of Rajasthan for RWH development. Tripathi and Pandey (2005) used an estimated runoff coefficient of 0.8 to examine if villages in the Kutch District of Gujarat would benefit from RWH or not. None of these studies considered potential RWH impacts on groundwater levels and surface flow in the catchments they prioritised, or how many structures would be suitable without significantly altering the catchment water balance.

Lumped or conceptual water balance models have been used to estimate groundwater recharge from different RWH techniques in the world (Hassan and Bhutta 1996; Ouessar, Sghaier et al. 2004; Badarayani, Kulkarni et al. 2005; Pretorius, Woyessa et al. 2005; Ouessar, Bruggeman et al. 2008), in addition to numerical and analytical techniques (Sorman and Abdulrazzak 1993; Khazai and Spank 1997; Kahlown and Abdullah 2004; Jha and Peiffer 2005). Neumann et al. (2004) developed a conceptual methodology to calculate recharge from RWH structures using Darcy’s Law, and analysed theoretical aquifer impacts using MODFLOW. The study concluded that the impact of RWH on water levels in a catchment may be minimal for all but the immediate vicinity of the structure itself. Decline rates in RWH depths was suggested as an indicator for the structures efficiency in recharging the aquifer, varying from as low as 3.5 mm/day (which
indicates evaporative losses), and as high as 51 mm/day. Streamflow impacts were not considered. Other studies specific to India have focused on measurements from wells to infer recharge from RWH. Badiger et al. (2002) monitored 42 wells in four micro-catchments and the impact of recharge with distance from the wells. They inferred that recharge from RWH was about 3 – 8% of rainfall. Gontia and Sikarwar (2005) reported that groundwater levels rose by 8 m in wells in the Saurashtra region of Gujarat and this rise was assumed to come from RWH, though no measurements were taken from the structures themselves. Gore et al. (1998) quantified the effects of RWH in 16 observation wells in Maharashtra state, by modelling groundwater coupled with a water balance model, concluding that there was an overall increase in groundwater from RWH recharge of 8 ha.m/year. In the foothills of northern India, field studies over 10 years showed the possibilities of RWH to reduce the impact of severe droughts on agriculture, but in this instance water stored in structures was directly used for irrigation, rather than for percolation (Grewal, Mittal et al. 1989). Sharda et al. (2006) quantified recharge from a number of RWH structures in Gujarat, using the water balance method and the water table fluctuation method. They found that structures had a limited capacity to induce maximum recharge, and that a cumulative rainfall of 104.3 mm was required to induce 1 mm of recharge.

Apart from the modelling studies by Gore et al. (1998), Neumann et al. (2004) and the field analysis by Badiger et al (2002) and Sharda et al. (2006), there are few other studies that have quantified the impacts of RWH in India, and of those, none considered streamflow impacts at a larger catchment scale. Despite the positive impact RWH brings for irrigated agriculture by increasing groundwater availability, there is a serious lack of understanding of catchment-scale impacts of RWH, and this has been acknowledged in many papers (Barah 1996; Kumar, Ghosh et al. 2006; Sakthivadivel 2007; Shah 2007a; Kumar, Patel et al. 2008). There is a need for improved understanding of how RWH functions and the impact RWH structures have on groundwater availability, as well as on the local and downstream environment (Gale 2005). Data is sparse; therefore extensive data collection through hydrological instrumentation is also needed. Data will then aid in
the use of water balance models that can extrapolate RWH impacts to a larger catchment scale.

2.2.4. **Methods for Measuring RWH Impact**

Quantifying groundwater recharge is important to measure RWH impacts and is also necessary for sustainable groundwater resource management in semi-arid and arid areas, where groundwater resources are economically important (de Vries and Simmers 2002). But recharge is one of the most difficult components of the water balance to measure, because it needs to be measured below the visible surface and is highly variable; particularly in arid environments, where it can be the smallest component of the water balance (Bond 1998). All well-established recharge-estimation methods have limitations, most of which yield results that are problem and scale dependent (de Vries and Simmers 2002). To quantify the impact of RWH, it is necessary to estimate the amount of runoff stored, evaporation loss, subsequent recharge that reaches the groundwater table and possible overflow from the structure. Recharge from RWH can be estimated using physical measurements at the local-scale for an individual structure. However considering the difficulty and time required for physical measurements of recharge, modelling provides a cheaper, faster way to consider larger scale catchment effects of RWH.

2.2.4.1. **Physical Methods for measuring Recharge**

Groundwater recharge is the movement of water beyond the root zone that reaches the underlying aquifer (Bond 1998). Potential recharge ($R_{ep}$) is that water which moves below the root zone, while actual recharge ($R_{gw}$) is that water which enters the groundwater table. The root zone is a specified depth that varies with many factors including plant species and variety, stage of growth, crop vigour, soil conditions and watertable conditions (de Vries and Simmers 2002; Humphreys, Edraki et al. 2003).
There are several physical methods for estimating recharge based on soil physical principles and techniques. These methods attempt to directly estimate recharge, which is a difficult, time-consuming and expensive task, because soil is spatially variable and hence large numbers of values are required to measure a distribution (Shaw 1988). Most of the methods are based on the water balance. The steady state water balance is based on the law of conservation of mass, with hydrological inputs and outputs of the root zone represented by the following equation, which can be rearranged to calculate recharge (Eq 2-1).

\[ \Delta S = I + P - R_{off} - ET - R_{ep} \]  

\[ \Delta S \] = change in soil water content, \( I \) = irrigation, \( P \) = precipitation, \( R_{off} \) = runoff, \( ET \) = evapotranspiration, \( R_{ep} \) = potential recharge (recharge below the root zone).

For dynamic calculations (i.e. varying in time) saturated soil water movement is often described by Darcy’s Law (Eq 2-2).

\[ q = K \frac{\Delta H}{\Delta s} \]  

\( q \) = flux density, \( K \) = hydraulic conductivity,
\( \frac{\Delta H}{\Delta s} \) = hydraulic gradient or change in hydraulic head \( H \) (m) over distance \( s \) (m).

Darcy’s Law applies if the water flow is laminar and only describes steady or stationary flow processes, in which the flux remains constant and equal over the time step considered (Hillel 1998). Combining Darcy’s Law with the water balance for a soil unit allows dynamic calculation of fluxes. Extension to unsaturated conditions leads to a partial differential equation (Richards’ Equation), which can only be solved numerically.

Soil water movement is indirectly influenced by soil structural and textural characteristics, which are variable functions across space (McBratney and Pringle 1997). Soil variability has long been recognised and arises from complex interactions between time, parent material, topography, climate and organisms (Jenny 1941). Since soil, and hence the action of soil water movement, is spatially different within soils and between soils, recharge is therefore also spatially and temporally variable. This means estimation of this component of the water balance is quite difficult.
• **Methods based on Darcy’s Law**

Darcy’s Law can be used to estimate recharge in cases where hydraulic conductivity is already known (Gee et al. 2005). This method centres on the assumption that Darcy’s Law describes the soil water flux (Rose, Stern et al. 1965). When the measurements are performed below the root zone, the flux is assumed to represent $R_{ep}$ (Bond 1998). Advantages of methods using Darcy’s Law are that they are relatively cheaper than other physical methods and can cover a large area, using commonly available instruments such as neutron probes and tensiometers. The disadvantages are that the estimation of hydraulic conductivity and small hydraulic gradients may not be accurate and use of the instruments is labour intensive and can be expensive to maintain (Gee and Hillel 1988).

Similar to the straight application of Darcy’s Law, is the Zero Flux Plane (ZFP) method in which both the hydraulic conductivity and the recharge flux can be calculated (Rose, Stern et al. 1965). In the first case the flux at the surface needs to be downward or zero and calculations consider the whole profile. The change in water content with depth determines the drainage flux or $R_{ep}$. The ZFP method is based on the assumption that, after wetting, evaporative drying of the soil occurs from the top down. This means that lower in the profile (below the ZFP) the flux is downward, while higher up in the profile (above the ZFP) the flux is up. If the depth of the ZFP is identified, then changes above the ZFP are a result of evaporation, while changes below the ZFP are the result of $R_{ep}$. To measure the ZFP, the change in water content at several depths needs to be determined. Potential recharge is then measured from changes in soil water content and soil water potential, using instruments such as tensiometers and neutron probes.

• **Lysimetry**

A lysimeter is a device in which a volume of soil is located in a container to isolate it hydrologically from the surrounding soil on all sides and at its base (Scanlon and Healy 2002, Bond 1998). The drainage flux is measured accurately from the outflow at the base. Lysimeters provide the only direct measure of water flux from a surface, so they provide a standard against which other methods can be tested and calibrated (Rosenberg, Blad et al. 1983). Lysimetry provides all the terms of the water balance equation.
However they are very expensive and labour intensive, and cover only small spatial areas.

- **Tracer techniques and the Chloride Mass Balance (CMB)**

  The Chloride Mass Balance (CMB) method of estimating $R_{ep}$ is often used because of its low cost (Wood 1999), and is an example of a tracer method. The tracer method assumes that as water moves through the soil it carries with it stable chemicals that do not react or interact with the soil. By comparing profiles of these conservative tracers, the net movement of water can be inferred and hence $R_{ep}$. The basis of the CMB method is that the flux of water can be calculated across a plane if the following conditions are prevalent (Wood 1999): chloride from the groundwater originates from precipitation, the chloride is conservative in the system, the chloride-mass flux has not changed over time and there is no recycling or concentration of chloride within the aquifer. These conditions are for steady state and for natural systems, where $\Delta S$ is zero. Errors within the CMB method are due to spatial variation of chloride, but CMB modelling is identified as one of the most reliable methods, similar to the water balance method (Wood 1999). However Grismer et al. (2000) found that the CMB method greatly underestimated potential recharge rates in a non-irrigated area compared to other methods.

Tracer techniques are less data intensive than techniques such as the water balance. However there are many errors associated with: the uptake of the tracers by vegetation; anions exclusion and adsorption by the soil matrix; preferred pathways and macropore presence; lateral movement of solutes; and sampling density. Consequently tracer techniques are a technique preferred at small scales where processes can be better understood (Walker 1998).

- **Water balance**

  Rearrangement of the water balance allows potential recharge to be determined at large time scales.

  $$R_{ep} = I + P - Roff - ET - \Delta S$$  \[Eq 2-3\]
$\Delta S$ can assumed to be zero in a hydrological year (May – April) (Zhang, Walker et al. 2002). Consequently each component on the right hand side is established from field techniques. While $R_{ep}$ can be inferred from the water balance, accurate summation and frequent measurement of the other variables in the water balance is needed (Beecher, Hume et al. 2002). There is also an accumulation of errors for each variable on the right hand side and thus for $R_{ep}$. Grismer et al. (2000) found the greatest source of error in the water balance technique to estimate $R_{ep}$ is associated with the estimation of runoff and soil-water holding capacities of the soils, but with long-term data it can show valuable patterns. Humphreys et al. (2003) link the error for determining $R_{ep}$ to the value assigned to ET. Because of the large uncertainties in the $R_{ep}$ rate by this method, the usefulness of this method to arid and semi-arid regions is questionable (Gee and Hillel 1988). As a result measurements need to be very accurate. But for RWH structures, where $R_{ep}$ can be a larger component of the water balance than under other land uses, and evaporation is from open water, it may be an applicable method to use.

- **Water Table Fluctuation Method**

  The water table fluctuation method requires knowledge of the specific yield of the aquifer and change in groundwater levels over time (Healy and Cook 2002). The amount of recharge ($R_{gw}$) can be estimated from the rise in the water table ($\Delta h$) over time ($\Delta t$) (Healy and Cook 2002; Scanlon, Healy et al. 2002) by the specific yield ($S_y$):

  \[
  R_{gw} = S_y \frac{\Delta h}{\Delta t}
  \]

  Assuming a constant specific yield can introduce errors in the recharge estimations (Sophocleous 1991). However many studies have used the WTF, despite uncertainties of aquifer parameters, because of the ease of data collection (Crosbie, Binning et al. 2005; Marechal, Dewandel et al. 2006; Muralidharan and Andrade 2007; Wendland, Barreto et al. 2007). Because the WTF method is measured at a single point, due to the effects of mounding and pumping, the fluctuations might not be spatially significant. However by increasing the number of wells or piezometers in the monitoring network, spatial scale recharge characteristics of an aquifer can be inferred (Leduc, Bromley et al. 1997; Panda, Mishra et al. 2007).
• **Concluding remarks on physical methods**

There are many different physical methods available to measure recharge. However most are labour and time intensive and expensive. Additionally the spatial and temporal variability associated with recharge makes accurate estimation difficult. Best results are generally obtained by using a combination of methods. Due to this variability, modelling could be a useful method to estimate recharge and also to understand the impact of recharge across a catchment, but the model output would need to be validated against physical measurements.

### 2.2.4.2. Water Balance Modelling

Water balance modelling has been developed to extrapolate results from physical measurements to larger scales for different time periods or management scenarios. The ultimate aim of a water balance model is to improve decision-making about a hydrological problem (Beven 2001). For example hydrological models can predict how future changes in climate and land use may affect recharge rates and downstream flows (Scanlon, Healy et al. 2002). However model output accuracy is dependent on the accuracy of the input data, and the appropriateness of the model being used for the situation (Silberstein 2006). All hydrological models incorporate the water balance as the underlying principle, simulating vertical and horizontal soil water movement, vegetation water use and plant growth, and can range from simple, requiring few parameters, to complex models (Beven 2001). Despite their drawbacks, models can provide at least an estimate of the impacts of different land use, for example the impact of RWH in a catchment.

Hydrological models can be classified in a number of ways. They can be described as lumped or distributed (Beven 2001). Lumped models treat the catchment as a single unit, with variables representing averages over the catchment area. In contrast, distributed models make predictions that are distributed in space, with variables that represent local averages by dividing the catchment into a large number of elements or grid squares and solving variables associated for every square. Deterministic models describe the
processes by which the systems function, provided that their mechanisms are understood and data is available (Beven 2001). In contrast, a stochastic model gives a range of possible outcomes for a given set of inputs and can express the likelihood of each one happening as a probability. While deterministic models can also provide a distribution of outcomes, this is usually external to the model. Deterministic models provide only one outcome from a simulation with one set of inputs and parameter values.

The key processes and concepts that need to be defined in a catchment-scale water balance model include the compartmentalisation of the soil regolith, infiltration – runoff partitioning, land use definition (which includes soil hydraulic properties), evaporation, stream routing and transmission losses. These processes can be more complex depending on the system in question, for example a semi-arid or arid region has distinctive rainfall-runoff behaviour and wide spatial and temporal variability (Pilgrim, Chapman et al. 1988). Furthermore these processes need to suit the problem being examined, and are chiefly influenced by the amount of data available. Lack of observed data in semi-arid and arid regions is a common problem for runoff modelling (Pilgrim, Chapman et al. 1988). If there is a lack of data, the model should be relatively simple, because calibration and validation may not be possible (Guntner, Karlo et al. 2004). A model of this sort would allow the researcher to model their understanding of a certain system to direct future data collection.

- **Soil regolith**
  A common approach is to model the soil regolith as one layer which represents the soil water storage of the root zone. The soil layer or bucket fills with rainfall, and irrigation if appropriate, and empties via evapotranspiration and recharge below the root zone. More complex models can accommodate multi-layered soil profiles and with various types of vegetation and land management options. A multiple layer tipping bucket model has more than one bucket, each representing a different layer in the soil. Water moves downwards from one bucket to the next when the amount of water in the upper bucket exceeds its storage capacity. The size of the bucket is determined by the water content at saturation, field capacity, permanent wilting point and the depth of the soil layer, where
the cumulative bucket size is dependent on the rooting depth (Walker, Zhang et al. 2002). Examples of such a model set-up include PERFECT (Littleboy, Silburn et al. 1992; Abbs and Littleboy 1998) and APSIM (McCown, Hammer et al. 1996). These models can be extrapolated relatively easily using GIS software or interpolation tools.

Rather than an overflowing bucket, the Richard’s equation is an alternative for moving water down the soil profile as seen in the models SWIM (Ross 1990), WAVES (Walker and Zhang 2002) and SWAP (Tripathi, Panda et al. 2003; Anuraga, Ruiz et al. 2006; Singh, Kroes et al. 2006a; Singh, Jhorar et al. 2006b). The Richards’ equation approach treats soil water movement as continuous rather than a series of cascades and uses finite difference or finite element approximation to solve the system of differential equations. As a result models like SWIM reproduce changes in water content with depth, rather than using a single soil storage parameter (Ross 1990).

- **Rainfall Runoff Relationships**

Runoff is a key component in the water balance. In arid environments Hortonian overland flow (infiltration excess) tends to be the dominant runoff process (Lange, Liebundgut et al. 2000), and can be about 30 – 40% of annual rainfall (Batchelor, Rama Mohan Rao et al. 2003). In addition, arid zones generally have high rainfall intensities which can be highly variable in space and time, further increasing the likelihood of Hortonian overland flow. Unfortunately due to the high variability in arid catchments and low population densities, very few are gauged, so where data is lacking, simple approaches to modelling runoff can be used. These include:

- Using Richards’ equation. Two separate runoff processes can be simulated. The first is when the soil profile, or upper layers, becomes saturated and the excess water runs off (Dunne overland flow). The second process is when rainfall intensity exceeds the infiltration capacity of the non-saturated soil (Hortonian overland flow) (Walker and Zhang 2002).

- The USDA Soil and Conservation Service (SCS) curve number (CN) method, which partitions daily rainfall between infiltration and runoff. The CN values represent potential maximum soil retention for various land covers and
textures (USDA-SCS 1985). The curve number method does not distinguish between Hortonian or Dunne runoff, but focuses on the relationship between soil, land use and rainfall (Owens, Silburn et al. 2003). Models that use the \( CN \) method include EPIC, PERFECT, APSIM-Soilwat and SWAT. Many studies and water balance models have used the SCS-\( CN \) method to estimate runoff (Narayanpethkar, Gurunadha Rao et al. 1994; Van Wesemael, Poesen et al. 1998; Gheith and Sultan 2002; Mandal, Sarma et al. 2002; Senay and Verdin 2004; Zade, Ray et al. 2005; Martin-Rosales, Gisbert et al. 2007; Ouessar, Bruggeman et al. 2008). Tiwari et al (1991) modified the SCS-\( CN \) method for Indian conditions and applied them to the Kaliaghai river basin, where \( I_a \) (initial abstraction) is 0.3:

\[
Q = \frac{(P - I_a S)^2}{P + I_a S} \tag{Eq 2-5}
\]

\( Q \) = direct flow volume expressed as depth, \( P \) = total rainfall, \( S \) = potential maximum soil retention, \( CN \) = curve number value used to estimate potential maximum soil retention (\( S \)).

\[
S = \frac{25,400}{CN} - 254 \tag{Eq 2-6}
\]

If rainfall depth is the only data available to a modeller, the \( CN \) method gives the best practical estimation of runoff (Smith 1997).

- A runoff coefficient, which describes the fraction of rainfall occurring as runoff (Sargaonkar, Vijya et al. 2006).
- Using a Unit Hydrograph, which is a linear transformation of the excess rainfall into runoff, for example the IHACRES model (Jakeman and Hornberger 1993).

- **Land use and Hydrological Response Units**

Land use information and hydrological characteristics of soil form the basis of hydrological model inputs (Helmschrot and Flugel 2002). Land use maps, created through remote sensing, can provide such information for model inputs. The top boundary condition, or type of land use, determines the amount of water input
(infiltration) from rainfall and the amount of output via evapotranspiration. Land use includes everything for which land is used for by humans, from farms to housing. Each unique land use has a different impact on the water balance equation. For example, forested catchments have higher evapotranspiration than grassed catchments, while in semi-arid areas the difference between evapotranspiration in these catchments decreases as the precipitation : evaporation ratio decreases (Zhang, Dawes et al. 2001). Thus land use management impacts the catchment water balance and hence water yield and groundwater recharge. Each unique combination of land use and soil type can be described in a model as a hydrological response unit (HRU). Winter (2001) defined HRUs on the basis of land-surface form, geology, and climate. Fundamentally, HRUs have a complete hydrologic system consisting of surface runoff, groundwater flow, and interaction with atmospheric water.

Key controls of evapotranspiration are rainfall interception, net radiation, advection, turbulent transport, leaf area, and plant-available water capacity. Actual evapotranspiration can be calculated by:

- Catchment water balance
- Penman-Monteith equations or equivalents (such as Priestley-Taylor)
- Eddy Covariance
- Energy balance
- A simple function that uses soil moisture content (Fernandez-Illescas and Rodriguez-Iturbe 2004)

While land use provides the input or top boundary condition into hydrological models, the essential parameters for soil-water balance models are soil hydraulic characteristics. For physically based soil water movement models based on Richard’s Equation, the crucial soil parameters are soil hydraulic conductivity and water retention characteristics. However, these soil properties are highly variable in space and time and measurement is time-consuming and expensive. Therefore to calculate soil hydraulic properties easily and over a large area pedotransfer functions (PTFs) are commonly used. Pedotransfer functions are an effective and cheaper method of deriving soil hydraulic properties,
which take readily available data, such as field morphology, texture, structure, and pH, then translate them into estimates of other soil properties including hydraulic conductivity and water retention characteristics (Minasny and McBratney 2002). As PTFs depend on the data on which they are based, they are restricted to a country or region (Minasny, McBratney et al. 1999).

- **Transmission losses**

Transmission losses refer to water which is lost during water flow in channels. It is important to incorporate this process in any catchment-scale hydrological model because it forms a part of the water balance (Sharma and Murthy 1994a). Transmission losses are controlled by the channel geometry, upstream flow volume, duration of flow, bed material size and sediment load and are a key part of the river hydrology in semi-arid basins (Lange 2005). In arid areas, in the lower reaches of ephemeral rivers, discharge decreases downstream due to transmission losses. These losses are generally large but can be highly non-linear and variable in space (El-Hames and Richards 1998; Dunkerley and Brown 1999; Lange 2005).

As highlighted by Sharma and Murthy (1994a) there are many methods to estimate transmission losses, which include inflow-loss rate equations, simple regressions equations, simplified differential equations for loss rate, storage routing as a cascade of leaky reservoirs, and kinematic wave models incorporating infiltration. These all depend on sufficient collection of data and often knowledge of upstream and downstream flows. A method specific to arid regions of India, is a set of three developed regression equations, relating transmission loss to channel characteristics and flow volume, which could be transferred to ungauged basins with similar climatic and landscape conditions (Sharma and Murthy 1994b).
• **Routing**

Routing is the movement of water in a river down a catchment, which is dependent on the river storage, by introducing translation and dispersion in the flood wave. This can be calculated using (ranging from simple to complex):

- Linear routing (if the empirical parameter \( m = 1 \)) where \( S \) storage is calculated by:

  \[
  S = kQ^m
  \]

  \( k \) is an empirical parameter, which determines the duration and spread of \( S \) (storage, \( m^3 \)) using \( Q \) = discharge in the river (\( m^3/s \))

- Muskingham method
- Muskingham-Cunge method, which introduces diffusion in the channel, with hydraulic diffusivity and celerity (velocity) parameters (Lange 2005)
- Full Saint Venant Equations (Beven 2001)

Depending on data availability different approaches can be used. Simpler methods do not represent all the processes modelled, but are less data dependent.

• **Models that have been used to measure the impact of RWH or small farm dams**

A number of models have been used to examine the impact of small farm dams on catchment hydrology, which are similar in function to RWH in India. For example Ouessar et al. (2008) adapted the complex catchment scale model SWAT so that it could measure the impact of water-harvesting systems in a 270 km\(^2\) arid catchment in Tunisia. In Australia, farm dam impacts have been measured using a simple lumped catchment model called TEDI (Nathan, Jordan et al. 2005) and CHEAT (Lowe, Nathan et al. 2005; Jordan, Wiesenfled et al. 2008). Using TEDI, Savadmuthu (2002) found that the impact of farm dams on annual runoff is very high during drier years and is marginal during wetter years, although annual runoff is historically low during drier years. Sakthivadivel et al. (1997) used the model ROSES (Reservoir Operation Simulation Extended System) to model daily hydrologic behaviour of cascading small tanks to guide in small tank rehabilitation works. Letcher, Schreider et al. (2001) looked at two algorithms for analysing changes in stream flow response due to changes in land use and farm dam
development in three catchments and Schreider, Jakeman et al (2002) used IHACRES to see statistically significant reductions in the quantity of potential stream flow response caused by farm dam development in Australia. There are currently no water balance modelling studies that incorporate both surface water and groundwater interactions, specifically in relation to RWH structures built for the primary purpose of recharge in India.

- **Concluding Remarks**

Different hydrological processes are dominant in different land uses and climatic conditions, and an appropriate model must be chosen that best represents the problem and the landscape. For example, in the case of RWH, runoff prediction and the description of attributes of the soil surface might be more important because these areas receive high intensity storm rainfall events in the monsoon. Daily time steps are best suited for the estimation of recharge, because recharge is generally a larger component of the water budget at smaller time scales. Smaller time steps can also minimise accumulation errors from water balance models (Scanlon, Healy et al. 2002), so can give reasonable estimates of recharge because they generally work on a time series that are shorter than a year (Walker and Zhang 2002). With any model however, reliability of estimates should be calibrated against existing data and the results should be validated (Scanlon, Healy et al. 2002).

An array of water balance models exist from the simple single layer bucket methods of WATBAL and PERFECT to the more complex APSIM, WAVES, SWIM and SWAT. In addition many scientists have developed their own models to simulate a water balance problem they are addressing (Bellot, Bonet et al. 2001; Healy and Cook 2002; Shentsis and Rosenthal 2003; Ruud, Harter et al. 2004; Tsutsumi, Jinno et al. 2004; Bari, Smettem et al. 2005; Portoghese, Uricchio et al. 2005). However with any model choice a clear objective is important and an understanding of the key processes and data appropriate to achieve the objective is needed (Finch 1998). With increased complexity more parameters are required and with this, the potential for increasing uncertainty and effort in data collection. So while modelling may be able to extrapolate field scale information
to larger catchments, the purpose, data requirements and complexity of the model must be considered. In relation to RWH designed to recharge groundwater, the surface water–groundwater interaction is important, but currently no model or modelling study has explicitly addressed this.

### 2.3. Groundwater Sustainability

The biophysical sustainability of natural resources is one of the main goals for management. Groundwater sustainability is most relevant when considering the impacts of RWH, which augments groundwater supply, but RWH development also tends to increase the area of irrigation and therefore groundwater extraction (Srivastava, Kannan et al. 2008). However, as this literature review highlights, groundwater sustainability is difficult to define.

Since the Rio Declaration on Environment and Development that formulated Agenda 21, sustainable development has become the primary goal for resource management. The World Commission on Environment and Development defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland 1987). Loucks (1997) applied this to water resource systems, where sustainable water resource systems are those that are ‘designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity’ (page 518). However, there are many difficulties associated with defining sustainability, which has been discussed in great length, due to the value judgments needed to be made about what is an achievable goal for the present that does not affect future outcomes, and what the future outcomes may actually be (Loucks 1997). Therefore trying to quantify sustainability is difficult, because systems and the ‘needs’ are always changing (Sarang, Vahedi et al. 2008). Nevertheless a number of studies have tried to quantify the sustainability of water resource systems by quantifying measures of reliability, resilience
and vulnerability (Hashimoto, Stedinger et al. 1982; Loucks 1997; Ajami, Hornberger et al. 2008). Reliability is how likely the system is to fail or the frequency of failure, resilience is how quickly the water resource system recovers from failure and vulnerability is how severe the consequences or the extent of failure may be. These measures relate to Holling’s seminal paper (1973), who first described the concept of resilience as the ability of an ecological system to persist with the same basic structure when subjected to stress.

Groundwater sustainability is defined broadly as the development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing ‘unacceptable’ environmental, economic or social consequences (Alley and Leake 2004). Understanding the impacts of management, including pumping and RWH, are important to manage groundwater sustainability. Definitions for groundwater sustainability are argued in many papers (Loucks 2000; Sophocleous 2000), and often refer to the concept of safe yield, defined as the maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge (Sophocleous 1997; Sanford 2002). However this term is now discredited in much of the literature (Sophocleous 1997; Sophocleous 2000; Alley and Leake 2004), because safe yield does not address the impacts of groundwater discharge on ecosystems, and on surface water. This means safe yield can be maximised but streams could dry up as discharge is ‘captured’ (Maddock and Vionnet 1998). To understand long-term development of groundwater, the amount of capture must be determined (Bredehoeft 2006). However as Custodio (2002) points out, negative impacts of aquifer development, including water-level drawdown, do not necessarily imply that abstraction is greater than recharge. They may be due to well interferences and the lag period that follow changes in the aquifer water balance. Custodio (2002) argues that aquifer overexploitation is not necessarily detrimental if it is not permanent.

However sustainable yield of an aquifer must be less than long-term recharge if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and groundwater dependent ecosystems (Sophocleous 2000). Initially
all groundwater developments mine water, but the eventual reduction is later balanced by surface water supply and induced recharge (Alley, Healy et al. 2002). Sophocleous and Devlin (2004) suggest that a general knowledge of recharge rates is needed to decide how to manage the groundwater resource, so that pumping can be balanced by an equal capture of discharge and/or recharge. One way of managing groundwater extraction is that yield should vary over time as environmental conditions vary (Sophocleous 2000). However uncertainty remains on how to precisely determine sustainable yield, and link it to the concept of sustainable development. In India, a water budget approach to sustainable groundwater at the State level is based on the safe yield policy depending on a given percentage of rainfall. The target is to have less abstraction than recharge, which means that capture is not addressed (Kalff and Woolley 2005). While such definitions are important to direct management, implementation of the safe yield policy at each individual well is equally important. This depends on the strength of the institutional arrangements present.

2.4. Groundwater Institutions in India

Rainwater harvesting is seen by many as a solution to the deepening groundwater crisis in India, which is the result of the groundwater irrigation boom that has occurred in the country since independence. But where RWH is introduced, the area under irrigation also increases as more groundwater becomes available, so any benefit from increasing supply may be counteracted by increasing demand (Srivastava, Kannan et al. 2008). This could not only lead to greater depletion of groundwater stores, but less resilience in the irrigation community when a shock such as drought occurs, as the reliance on groundwater for livelihood has increased (Moench 2007). While RWH is an important tool for supply-side management of groundwater, such focus disregards the demand-side aspects of groundwater management and can not be considered in isolation.
2.4.1. Institutions and Property Rights

How a common resource, such as groundwater, is managed, depends on the existing laws, and institutional arrangements. Institutions determine the state of resources at a point in time as they provide operational and conservation rules that guide resource use and management, including who controls the resource, how conflicts are resolved, and how the resource is to be managed (North 1990; Agrawal and Yadama 1997; Heltberg 2001). An important aspect of effective property rights and institutional arrangements is the prevention of ‘free riding’ or overconsumption of a resource. Much of the world is dependent on resources, such as groundwater, that are subject to the possibility of an open-access or a ‘Tragedy of the Commons’ scenario (Hardin 1968). An open-access scenario is a lack of ownership and control of the resource, where access and conservation rules are not present resulting in overexploitation (Bromley 1992; Heltberg 2001). Institutional arrangements are therefore very important to safeguard the condition of resources at any point in time (Agrawal and Yadama 1997).

Different property rights regimes exist to manage common resources, which are defined on the basis of property rights held over resources by the users (Eggertsson 1990). Exclusive rights can be held by individuals, which is private ownership. Privatization creates exclusive, private and transferable rights over the flow of natural resources to an individual (Grafton 2000). Alternatively, property rights can be held by the state. State property right regimes separate ownership and control from actual use, where ownership lies with the citizens, and management and control resides with bureaucrats, while use resides with a subset of the citizenry (Bromley 1992). There are many examples of state-based property rights in developing countries that have led to degradation of natural resources, as those resources became de facto open-access, especially where state-based rights have superseded pre-existing private or community rights (Bromley and Chapagain 1984; Gadjil and Iyer 1989). Amongst other things this is because of high monitoring and enforcement costs, which make centralised control ineffective (Ostrom 1990).
Finally, resources can be held as commonly owned or as a common property resource (CPR), whereby a community controls access to a resource by excluding outsiders and regulating its use by insiders through access and withdrawal rules. A common property resource regime represents private property for the group since all others are excluded from use and decision making, and individuals have rights and duties (Richards 1997). Decentralising the management of resources to the users through CPR institutions can be an appropriate solution in developing countries, where customs and social conventions result in cooperative solutions (Wade 1987; Ostrom 1990). Advantages of CPR are that the users can have more local knowledge of the resource, so that rules are better adapted, they are more flexible in changing the rules and they are able to implement efficient monitoring of the resource (Ostrom 1990). Problems of CPR relate to: some appropriators will not organize; some self-organised efforts will fail; local tyrannies may prevail; stagnation may occur; inappropriate discrimination may result; access to scientific information may be limited; conflict may arise among appropriators; and, appropriators may be unable to cope with large-scale common property resources (Ostrom 1999).

Traditionally in India, natural resources were managed as village-based CPR. However, with the colonisation by the British, management and ownership of natural resources became a state matter. This change in property rights led to a decline of self-governance (Jodha 1985). With the independence of India in 1947, decisions regarding common resources were made by a centralised government. Property rights shifted from local villages to the state, thus breaking down traditional village institutions (Bromley 1992; Randhir and Lee 1996). There are many documented examples that explain the change from CPR to de jure government property regimes to de facto open-access regimes across India (Bromley and Chapagain 1984; Jodha 1985; Gadjil and Iyer 1989; Hanna, Folke et al. 1996). In contrast there is a wide range of literature documenting many successful examples of CPR operating in the world, where users of common resources, such as forest and surface irrigation systems, develop rules and regulations without relying on external authorities (Berkes 1989; Bromley 1992; Ostrom, Walker et al. 1992). But there
are very few documented examples of successful common property groundwater resource institutions.

2.4.2. Institutional Arrangements for Groundwater in India

Groundwater is a common resource, which means that the resource is so large that it is costly to exclude potential users, and also the supply is limited; consumption by one user reduces its availability to others (Ostrom, Walker et al. 1992; Ostrom, Gardner et al. 1994). However groundwater property rights in India currently do not address these characteristics. Groundwater rights are attached to land rights. There is no legislation to regulate and monitor groundwater use, so the land owner can extract as much groundwater as desired, and in India there are over 12 million private well owners managing their own groundwater use (Saleth 2005) (Figure 2-3). In addition, the highly fragmented ownership of land in India, means groundwater use is unplanned, unregulated and uncoordinated (Mukherji and Shah 2005; Villholth 2006). The dependence on groundwater has increased significantly in the last 50 years, but well-constructed institutions to manage this resource do not currently exist and have not been developed in India (Kemper 2007). Most of the existing water institutions, which were developed during the colonial period, are increasingly less relevant to address the current groundwater challenge (Saleth 2005).

Groundwater management is highly centralised in India, and is conferred on the States under the State list of the Seventh Schedule of the Indian Constitution. The state governments define the law for the control and regulation of groundwater use. The Ministry of Water Resources (MWR) is recognised as the nodal agency for water resources in India. Under the MWR, there are a number of technical agencies, including the Central Groundwater Board (CGWB). The CGWB is responsible for carrying out nationwide surveys and assessment of groundwater resources, and guiding the states appropriately in scientific and technical matters relating to groundwater.
In the early 1970s the Central Groundwater Board, in response to the alarming increase in groundwater overdraft, designed a Model Groundwater Bill for groundwater regulation. Despite this, the Bill has not been implemented effectively. The Model Groundwater Bill of 1992 is a revision of the 1970 Bill, and makes obtaining groundwater use permits compulsory and requiring groundwater users to be registered. The Bill also prohibits sinking of wells in recognised degraded groundwater areas and sets out punishments for violators (Shankar 1992). The Bill was again revised in 1996, and 2005. Singh and Singh (2002) consider the Bill to have failed due to a combination of factors including: a lack of political will; lack of awareness amongst farmers; strong farmer lobbies in some states; the non-availability of any other source of water supply in some areas; the existence of millions of wells; and a lack of understanding of groundwater systems. In Gujarat for example, powerful farmers have lobbied politicians to avoid regulations and obtain electricity connections. The Bill also is not specific to any location and does not set withdrawal limits (Saleth 2005), and any monitoring is difficult due to the high transaction costs of metering millions of wells across poor road networks (Shah 2007a). Current institutional arrangements to manage the groundwater resource do not capture the complexity of the resource, and corruption and inequity are present (Narain 1998).
As a result, the groundwater resource in India is currently facing an open-access scenario. Groundwater use is governed by a *de facto* system of rights based on self-supply and determined by farm size, the depth of wells, the number of wells, pumping capacity and economic power to build wells and pump water (Saleth 2005). Some consider groundwater development to be self-regulating because aquifer hydrogeology imposes checks on further development, due to the economics of pumping from greater depths (Shah 2007b). However if such a situation arises the consequences could be significant for communities that rely on this resource, which are predominantly poor small-holder farmers (Gale, Neumann et al. 2002). Therefore effective groundwater institutions are needed to prevent such situations occurring.

A growing body of literature has highlighted the value of communal groundwater user groups (Kemper 2007). It has also been suggested that the impetus for communal ownership could come from the ‘groundwater recharge movement’, which encourages RWH. However the groundwater movement is aimed at augmenting groundwater supply, rather than regulating extraction (Mukherji and Shah 2005). Additional difficulties for collective action of communities lie in the nature of the resource itself. Groundwater use means farmers do not need to organise, bargain, or negotiate to develop an irrigation system, and users can sink wells independently of other users (Schlager 2007). Groundwater is an ‘invisible resource’, so groundwater users may never know the resource boundaries or aquifer capacity without scientific information (Moench 2007). Additionally, groundwater users may never know the effect of their pumping on other users or the number of users of the resource, because the resource is so large (Moench 2007). This easy access and lack of information at the operational level about the resource makes it difficult for groundwater users to develop self-governance norms (Kemper 2007; Schlager 2007). However there are scattered examples from India, Pakistan, Yemen and Egypt where groundwater users have effectively self-imposed restrictions on the use of groundwater through communal ownership of the resource because they were able to exclude potential users, had accessible hydrogeological information and had the support of local governments (van Steenbergen 2006). But
largely the body of literature examining and researching groundwater institutions is limited (Gopalakrishnana, Tortajada et al. 2005).

- **Concluding remarks**

Extraction of groundwater in India is not controlled effectively under the current institutional arrangements, which have had little effect regulating and monitoring the millions of groundwater users in India and has led to an open-access scenario. The centralised approach to manage groundwater, through the 1970s Model Groundwater Bill, has not been successfully implemented in any state except Gujarat. Even here there has been little impact because of strong farmer lobbies. There is also a great need to define appropriate groundwater property rights, which are still based on old colonial laws. A publicly well-known example of the lack of application and relevance of this law is the overuse of groundwater by Coca-Cola India’s bottling plant in the state of Kerala. However the case reached the Supreme Court as the land owner, Coca-Cola, had depleted local groundwater tables in surrounding poor communities, and the bottling plant was closed (Gronwall 2006). One option for managing groundwater is through communal ownership, which was the traditional form of natural resource management in India. But relatively little is known about local informal institutions that govern groundwater use (Mukherji and Shah 2005). Due to the heavy reliance on groundwater, particularly for the poor, who are disproportionately dependent on groundwater, the nature and function of informal groundwater institutions must be examined.

### 2.5. Conclusion on Reviewed Literature

Rainwater harvesting is a small-scale catchment development tool with a long tradition in many countries, including India. While RWH techniques are countless, in many parts of India RWH captures and stores the intensive monsoonal runoff to recharge groundwater. While anecdotal evidence of the social and economic gains of RWH are abundant, due to the increased capacity of small-holder farmers to irrigate, the technical aspects of how
this catchment development tool actually functions and impacts larger scale catchment water balances are little understood. As RWH changes the water balance, the downstream impacts of RWH should also be considered.

Local-scale measurement of recharge from RWH is difficult as most field methods are expensive, time consuming, or do not deliver the desired accuracy. In addition high temporal and spatial variability of rainfall, soil and aquifer hydraulic properties means that long time series of data are needed. Data however, is very limited in semi-arid/arid regions where populations are sparse and economic resources are limited (particularly in developing countries). Simulation modelling of catchment hydrology might offer a way of assessing the impact of RWH at a larger catchment scale, but model input and accuracy will determine the usefulness of the final results. One option in the face of limited data is to first use models to better understand the process and dynamics of RWH to guide further detailed investigations. Further to this, the concept of sustainability could be applied to the simulation model to examine and compare the impacts of different management scenarios, such as RWH, on irrigated agriculture and water balances. To evaluate the impact of RWH, local scale estimates of recharge from individual RWH structures need to be obtained, and then using a simulation model, the impact of RWH at a catchment scale could be better understood.

Groundwater management in India is an open-access scenario, largely unaddressed by the current property rights and institutional arrangements, and management has focused more on the supply-side through groundwater recharge. Common property resource institutions, where local communities make access and conservation rules themselves, have been highlighted as a viable option for management of groundwater, but in general there is very little research on the subject of institutions related to groundwater in India.
3. **STUDY AREA DESCRIPTION**

3.1. **General Description**

3.1.1. **Location**

The case study area for this project is the Arvari River catchment, which is located in the state of Rajasthan (Figure 3-1). Rajasthan is the largest state in India, covering an area of 342,226 km² and is predominantly agrarian: 70% of its population depends on agriculture-based activities. Although the state covers 10.5% of India’s geographical area, it shares only 1.2% of its water resources (Narain, Khan et al. 2005).

The Arvari River catchment is in the eastern part of the state, in the district of Alwar, and makes up about 7% of the larger Banganga River Basin as a tributary. The Arvari River catchment sits between latitude 27.1°30 and 27.22°15 and longitude 76.16°30 and 76.4°55. The catchment drains into Sainthal Sagar dam, a medium size irrigation project built in 1898. The inflows into the dam come from the semi-arid ephemeral rivers of the Bidila and the Arvari. For this case study of RWH impacts, the catchment area of
Sainthal Sagar Dam is considered, commonly referred to as the catchment of the Arvari River. The Arvari River catchment is mainly in the Thanagazi block of the Alwar district (administrative divisions), and covers an area of about 476 km$^2$. Geologically the catchment is a part of the Aravalli Hill range, which is one of the oldest mountain ranges in the world (Bhuiyan, Singh et al. 2006).

Figure 3-1: Position of the case study catchment, the Arvari River catchment (or catchment of Sainthal Sagar Dam) in the eastern part of the state of Rajasthan, India. The villages, which were the focus of the data collection study, are highlighted.

There are no direct sources of information relating specifically to the Arvari River catchment. However many state and national government records refer to the Alwar district and the Thanagazi block. The State Groundwater Department also refers to the Banganga River Basin. The general study area description is inferred from these sources.
3.1.2. Social Aspects

In the Alwar district, 85% of the population lives in rural areas. The average population density is 273 persons/ km$^2$. In the Thanagazi block the current population is 144,119, with a rate of growth of 2.67% each year (Rathore 2003).

Agriculture is the main source of livelihood, which increased from 67% in 1981 to 76.5% in 1991 (Rathore 2003). The lack of surface water bodies in this area has made people entirely dependent on groundwater resources for water needs (Bhuiyan, Singh et al. 2006). There has been a shift in the use of energy for pumping wells; bullock operated wells have declined to 11%. There is a shortage of electricity in this area, so predominantly diesel pumps are used. The number of wells in the Alwar district and Thanagazi block is increasing every year. The number of diesel pumps increased from 1,605 in 1991 to 3,741 in 2001. In the Thanagazi block, 96.3% of wells are privately owned. To increase groundwater access, deepening of wells is a common practice, along with digging of new wells (Rathore 2003).

A large percentage of the population of the Arvari River catchment is Scheduled Castes (SC), Scheduled Tribes (ST) or Other Backward Classes (OTC). These population groupings, recognised by the Constitution of India, are known as the ‘depressed classes’ under the earlier British colonial government. These classifications are based on the social and economic conditions of the communities. In the Alwar district the male to female ratio is 1000:887, and literacy in rural areas is 58% (77% for males, 39% for females) (NIC Alwar 08/07/2009).

3.1.3. Regional Climate

The climate of the Banganga River Basin is semi-arid with hot summers between March and June. May and June are the hottest months of the year with a mean daily maximum and minimum temperature in May of 42.1$^0$C and 25.7$^0$C. The winter extends from
November to March, with temperatures dropping to a minimum of 7.7°C and a maximum of 21°C in January.

The average rainfall of the Banganga River Basin is 637.6 mm, with an average of 31 rainy days a year (1901-1998). Eighty percent of this rainfall falls during the south-westerly monsoon between June and September (Ground Water Department Jodhpur 1999). The closest rainfall station to the Arvari River catchment is in the town of Thanagazi (15 km to the North of the catchment). Figure 3-2 shows the daily rainfall pattern at Thanagazi from 1980-2006 (no data for 1999). The majority of rain falls within the monsoon period in each year, with many large events of up to 150 mm. The moving two year average line in Figure 3-2 shows no significant trends in rainfall from 1980-2009. However there is some increase in rainfall in the early 1980s and the mid-1990s.

![Figure 3-2: Daily rainfall (mm) at the Thanagazi station from 1980 – 2006 with a moving average line over two years to indicate any trends (no rainfall data available for 1999).](image-url)
Figure 3-3 demonstrates more clearly what is suggested in the moving trend line of Figure 3-2. The early 1990s has more daily rainfall between 25 mm - 100 mm than the late 1990s and early 2000s (Figure 3-3 b). The increase in the mid-1990s of rainfall is also seen in the larger number of rainfall events during this period (Figure 3-4). These larger rainfall days are important in RWH operation, as field observations and communication with farmers suggested that greater rainfall events induced more runoff and thus storage in RWH structures. From this rainfall data, the average number of rainfall days greater than 35 mm per year is eight. Overall the data indicates both inter- and intra-annual variation in rainfall.

Figure 3-4: Number of rainfall events greater than 35 mm at Thanagazi station from 1980-2006

Total annual potential evapotranspiration is 1523.7 mm, highest in May (271.5 mm) and lowest in December (155.6 mm). Monthly average daily potential evapotranspiration values are shown in Figure 3-5.
3.1.4. Geomorphology and Geology

Within the general Aravalli Hill region are rocky uplands, shallow to moderately deep colluvial plains and narrow alluvial plains (Shyampura and Sehgal 1995). Within the Arvari River catchment dominant landscape features are:

- Flat topped hill ridges of high relief basement rocks as high as 730 m and inter-ridge valleys with plains stretching southward. The average height of the ridges ranges from 690 m to 640 m in the central part of the area. The southern and eastern areas have low to moderately high hills (500 – 600 m) with low gradients (Rathore 2003; COMMAN 2005b).

- Valleys, which contain sediments of varying thickness (COMMAN 2005b).

The geological sequence generally consists of limestone, quartzite, phyllites, alluvial sediments and wind blown sand, silt and clay (Table 3-1).
Table 3-1: Geological Sequence in the Banganga River Basin (Ground Water Department Jodhpur 1999).

<table>
<thead>
<tr>
<th>Super Group</th>
<th>Group</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Alluvium and wind blown sand comprised of sand, silt, gravel, clay and kankar</td>
<td></td>
</tr>
<tr>
<td>Delhi</td>
<td>Argillaceous meta sediments, consisting of phyllites, quartzites, amphibolites and impure dolomitic limestone</td>
<td></td>
</tr>
<tr>
<td>Ajabgarh</td>
<td>Arenaceous meta-sediments, consisting of quartzite, conglomerates, gritty quartzites interbedded with phyllite, quartz sericite schist</td>
<td></td>
</tr>
<tr>
<td>Alwar</td>
<td>Unconformity</td>
<td></td>
</tr>
</tbody>
</table>

Bhilwara and Aravalli (Pre-Delhi). Granites, Granitic Gneisses (Archaean)

3.1.5. Hydrogeology

Hydrogeological provinces in India can be grouped into three main divisions; hard rock regions (nearly 65% of India), alluvial regions of major river basins (mostly in the northern parts of India) and consolidated sedimentary formations (about 5% of India) (Table 3-2) (COMMAN 2005a).

In the Banganga River Basin, groundwater occurs in shallow alluvium layers and deeper hard rock areas. The alluvial system overlies the fractured hard rock aquifers, where the coarse nature of alluvium usually results in phreatic conditions, and the hard-rock aquifer is connected hydraulically (Table 3-3) (Gale, Neumann et al. 2002). Abstraction from wells in the hard rock aquifer can seasonally drain overlying alluvium (Gale 2005). The alluvial deposits are sandy to coarse and form aquifers a few tens of metres thick. The underlying aquifer is fractured igneous and metamorphic rocks (Gale 2005).
Table 3-2: Generalized aquifer characteristics, yields and recharge estimates for India (COMMAN 2005a)

<table>
<thead>
<tr>
<th>Geologic Formation</th>
<th>Specific Yield ($S_y$) %</th>
<th>Transmissivity (m²/day)</th>
<th>Hydraulic Conductivity (m/day)</th>
<th>Well yield (L/sec)</th>
<th>Recharge from rainfall %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconsolidated formations</td>
<td>5 – 18</td>
<td>250 – 4000</td>
<td>10 – 800</td>
<td>40 – 100</td>
<td>8 – 25</td>
</tr>
<tr>
<td>Semi-consolidated formations</td>
<td>1 – 8</td>
<td>100 – 2300</td>
<td>0.5 – 70</td>
<td>10 – 50</td>
<td>10 – 14</td>
</tr>
<tr>
<td>Igneous and metamorphic rocks</td>
<td>1 – 4</td>
<td>10 – 500</td>
<td>0.1 – 10</td>
<td>1 – 10</td>
<td>1 – 12</td>
</tr>
<tr>
<td>Volcanic rocks</td>
<td>1 – 3</td>
<td>25 – 100</td>
<td>0.05 – 15</td>
<td>3 – 6</td>
<td>6 – 14</td>
</tr>
<tr>
<td>Carbonate rocks</td>
<td>3 – 7</td>
<td>Highly variable</td>
<td></td>
<td>5 – 25</td>
<td>Not available</td>
</tr>
</tbody>
</table>

Table 3-3: Hydrogeological formations in the Banganga River Basin (Ground Water Department Jodhpur 1999)

<table>
<thead>
<tr>
<th>Hydrogeological formations in the Banganga River Basin</th>
<th>Average yield from dug wells (m³/day)</th>
<th>Average yield from tube wells (m³/hr)</th>
<th>Depth of substrate (m)</th>
<th>% Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvium</td>
<td>59 – 100</td>
<td>2.3 – 67.5</td>
<td>2.6 – 36.7</td>
<td></td>
</tr>
<tr>
<td>Quartzite</td>
<td>40 – 75</td>
<td>0.4 – 9.0</td>
<td>3.1 – 37.8</td>
<td>15%</td>
</tr>
<tr>
<td>Slate</td>
<td>42 – 48</td>
<td>5.5 – 27.5</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Schist</td>
<td>36 – 44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>25 – 40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the area of the Arvari River catchment, aquifer properties have been identified for some of the villages (Table 3-4). According to the Alwar State Groundwater Board, the
Arvari River catchment area is divided into zones of ‘slate’ with yields of 50 – 150 m$^3$/day and ‘hills’.

Eleven hydrological tests were performed on tube wells in the alluvial aquifer in the Banganga River Basin. Transmissivity values ranged widely from 2.00 – 838.02 m$^2$/day, and storativity values between 0.00066 – 0.01707. Specific yield in the alluvial aquifers of the Banganga River Basin range from 0.07% – 0.15%. In hard rock, depending on the fractures, joints and foliation, the values range from 0.02% – 0.03% Basin (Ground Water Department Jodhpur 1999).

The groundwater resource in the Thanagazi block is classified as over-exploited. The water tables in this region vary from 15 – 25 m below the surface, but the annual fluctuation is high, particularly in years of monsoon failure when recharge is low (Shyampura and Sehgal 1995).

Table 3-4: Aquifer geology in different villages of the Arvari River catchment
(Ground Water Department Jodhpur 1999)

<table>
<thead>
<tr>
<th>Village Name</th>
<th>Aquifer Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhi</td>
<td>Schist</td>
</tr>
<tr>
<td>Thali</td>
<td>Schist</td>
</tr>
<tr>
<td>Raisar</td>
<td>Quartzite</td>
</tr>
<tr>
<td>Rasala</td>
<td>Granite</td>
</tr>
<tr>
<td>Jhiri</td>
<td>Schist</td>
</tr>
<tr>
<td>Agarkidhani</td>
<td>Slate</td>
</tr>
<tr>
<td>Dewra</td>
<td>Quartzite</td>
</tr>
<tr>
<td>Pratapgarh</td>
<td>Schist</td>
</tr>
</tbody>
</table>
3.1.6. Soils

According to the National Bureau of Soil Survey and Land use Planning (NBSS and LUP), three broad soil types can be described in the Arvari River catchment (Shyampura and Sehgal 1995):

- Soils of the hills that are gravelly and light textured. They are generally found on rocky-outcrops, are shallow, well-drained and are loamy skeletal soils, which are severely eroded and strongly stony.
- Soils found on gently sloping terrain, with loamy-sand, sandy loam texture and these are well-drained. They are moderately shallow, calcareous, and are very severely eroded and strongly stony.
- Soils in the valleys, which are deeper and well drained. They are generally fine loamy soils on very gently sloping plains with dotted hillocks having loamy surface and slightly eroded.

Hydraulic characteristics of two of the most common soils, one found under agriculture and one in commons (hills/sparse forest) land use in the Arvari River catchment are described in Table 3-5 (Shyampura, Singh et al. 2002). The soils under agriculture (Bansur series No. 47) are deeper and have a much higher field capacity ($FC$) and wilting point ($WP$) than the soils in the higher elevations (Kanwat Series No. 50), which is mostly commons land.
Table 3-5: Hydraulic properties of two common soils found in the Arvari River catchment, under agriculture and commons land use (Shyampura, Singh et al. 2002)

<table>
<thead>
<tr>
<th>1. Bansur series No. 47 – Agricultural land use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizon</strong></td>
</tr>
<tr>
<td>Ap</td>
</tr>
<tr>
<td>Bw1</td>
</tr>
<tr>
<td>Bw2</td>
</tr>
<tr>
<td>Bw3</td>
</tr>
<tr>
<td>C1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Kanwat series No. 50 – Commons land use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizon</strong></td>
</tr>
<tr>
<td>Ap</td>
</tr>
<tr>
<td>C1</td>
</tr>
<tr>
<td>C2</td>
</tr>
<tr>
<td>C3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

3.2. Study Data Collection

3.2.1. Monitoring Network

Six villages were chosen for detailed studies of wells and RWH structures in 2007 and 2008, based on position and accessibility in the Arvari River catchment. These focus areas are located mainly in the middle and upper reaches of the catchment (Figure 3-1). In each focus area a RWH structure was monitored, along with dug wells close to the structure (Table 3-6 and Table 3-7). In Bhaonta, two cascading *Bandhs* were monitored,
in Lalpura and Jhiri earthen *Johads* were monitored, and finally in Hamirpur, Nitata and Kaled *Anicuts* that lie across the main reach of the river were observed.

In the RWH structures, water depths and the surface area of the stored water were recorded daily during the monsoon season in 2007 and 2008. Surface area was not measured for the *Anicuts* that lay on the river (Hamirpur, Kaled and Nitata), as the length of water was not safely or practically accessible. At the end of the monsoon, as water levels in the wells began to fall, and water level depth differences in the structures declined, measurements in the RWH structures and dug wells were taken weekly until all stored water had either recharged or evaporated from the structures.

Table 3-6: Name and specifications of monitored RWH structures for each focus area for the field study in the Arvari River catchment in 2007 and 2008

<table>
<thead>
<tr>
<th>Village</th>
<th>Structure Name</th>
<th>Photo and Map in Appendix 1</th>
<th>RWH Type</th>
<th>Max. Storage area (ha)</th>
<th>Max. Storage depth (m)</th>
<th>Approx. Capacity (m$^3$)</th>
<th>Approx. Catchment area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhaonta</td>
<td>Sankara</td>
<td>a, c</td>
<td><em>Bandh</em></td>
<td>2.9</td>
<td>8</td>
<td>23.4</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Beruji</td>
<td>b, c</td>
<td></td>
<td>1.9</td>
<td>4</td>
<td>7.8</td>
<td>300</td>
</tr>
<tr>
<td>Lalpura</td>
<td>Koda Wala</td>
<td>d, e</td>
<td><em>Johad</em></td>
<td>2.0</td>
<td>3</td>
<td>7.1</td>
<td>150</td>
</tr>
<tr>
<td>Jhiri</td>
<td>Amli</td>
<td>f, g</td>
<td><em>Johad</em></td>
<td>1.4</td>
<td>3</td>
<td>4.2</td>
<td>NA</td>
</tr>
<tr>
<td>Hamirpur</td>
<td>Jabar Sagar</td>
<td>h, i</td>
<td><em>Anicut</em></td>
<td>1.8</td>
<td>3</td>
<td>5.0</td>
<td>10 500</td>
</tr>
<tr>
<td></td>
<td>Todee Sagar</td>
<td>j, k</td>
<td><em>Anicut</em></td>
<td>2.3</td>
<td>2</td>
<td>4.6</td>
<td>15 200</td>
</tr>
<tr>
<td>Nitata</td>
<td>Bhojya Kala</td>
<td>l, m</td>
<td><em>Anicut</em></td>
<td>0.7</td>
<td>1.5</td>
<td>1.1</td>
<td>300</td>
</tr>
</tbody>
</table>

There are no official piezometers in the catchment. Water levels in twenty-nine dug wells were monitored throughout 2007 and 2008 (Figure 3-6). These included wells close to the monitored RWH structures and eight wells outside the focus areas that were
not as close to RWH structures (Table 3-7). All well measurements were taken from the ground surface and then calculated to metres above sea level (ASL) using a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) (Jarvis, Reuter et al. 2008), which has a standard deviation of less than 16 m (Gallant and Hutchinson 2006).

In 2007 three rain gauges were set up in Bhaonta, Hamirpur and Sirinagar (Figure 3-1). In August 2008 additional rain gauges were installed at Kaled and Lalpura. These rain gauges collected daily rainfall amounts.

Figure 3-6: Position of monitored wells in the Arvari River Catchment
Table 3-7: Rain gauges and number of wells monitored at each focus area in the Arvari River Catchment in 2007 and 2008

<table>
<thead>
<tr>
<th>Focus Area</th>
<th>Rain gauge</th>
<th>Number of dug wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhaonta</td>
<td>Yes</td>
<td>6</td>
</tr>
<tr>
<td>Lalpura</td>
<td>2008 only</td>
<td>2</td>
</tr>
<tr>
<td>Jhiri</td>
<td>No</td>
<td>1</td>
</tr>
<tr>
<td>Hamirpur</td>
<td>Yes</td>
<td>3</td>
</tr>
<tr>
<td>Kaled</td>
<td>2008 only</td>
<td>5</td>
</tr>
<tr>
<td>Nitata</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Various – along roads</td>
<td>No</td>
<td>8</td>
</tr>
</tbody>
</table>

3.2.2. Catchment Rainfall Variation

Rainfall variability in the catchment is large, with highly localised events (Figure 3-7). In 2007 the focus areas with rain gauges (Bhaonta, Hamirpur and Sirinagar) received a similar amount of rain. Lower in the catchment, Sirinagar received the greatest amount of rainfall, with one large event of over 100 mm. In contrast, in 2008, the upper catchment received much more rain and had more rainy days with greater event sizes than the lower catchment at Sirinagar (Table 3-8). Using a t-test, site is a significant variable for rainfall in both 2007 and 2008, confirming the strong variation that can be observed in Figure 3-7.
Figure 3-7: Daily rainfall (mm) from rain gauges in the Arvari River catchment in 2007 and 2008

Table 3-8: Annual rainfall (mm) and number of rainy days in the Arvari River catchment for 2007 and 2008

<table>
<thead>
<tr>
<th>Focus Area</th>
<th>Total Rainfall (mm)</th>
<th>Rainy Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td>Bhaonta</td>
<td>361</td>
<td>751</td>
</tr>
<tr>
<td>Hamirpur</td>
<td>449</td>
<td>897</td>
</tr>
<tr>
<td>Sirinagar</td>
<td>499</td>
<td>494</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>436</strong></td>
<td><strong>714</strong></td>
</tr>
</tbody>
</table>

The magnitude of the daily rainfall was also very different between gauges (Figure 3-8). In 2008 there were a greater number of days with falls greater than 10 mm, which is
important when considering the function of RWH, where large events are needed to generate sufficient runoff to fill the storage area (Muralidharan and Andrade 2007).

Figure 3-8: Variation in daily rainfall depth intervals (mm) in the Arvari River catchment during the monsoon season (June-September) of 2007 and 2008

The average annual rainfall in 2007 in the catchment was much lower than the average annual rainfall (mm) of 705.8 mm at the Thanagazi station (1980-2006) (Table 3-8). Conversely, in 2008, rainfall was above the average in the upper reaches of the Arvari River catchment, Bhaonta and Hamirpur. With respect to event size, in 2007 all rain gauges in the catchment had a less than average number of large events. However in 2008, Bhaonta and Hamirpur had respectively 10 and 12 large events, which was above the Thanagazi average of 8.
The data from the catchment rain gauges displays high spatial variability during the monsoon season in both event size, and temporal distribution. Compared to the longer term rainfall data from Thanagazi, the 2007 annual rainfall was below average with a smaller number of large events. In contrast 2008 had higher average annual rainfall, the monsoon season spread over a longer period of time and with larger rainfall events. This will have an impact on RWH structures, which require large rainfall events to fill storages, a common rainfall-runoff characteristic in semi-arid areas (Pilgrim, Chapman et al. 1988). Nevertheless it should be noted that rainfall is highly localised, so that some structures may receive more rainfall than others within a small area.

3.2.3. Soils - Sampled Texture Profiles

Twenty five soil sampling sites were examined in a number of places throughout the catchment in 2007 (Figure 3-9). The sites included agricultural and commons land uses in the focus areas, the RWH storage area in the focus areas, and any exposed soil profiles along the roads between the focus areas.

Texture was examined using the bolus technique to a 1 m depth (Boudling 1994). In most of the soils however, very high gravel contents and large stones were reached well before 1 m. The characteristics described in the general soils report (Section 3.1.6) were confirmed from the field examinations, where soils are generally moderately shallow and well drained. They are also highly stony and severely eroded. The heavy erosion of the surrounding Aravalli Hills, particularly during the intense rainfall of the monsoon, has influenced the formation of soils in the area. Exposed saprolite is extensively observed in the area. Generally two soil types were discerned; a highly eroded soil in the hills, and a deeper soil in the plains (Figure 3-10).

The land use reflects soil type closely (Figure 3-10). Productive land for agriculture had a higher clay percentage, was deeper and found on the plains. The more undulating and high sloping areas had higher percentage sand, a greater percentage of rocks, and were very shallow.
Soils in the RWH structure storage areas varied from sandy loams to light medium clays and were generally very shallow (Table 3-9). Generally the structures were located at the base of hills in shallow soils. However there was a higher clay percentage in the upper 30 cm of the RWH storage areas, possibly due to sedimentation. With each monsoon fine sediments are carried with runoff into these storage areas, resulting in a build up of clay sediments. Below this layer the general soil characteristics of the hillier soils were found. This sedimentation layer could have future implications for the effectiveness of RWH, which would warrant future study and depends largely on the maintenance of the structure.
Figure 3-10: Two general soil profiles and texture characteristics in the Arvari River catchment from the field survey under the main land uses, a. Agriculture and b. Commons

Table 3-9: Textures in the storage area of RWH structures from the field survey in 2007

<table>
<thead>
<tr>
<th>Location</th>
<th>RWH Type</th>
<th>Texture at 0 – 30 cm</th>
<th>Texture at 30 – 60 cm</th>
<th>Texture at 60 – 100 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhaonta</td>
<td>Beruji Bandh</td>
<td>Silty clay loam</td>
<td>Light clay</td>
<td>Stony &gt; 50cm</td>
</tr>
<tr>
<td></td>
<td>Sankara Bandh</td>
<td>Silt loam</td>
<td>Highly stony &gt; 45cm</td>
<td></td>
</tr>
<tr>
<td>Lalpura</td>
<td>Johad</td>
<td>Loam fine sandy</td>
<td>Sandy clay</td>
<td>Light clay</td>
</tr>
<tr>
<td>Jhiri</td>
<td>Johad</td>
<td>Light medium clay</td>
<td>Highly stony &gt; 25cm</td>
<td></td>
</tr>
<tr>
<td>Hamirpur</td>
<td>Anicut</td>
<td>Loam fine sandy</td>
<td>Loam fine sandy</td>
<td>Loam fine sandy</td>
</tr>
<tr>
<td>Kaled</td>
<td>Anicut</td>
<td>Sandy loam</td>
<td>Silty clay</td>
<td>Stony &gt; 55cm</td>
</tr>
<tr>
<td>Nitata</td>
<td>Anicut</td>
<td>Loam fine sandy</td>
<td>Silt clay loam</td>
<td>Stony &gt; 68cm</td>
</tr>
</tbody>
</table>
3.2.4. Land use

The major land uses in the Arvari River catchment are commons and agriculture.

3.2.4.1. Commons

The commons land use is found on the higher elevations and hills. It includes sparse forest, which is used for grazing and wood collection. The forests are mainly mixed deciduous, which are edaphic in type (Shyampura and Sehgal 1995). There has been an increase in the forest area from 8.4% in 1989-90 to 14.4% in 1998-99.

3.2.4.2. Agriculture

The agricultural land use has three potential cropping seasons, *Kharif*, *Rabi* and *Zaid*.

*Kharif*, the monsoon crop, is planted after the first rains in June/July. Roughly 90 – 120 growing days later, the crop is harvested (September – October). *Kharif* crops are predominantly maize and pearl millet (Table 3-10). Maize requires more water than pearl millet, so if monsoon rains are less, more pearl millet is planted. About six good rainfall episodes are required to water the crops, with groundwater used to supplement irrigation where possible, if rainfall is not sufficient. Other *Kharif* crops include sorghum and pulses.

*Rabi*, the winter crop, is planted in late November – early December and is harvested around March. Wheat requires more irrigation than mustard, so if there is a good monsoon and well water levels are high, wheat is planted. If not, more mustard is planted. Other *Rabi* crops include barley and black lentils. *Rabi* is irrigated entirely with groundwater.
The *Zaid* or summer crop is only planted if there is sufficient groundwater. The area of planting is generally less than 10% of total agricultural land, because of the high evaporative losses. Vegetable crops are mainly planted in this season. All irrigation for *Zaid* is from groundwater.

Constraints to agriculture in this area include low, seasonal, high intensity, erratic and localised rainfall, high evaporation, shallow depth of soils (which tend to be highly stony and have high gravel content) and gentle to moderate slopes in the vicinity of hills. In the Alwar district dug wells and tube wells are the main source of irrigation. 52% of irrigated area is irrigated by wells, 47% by tube wells and 1% by canals. In Thanagazi 99% of irrigated area is by wells. This means there is almost complete dependence on groundwater for irrigation in this area, particularly in the *Rabi* and *Zaid* crop seasons.

Table 3-10 suggests that pearl millet is grown in larger areas than maize in the *Kharif* season, but from field observations in 2007 and 2008, maize was most predominant in the Arvari Catchment. The total irrigable area in the Banganga Basin covers about 47% of the basin. This is similar to the irrigable area in the Thanagazi block which has increased in the last 20 years from 35% to almost 50% (Table 3-11), as more marginal land has been brought under cultivation.

**Table 3-10: Thanagazi block crops (as % of total cropped area) (NIC Alwar 08/07/2009)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Millet</td>
<td>32.4</td>
<td>25.9</td>
<td>28.9</td>
<td><em>Kharif</em></td>
</tr>
<tr>
<td>Maize</td>
<td>11.1</td>
<td>9.7</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>19.0</td>
<td>21.5</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td>Black Lentil</td>
<td>19.4</td>
<td>15.0</td>
<td>10.3</td>
<td><em>Rabi</em></td>
</tr>
<tr>
<td>Barely</td>
<td>8.9</td>
<td>3.6</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Rape and Mustard</td>
<td>4.5</td>
<td>20.7</td>
<td>16.2</td>
<td></td>
</tr>
<tr>
<td>Sorghum</td>
<td>1.1</td>
<td>0.7</td>
<td>1.1</td>
<td>Both seasons</td>
</tr>
</tbody>
</table>
Table 3-11: Fraction of each land use in the Thanagazi block over three time periods (NIC Alwar 08/07/2009)

<table>
<thead>
<tr>
<th>Land use</th>
<th>% of Total Land Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td>65</td>
</tr>
<tr>
<td>Agriculture (rain-fed Kharif only)</td>
<td>20</td>
</tr>
<tr>
<td>Irrigated Agriculture (Kharif and Rabi)</td>
<td>15</td>
</tr>
<tr>
<td>Total Agriculture</td>
<td>35</td>
</tr>
</tbody>
</table>

There is a large amount of livestock in the area, buffaloes and cows provide milk and oxen and camels provide draught power.

3.2.4.3. Rainwater Harvesting (RWH)

The local NGO, Tarun Bharat Sangh and the community have built 366 RWH structures in the Arvari River catchment since 1985 (photos of the various RWH structures are in Appendix 1). Based on the local nomenclature, several different types of RWH structures can be distinguished in the catchment:

- **ANICUT**

  Anicuts are built across the main nallah (reach) of the river. They are generally made of cement and stone or concrete. Of these, the Anicuts at Hamipur, Samra, Basi and Kaled sit across the main river reach in the middle catchment area. Due to their position, these structures supposedly have a very large impact on local groundwater tables and on streamflow. Their main purpose is to recharge the aquifer.

- **BANDH**

  In English Bandh means dam, but in relation to the Arvari River catchment, Bandhs are similar to Anicuts. Bandhs mainly sit across tributaries of the main river reach in this catchment. They generally consist of a concrete core, but the outer edges are of earth, and some are entirely made of earth. The main purpose of a Bandh is recharge.
• *Johad* and *Johadi*

*Johads* are earthen dams shaped like a crescent moon. They are found at the foothills of slopes, collecting water from a small hilly catchment area. The main purpose of *Johads* is for livestock drinking water with some contribution to recharge. *Johadis* are smaller *Johads*.

• *Talab* and *Talai*

In each village of India, a *Talab* or *Talai* can be found. A *Talab* is a deep hole or pond-like structure that has high raised edges on 3 sides made of earth (similar to *Johad*). Monsoon water is collected in the *Talabs* for village use and livestock drinking with some small contribution to recharge. *Talais* are smaller *Talabs*.

• *Medbhandhi*

*Medbhandis* are constructed in farmed fields. The lower sides of the field are raised slightly to retain runoff to increase soil moisture content, and are made from earth. The purpose of a *Medbhandi* is to retain soil moisture for *Kharif* and *Rabi* crops.

In general, the upper hillier catchment area of the Arvari River catchment has more RWH development, particularly on the north-eastern side, compared to lower in the catchment (Figure 3-11). *Anicuts* and *Bandhs* have larger catchment areas and storage areas than *Johads* and *Talabs* (Table 3-12). The most common type of RWH structure in the catchment is the *Johad*, with over 127 throughout the catchment (Table 3-12, Figure 3-11 a). *Bandhs* and *Anicuts* are less numerous, and found closer to the river. The distribution of the structures was not planned at a catchment scale, depending on which villages were most interested in RWH development, structures were built. TBS only develops RWH when approached by interested communities. However within each village, local knowledge and understanding of hydrogeology is used to decide where and how the structures should be built for best storage and recharge effects (Kumar and Kandpal 2003).
While there are a number of structures built by government agencies and even older pre-independence structures, this study will concentrate on the impact of the TBS structures, assuming the older structures are part of the natural landscape and catchment hydrology.

Based on the information obtained from TBS about the structures they have built, approximately 1.44% of the catchment surface area is covered by storage of RWH (Table 3-12). This discounts Medbandhi, which were not considered in the field study because their impact on recharge is not considered significant. This estimate of RWH catchment areas is an underestimate of the total catchment area of RWH structures, as some of the catchment areas of RWH would overlap. However in this study a RWH density of 1.44% is tested.
Table 3-12: Average physical parameters of RWH structures built by TBS and the community since 1985 – 2005 in the Arvari River Catchment (pers comm. TBS)

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Number</th>
<th>Catchment area (ha)</th>
<th>Storage surface area (ha)</th>
<th>Maximum storage depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anicut</td>
<td>28</td>
<td>1090</td>
<td>3</td>
<td>2.7</td>
</tr>
<tr>
<td>Bandh</td>
<td>84</td>
<td>460</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Johad / Johadi</td>
<td>127</td>
<td>54</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>Talab / Talai</td>
<td>39</td>
<td>30</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Medbhandi</td>
<td>88</td>
<td>8</td>
<td>4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

### 3.3. Conclusion

The Arvari River catchment, due to the large number of RWH structures present in the area, was chosen as the field study site to examine RWH impacts on local and catchment scales. The study area is in a semi-arid region, which is recognised as having highly variable climate spatially and temporally. This is confirmed in the analysis of rainfall from the rain gauges in the Arvari River catchment. The hydrogeology of the area is appropriate for RWH, with the shallow aquifer readily accessible by dug wells and the underlying fluvial deposits allow rapid percolation to recharge groundwater stores. There has been significant reinvestment in RWH here over the last 20 years in the area, which makes it an interesting case study to evaluate the impacts of RWH on a larger scale catchment. However the catchment is ungauged and there is no climate station within the catchment. Additionally the existing information on aquifer properties, geology and soils is at a very large scale, which does not capture the spatial and temporal variability at the smaller scales. This is a disadvantage when trying to examine hydrological processes in the area, but with increasing RWH in areas across India in similar situations to this catchment, it is important to start investigations in such areas. The data collection focused on six main areas where RWH, including *Anicuts, Bandhs* and *Johads*, and dug wells were monitored in 2007 and 2008. These focus areas concentrate in the upper and middle areas of the catchment.
4. **LOCAL-SCALE IMPACTS OF RAINWATER HARVESTING**

![Image of a catchment with cattle]

4.1. Introduction

One of the key purposes of rainwater harvesting (RWH) in India is to store runoff and thereby increase groundwater, thus changing local water balances. However, as pointed out in Chapter 2, there has been very limited quantification of both the local (Agrawal 1996; Sharda, Kurothe et al. 2006) and the catchment-scale impacts of RWH (Batchelor, Singh et al. 2002; Kumar, Ghosh et al. 2006). As a consequence, and due to the small-scale nature of RWH, some argue that the large-scale impacts can be considered mostly minor. However when RWH occurs at many locations in a catchment, the impacts could be quite significant. As highlighted by Batchelor et al. (2002), RWH can also change patterns of water use. Irrigated agriculture areas have increased where RWH

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1The first year of results from Chapter 4 was published in the proceedings of the Water Down Under Conference 2008, Adelaide and published in the Australian Journal of Water Resources 12 (3) pp 269-280 ‘Quantifying the impacts of rainwater harvesting in a case study catchment: The Arvari River, Rajasthan, India.’ Authors: C. Glendenning, R.W. Vervoort.
development has increased groundwater availability, and water intensive crops can be farmed. Furthermore, RWH could have impacts for downstream users, because as more runoff is stored upstream, less water than previously can move downstream.

The major difficulty with assessing the catchment-scale impact of RWH in India is the lack of long-term hydrological field measurements on RWH structures, groundwater levels and streamflow. Apart from the detailed two year study by Sharda et al. (2006), there appear to be no other thorough direct measurements of groundwater variation due to RWH. This is particularly true in Rajasthan, and in the Arvari River catchment, where there have been no quantified studies of RWH, despite RWH implementation in this catchment since 1985. This is a common problem in many areas of India where RWH is practised. Sharda et al (2006) studied groundwater impacts of RWH in Gujarat and estimated that between 7 – 10% of rainfall becomes groundwater recharge by RWH. However, this was based on relatively small catchments of 200 – 612 ha, with a very dense network of observation wells. It is unclear how this would scale to a larger catchment area such as the Arvari River catchment. Similar recharge estimates of 3 – 8% of rainfall were reported by Badiger et al. (2002) from RWH structures called Paals in the Alwar district. Another study on a single check dam in granitic terrain in Andhra Pradesh estimated much higher proportions of between 27 – 40% of rainfall recharged (Muralidharan and Andrade 2007). Finally, another study found recharge rates for percolation tanks in alluvial formations in the Pali district of Rajasthan to vary from 14 – 52 mm/day, with 65 - 89% of water stored becoming percolation, and 11 – 35% lost to evaporation, though the methodology used in this study was unclear (Narain, Khan et al. 2005).

In the absence of substantial long term and spatially-detailed hydrological data, catchment-scale impacts could be best studied using a water balance model. However even for a simple model, a basic level of field data is needed to understand the local hydrological processes and for possible calibration and validation. This might include data such as rainfall, streamflow, potential recharge estimates in time and space for RWH structures, combined with an understanding of the hydrogeological characteristics of the
catchment. Given the shortage of data on RWH, collection of local data in the Arvari River catchment is a major part of this study. This chapter reports on the collection of the field data in the case study catchment. This data will give an overview of observed local impacts of monitored RWH and response in dug wells in 2007 and 2008, from which catchment variability can be inferred. In addition the data will be used in later chapters to develop and verify a catchment-scale model.

4.2. Rainwater Harvesting Data Analysis

4.2.1. Methods

Field data collected in 2007 and 2008 were used to calculate the potential recharge ($R_{ep}$) of monitored RWH structures built by Tarun Bharat Sangh (TBS) and the community (Table 3-6). The issue of scaling and trying to encompass all the major characteristics of the catchment, particularly in relation to the hydrogeology of the catchment and the different types of RWH, was considered in the choice of the location of the field surveys. Owing to various factors, including accessibility and time limitations, detailed studies concentrated on six focus areas in the upper and middle reaches of the catchment; Bhaonta, Lalpura, Jhiri, Hamirpur, Kaled and Nitata (as described in Section 3.2.1). Streamflow (catchment runoff) was monitored downstream at Sirinagar in 2007. Natural recharge was not measured.

4.2.1.1. Potential Recharge Estimates from RWH – Water Balance Method

Following the methodology described in Sharda et al. (2006), potential recharge ($R_{ep}$) estimates from the RWH structures were calculated for data collected in 2007 and 2008. Potential recharge was estimated on non-rainy days using the water balance approach
(Figure 4-1, Eq 4-1), when runoff into the structures is assumed to be zero. The volume of $R_{ep}$ ($m^3$) is calculated based on losses and additions of water taken from the storage of the RWH structures (Sharda, Kurothe et al. 2006):

$$R_{ep} = -A_s(\Delta h + ET) - O_t$$

Eq 4-1

$A_s$ = average surface area ($m^2$) of stored water, $(A_{s1} + A_{s1-1} + \sqrt{A_{s1} \cdot A_{s1-1}})/3$

(This is the Heronian mean)

$ET$ = evaporation (this study used daily potential evaporation from Fig 3-5) (m),

$O_t$ = overflow ($m^3$), which did not occur during the field data collection

$\Delta h$ = increase in depth (m) in water level of the structure

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**Figure 4-1: After Sharda et al. (2006), the water balance of the storage of a RWH structure**

On rainfall days the volume of $R_{ep}$ was calculated based on the relationship between $R_{ep}$ on non-rainy days and the average depth of water in the structures (Sharda, Kurothe et al. 2006);

$$R_{ep} = a h_{av}^b$$

Eq 4-2
\(a\) and \(b\) = curve fitting parameters fitted using a linear model

\[ h_{av} = \text{average depth where } (h_t + h_{t-1} / 2). \]

This analysis assumes that the majority of runoff from rainfall would reach the structures on the same day as the rainfall. This is acceptable considering the small catchment areas for RWH structures. Domestic goats and buffaloes drank and bathed in the structures, but this was not included as it was considered an insignificant loss of daily storage from the structures. Missing daily data for measurements of surface area and depth were approximated using a linear interpolation. Negative recharge values in the time series largely represented times when evaporation was greater than the change in depth and \(R_{ep}\) was therefore assumed to be zero on that day.

### 4.2.1.2. Recharge Efficiency of Structures

The hydrogeological efficiency or recharge efficiency of the RWH structures was determined by examining the relationship between the volume of \(R_{ep}\) and the volume of water stored in the structure for each year (Martin-Rosales, Gisbert et al. 2007). Recharge efficiency, \(\eta_{\text{recharge}}\), is expressed as (Beernaerts 2006):

\[
\eta_{\text{recharge}} = \frac{R_{ep}}{V_{\text{run-on}}} \quad \text{Eq 4-3}
\]

\(R_{ep}\) = total volume of potential recharge over a given period (m\(^3\)), calculated from the methodology in Section 4.2.1.1, \(V_{\text{run-on}}\) = total volume of water collected in the storage area over a given period (m\(^3\)), which was calculated by assuming the volume is a triangular prism shape in the RWH storage and calculating volume on a daily basis with the field data of surface area and depth. While this is not a totally accurate representation of the structure storage volume, it gives an estimate of the volume of run-on, and is consistent across storages.
4.2.1.3. River flow

Discharge was calculated on the days when overflow occurred at the Anicuts on the river (Hamirpur, Kaled and Nitata) using the broad-crested weir equation:

\[ Q = C . b . H^{3/2} \]  

Eq 4-4

\( Q \) = discharge (m\(^3\)/day)
\( C \) = coefficient of discharge for the weir = \( 1.7 = (2/3)^{3/2} \) (gravity acceleration\(^{1/2} \))
\( b \) = breadth of the weir (m)
\( H \) = the head of water above the crest measured at upstream (m)

4.2.1.4. Electrical Conductivity (EC) Measurements

During the monsoon, water emerged below the Anicuts on the river. Within the local community there is some debate as to whether this is base flow i.e. groundwater derived, or leakage from the Anicuts. Weekly measurements of EC (mS/cm) were taken from the monitored wells and from water in and below the monitored RWH structures in 2008 to determine the origin of the water.

4.2.2. Results

4.2.2.1. Potential Recharge Estimates from RWH – Water Balance Method

From Figure 4-2 and Figure 4-4 it can be seen that the collected data from the RWH structures is quite noisy. This is a reflection of the difficulties associated with estimating the planar surface area and the height of the structures. The surface area of all structures had highly irregular shapes. The presence of cattle, particularly buffaloes, created large
depressions around the edges of the storage area, which also added difficulty in accurately measuring the storage surface area and depths. The most difficult structure to accurately measure was Jhiri Johad, where buffaloes or children removed the base mark for measuring depth many times, and the storage area was riddled with many depressions. As a result this data is the noisiest.

As described in Section 4.2.1.1, in order to estimate $R_{ep}$ on rainy days, a linear relationship between calculated $R_{ep}$ volume on non-rainy days and average depth was developed (Sharda, Kurothe et al. 2006) (Figure 4-2). Statistical parameters for the fitted lines in Figure 4-2 for each structure are shown in Table 4-1. All relationships were significant. The shape of the relationship between average depth (m) and $R_{ep}$ volume (m$^3$) is the same for all structures, and the parameters are also similar to those found in Sharda et al. (2006). The relationship between average depth and $R_{ep}$ volume on non-rainy days was then used to estimate $R_{ep}$ volume on rainy days.

Table 4-1: Statistical parameters for Eq 4-2, describing the relationship between average depth (m) and $R_{ep}$ volume (m$^3$) on non-rainy days to calculate $R_{ep}$ volume (m$^3$) on rainy days

<table>
<thead>
<tr>
<th>Village</th>
<th>RWH structure</th>
<th>a</th>
<th>b</th>
<th>$R^2$</th>
<th>RMSE (m$^3$)</th>
<th>Standard deviation of $R_{ep}$ (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhaonta</td>
<td>Sankara Bandh</td>
<td>179.9</td>
<td>1.7</td>
<td>0.93</td>
<td>1601.3</td>
<td>873.1</td>
</tr>
<tr>
<td></td>
<td>Beruji Bandh</td>
<td>69.3</td>
<td>2.2</td>
<td>0.69</td>
<td>427.2</td>
<td>115.2</td>
</tr>
<tr>
<td>Jhiri</td>
<td>Jhiri Johad</td>
<td>82.1</td>
<td>1.8</td>
<td>0.62</td>
<td>536.8</td>
<td>403.9</td>
</tr>
<tr>
<td>Lalpura</td>
<td>Lalpura Johad</td>
<td>117.2</td>
<td>3.5</td>
<td>0.95</td>
<td>818.8</td>
<td>658.0</td>
</tr>
</tbody>
</table>
Figure 4-2: Fitted linear model to estimate $R_{ep}$ on rainy days using $R_{ep}$ calculated from the water balance method on non-rainy days. a. Sankara Bandh, b. Beruji Bandh, c. Jhiri Johad, d. Lalpura Johad

Total $R_{ep}$ volume was greatest at Sankara (Figure 4-3 a). Beruji Bandh was directly below Sankara Bandh, so the volume of recharge here is less, as less runoff reached this structure and depth was lower (Figure 4-3 b). Bandhs also had a shorter storage time than the Johads (Table 4-3). Beruji Bandh emptied the fastest of all structures, probably mainly due to smaller run-on volume, but also possibly due to the underlying geology, which could have higher infiltration rates than other areas. In all structures, total $R_{ep}$ volume increased in 2008. The monsoon season extended longer and rainfall was greater
in 2008, which is reflected in the $R_{ep}$ volume with a longer time series and greater volume than in 2007 (Figure 4-3).

There is greater daily $R_{ep}$ (mm) with greater storage depth in the structures, than with less stored water (Figure 4-4). For the two Bandhs (Figure 4-4 a and b) there is an approximately linear increase of daily $R_{ep}$ (mm) with increasing storage depth. Lalpura Johad also indicates an increase in daily $R_{ep}$ (mm) with greater depths, but the

**Figure 4-3: Estimated $R_{ep}$ (m$^3$) with daily rainfall (mm) from Bhaonta gauge for a. Sankara Bandh, b. Beruji Bandh, and with daily rainfall from Hamirpur gauge for c. Jhiri Johad, d. Lalpura Johad**
relationship might be more non-linear. The slopes of the fitted linear models in Figure 4-4 are similar for all structures, but lowest in Sankara Bandh, which is a reflection of the size of the structure. At Sankara Bandh, for each incremental increase in depth, a larger surface area of water is required compared to the other smaller structures, which have higher daily $R_{ep}$ response with increasing depth, but smaller $R_{ep}$ volume.

Figure 4-4: Average Depth (mm) by daily $R_{ep}$ (mm) for a. Sankara Bandh, b. Beruji Bandh, c. Lalpura Johad, (where $R_{ep}$ (mm) is calculated by dividing $R_{ep}$ (m$^3$) by average surface area (m$^2$))

An analysis of variance model was fitted for recharge by site, then structure and finally recharge by structure type, which were all significant variates. Due to the higher rainfall
in 2008, the RWH structures stored a greater volume of water, so that by site, structure and structure type, the statistical analysis indicated differences in the results between the two monitored years (Table 4-2). Using Tukey HSD, there were no significant differences between focus areas in 2007, whereas in 2008 Jhiri Johad was significantly different from the others. Bandhs and Johads are significantly different in 2008, but not in 2007. This is most probably due to higher average rainfall in 2008, which meant that the larger structures, the Bandhs, could store more water than the Johads and thus \( R_{ep} \) increased. The rainfall at Sankara Bandh (Bhaonta gauge) had the lowest rainfall in 2007, yet Sankara Bandh held the highest storage. This is due to the catchment area of this structure, which is larger than all the other monitored structures and is located in the steep rocky hills.

Differences in \( R_{ep} \) are difficult to interpret, given the variability in \( R_{ep} \) volume, which depends on the shape and size of structure storage, runoff characteristics (local rainfall and land cover), and infiltration characteristics in the storage area (soil depth and underlying bed rock), but these differences indicate the local variability. In the Johads, the soil depth was deeper and had higher clay content compared to Bandhs, which would influence the infiltration capacity of the stored water to reach the groundwater (Table 3-9).

<table>
<thead>
<tr>
<th>Table 4-2: Tukey HSD results of potential recharge by focus area and RWH type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant Difference by:</td>
</tr>
<tr>
<td>Focus area (Bhaonta, Lalpura, Jhiri)</td>
</tr>
<tr>
<td>RWH structure type (Bandh, Johad)</td>
</tr>
</tbody>
</table>

As rainfall increases, the volume of \( R_{ep} \) increases. Compared to 2007, in 2008 the total volume of \( R_{ep} \) at Sankara Bandh increased 3 times, Beruji Bandh 2.3, Jhiri Johad 2.0 and Lalpura Johad 2.1 times. As only two years of field data has been collected, it is difficult to determine the exact relationship between annual rainfall and annual recharge. The
observed data however, indicate the range of $R_{ep}$ values that can occur across a variable landscape. Such variability can be included in models via Monte Carlo simulations or can assist with parameter estimation.

The average daily $R_{ep}$ rates (Table 4-3) in 2008 are much greater than in 2007, as more rainfall in 2008 meant more stored water in the RWH storage areas and therefore more $R_{ep}$. Studies conducted on recharge through percolation tanks constructed in hard rock and alluvium formations in the Pali district (Western Rajasthan), showed similar percolation rates of 14 – 52 mm/day (Narain, Khan et al. 2005). Another study by Neumann et al. (2004) theoretically compared evaporation rates with different recharge rates from structures. They found that rates varied broadly for different reservoirs. Decline rates that were similar to evaporation rates (3.6 mm/day) suggested that reservoirs were 100% inefficient, acting only as evaporation pans. Other reservoirs with decline rates of 24 mm/day or greater suggested more recharge, which is similar to all monitored RWH structures in this study (Table 4-3). Neumann et al. (2004) points out that the rate of infiltration from structures can change throughout the season due to: change in hydraulic gradient, the shape of the storage area and runoff into the structure, carrying with it sediments which build up over time forming a layer.

<table>
<thead>
<tr>
<th>RWH Structure</th>
<th>Year</th>
<th>Total days of storage</th>
<th>Average daily $R_{ep}$ (mm/day)</th>
<th>Standard deviation of $R_{ep}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sankara Bandh</td>
<td>2007</td>
<td>169</td>
<td>45.6</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>206</td>
<td>55.6</td>
<td>0.15</td>
</tr>
<tr>
<td>Beruji Bandh</td>
<td>2007</td>
<td>138</td>
<td>20.9</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>201</td>
<td>27.8</td>
<td>0.03</td>
</tr>
<tr>
<td>Jhiri Johad</td>
<td>2007</td>
<td>273</td>
<td>12.3</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>308</td>
<td>19.5</td>
<td>0.01</td>
</tr>
<tr>
<td>Lalpura Johad</td>
<td>2007</td>
<td>240</td>
<td>15.7</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>382</td>
<td>23.5</td>
<td>0.04</td>
</tr>
</tbody>
</table>
4.2.2.2. Potential Recharge and Rainfall Relationship

As explained, rainfall in this study area is highly localised. This must be considered when examining the relationship between rainfall and potential recharge, because those structures that were closest to a rain gauge may have stronger relationships. At Sankara Bandh and Beruji Bandh, the rainfall gauge was approximately 2 km from the structures. However the nearest rain gauge for Lalpura Johad was 8.5 km away, and for Jhiri Johad 2.5 km.

The exponential function, as used by Sharda et al. (2006), was fitted to cumulative sum of rainfall and cumulative sum of $R_{ep}$ over the two year time series:

$$\log_{10}(R_{ep}) = a[b - e^{-cr}]$$

Eq 4-5

$R_{ep}$ = cumulative recharge (mm), $P$ = cumulative rainfall (mm), $a$, $b$ and $c$ = parameters

This function gives estimates of cumulative recharge from cumulative rainfall, which is useful to identify how much rainfall would be needed for a given amount of $R_{ep}$. Potential recharge was converted from m$^3$/day to mm/day by dividing by the average surface area of the structures (See Section 4.2.1.1).

Logarithmic and logistic sigmoid curves were also fitted, but the exponential function (Eq 4-5) had the best fit, with high $R^2$ (Table 4-4). In all structures, $R_{ep}$ from RWH reaches a maximum daily depth as cumulative rainfall continues to infinity, a relationship also described in Sharda et al. (2006) (Figure 4-5). This reflects the engineering design of the structures, which can only store a limited amount of runoff, regardless of how much rainfall and so can only induce a maximum depth of daily recharge.
Table 4-4: Statistical parameters for Eq 4-5 describing the relationship between the cumulative sum of $R_{ep}$ (mm) and cumulative sum of rainfall (mm)

<table>
<thead>
<tr>
<th>Structure</th>
<th>$R^2$</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sankara Bandh</td>
<td>0.89</td>
<td>2.78</td>
<td>1.94</td>
<td>0.004</td>
</tr>
<tr>
<td>Beruji Bandh</td>
<td>0.88</td>
<td>2.86</td>
<td>0.21</td>
<td>0.005</td>
</tr>
<tr>
<td>Jhiri Johad</td>
<td>0.93</td>
<td>2.78</td>
<td>0.75</td>
<td>0.003</td>
</tr>
<tr>
<td>Lalpura Johad</td>
<td>0.81</td>
<td>2.68</td>
<td>0.77</td>
<td>0.008</td>
</tr>
</tbody>
</table>

In Sankara Bandh (Figure 4-5 a) two distinct trends can be seen, which reflects the different rainfall patterns of 2007 and 2008. The intensity of rainfall in 2007 was smaller than in 2008 (Figure 4-6). This resulted in the higher cumulative recharge daily depth that is seen at Sankara Bandh. Jhiri Johad also displays this pattern, but 2007 cumulative $R_{ep}$ depth is higher than the 2008 cumulative $R_{ep}$ (Figure 4-5 b). This is more difficult to explain, but could be associated with a different rainfall pattern in this location, with perhaps a large rainfall event early in 2007. Beruji Bandh does not display this difference, because it is situated below Sankara Bandh storage, so runoff from a large rainfall event takes more time to reach this structure (Figure 4-5 c). Lalpura Johad similarly displays the lack of response to higher rainfall events (Figure 4-5 d). The steps in the data in Figure 4-5 is because recharge is continuous, while rainfall does not occur each day.
Figure 4-5: Cumulative potential recharge (mm) against cumulative rainfall (mm) using the exponential function (y axis is logged) a. Sankara Bandh, b. Beruji Bandh, c. Jhiri Johad, d. Lalpura Johad
Figure 4-6: Cumulative rainfall for 2007 (mm) against cumulative rainfall for 2008 (mm) (line represents $x = y$)

Figure 4-7 displays the cumulative rainfall required to induce 1 mm, 10 mm and 100 mm of $R_{ep}$ from the monitored RWH structures, calculated from the regressions in Table 4-4 and Eq 4-5, and are comparable with the results in Sharda et al. (2006). This is a positive result, because the data collected from the Sharda et al. (2006) study was across a smaller area and contained less noise than this study. Beruji Bandh, Jhiri Johad and Lalpura Johad display very similar results to the Sharda et al. (2006) estimates. However Sankara Bandh requires less cumulative rainfall to induce recharge. This may be because Sankara Bandh has a larger storage, and is situated in the steep rocky hills, where percolation is highest (Table 4-3). Beruji Bandh requires more cumulative rainfall to induce recharge, which is a reflection of the position of Beruji Bandh, below Sankara Bandh (which would first collect runoff), and in a smaller catchment area. The Johads, Lalpura and Jhiri, hold water in storage for the longest time (Table 4-3), due to lower infiltration rates in the storage areas. More rainfall is needed for these structures to induce more $R_{ep}$. These results highlight the difference in $R_{ep}$ between the larger and smaller RWH structures.
4.2.2.3. Recharge Efficiency of RWH Structures

Despite the uncertainties associated with the field measurements of RWH surface area and depth, stored run-on volume into each monitored RWH structure was estimated to determine the recharge efficiency. Given these uncertainties, there is not a large difference between years in these results (Table 4-5). In 2007 the volume stored in the structures was much less than in 2008, but this does not seem to influence recharge efficiency, as the volume of run-on is in a similar ratio to $R_{ep}$ volume across the two years.

The most efficient RWH structure is Beruji Bandh. More of the water stored in this structure became potential recharge than in any other structure, which could be because it had the shortest storage time and therefore less evaporative losses (Table 4-3). In 2008
there is a greater storage surface area in all the RWH structures, but shallower depths at the exteriors of the storage area. A larger surface area therefore means greater evaporation losses, as the high surface area to volume ratio of small reservoirs leads to higher evaporation loss (Keller, Sakthivadivel et al. 2000). This is possibly why Sankara Bandh, with the highest potential recharge volume, but also the largest storage surface area (and therefore higher evaporative losses), has lower recharge efficiency than Beruji Bandh.

Johads have similar recharge efficiency. The Johads at Jhiri and Lalpura held water in storage longer than in the Bandhs, and so evaporative losses would have been higher (Table 4-3). As described in Table 3-9, the deeper heavier clay layer in these structures, and underlying geology, mean that infiltration rates are smaller in Johads, so hold stored water for longer. These structures are known in the community to not have a large recharge component, which was confirmed in this study, and are purpose built to store water for cattle bathing and drinking.

<table>
<thead>
<tr>
<th>RWH structure</th>
<th>Recharge efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
</tr>
<tr>
<td>Sankara Bandh</td>
<td>6.0</td>
</tr>
<tr>
<td>Beruji Bandh</td>
<td>16.4</td>
</tr>
<tr>
<td>Jhiri Johad</td>
<td>2.1</td>
</tr>
<tr>
<td>Lalpura Johad</td>
<td>3.4</td>
</tr>
</tbody>
</table>

4.2.3. River flow and Storage

In much of the literature that considers RWH impacts, the upstream-downstream tradeoffs are often highlighted as a potential problem, but this has never been quantified. These tradeoffs were also considered when conducting field work in the case study, and discharge across three Anicuts that lie across the main reach of the river were monitored.
As already highlighted, there is a large variability in rainfall, which is reflected in the overflow from the \textit{Anicuts} on the river. In 2007, the \textit{Anicut} at Hamirpur overflowed on 8 days towards Kaled. At Kaled \textit{Anicut}, overflow occurred for 22 days and further downstream towards Sainthal Sagar dam, at Sirinagar, there was no river flow (refer to Figure 3-1 for catchment position). On the other tributary, at Nitata, the \textit{Anicut} overflowed on 6 days. In 2008, rainfall increase led to more overflow; Hamirpur 24 days, Nitata 11 days, but Kaled had the longest overflow, flowing daily through the months of July to early November (Figure 4-8).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4-8.png}
\caption{Daily discharge or overflow over the monitored \textit{Anicuts} on the Arvari River in 2007 and 2008}
\end{figure}

Discharge and days of overflow was greatest at the Kaled \textit{Anicut} in both years (Figure 4-8). Either more rain fell in the catchment of the Kaled \textit{Anicut}, or perhaps the larger \textit{Anicut} at Samra, which is above Kaled \textit{Anicut} and below Hamirpur \textit{Anicut}, released water slowly downstream. The latter reason seems more likely because in 2008 flow occurred daily from July until November (there was no rain after September in 2008). The peaks in all the \textit{Anicuts} fall at similar times, mostly when large rainfall events occurred and therefore there were greater runoff events into the river.
At Hamirpur Anicut, overflow started at a similar cumulative rainfall in both years (Figure 4-9 a). At Kaled and Nitata Anicuts the cumulative overflow from the structures was much greater in 2007 than for a similar cumulative amount of rainfall in 2008 (Figure 4-10 b and c). Due to the high variability of rainfall, the use of the same rainfall at Kaled and Nitata as Hamirpur may produce these results. However, it could also possibly suggest that more water reached the stream earlier in 2007 than in 2008 at these locations. Perhaps more water was captured upstream in 2008 than in 2007. In 2008 there were larger rainfall events, which RWH is most efficient in capturing. While this study can not compare the impact of RWH on streamflow before and after RWH works began, this analysis suggests that the rainfall – stream runoff relationship may have been altered. In 2008, even though 300 mm rain fell in a much shorter time period than in 2007 (Figure 4-6) due to the difference between the smaller number of rainfall events in 2007 and the larger number of rainfall events in 2008, the streamflow is not as great. This suggests that RWH may be capturing runoff in larger events, which would otherwise reach the river. This analysis also indicates that for overflow at the Anicuts to occur, concurrent events of rainfall is just as important as the cumulative amount of rainfall.
Figure 4-9: Cumulative sum of rainfall (mm) at Hamirpur against cumulative sum of overflow on the Anicuts on the Arvari River at a. Hamirpur, b. Kaled, c. Nitata

Given that no surface areas were measured for the water stored in the Anicuts, the depth of recharge from the Anicuts was estimated using the water balance method for days when there was no overflow, no rainfall and no runoff in the storage.

\[ R_{ep} = \Delta h - ET \]  

Eq 4-6

\( \Delta h \) = change in depth behind dam wall, \( ET \) = potential evaporation.

This assumes that \( R_{ep} \) occurs evenly over the storage surface area. As a result the actual total \( R_{ep} \) volumes would differ from these estimates, as these would be related to the surface area.
Figure 4-10 shows the differences in recharge at the *Anicuts*. Average daily recharge varied from 42 mm/day at Nitata, to 25 mm/day Kaled and 44 mm/day at Hamirpur. Kaled was the smallest structure, with the lowest dam wall height, which could be why $R_{ep}$ was lowest here. Interestingly in all *Anicuts* recharge appears higher in the low rainfall year (2007). In 2008 there was more overflow (Figure 4-8), so there was not a long enough time series to establish $R_{ep}$. Potential recharge could only be estimated once overflow had stopped and so actual $R_{ep}$ could be much higher. This could explain the lower values at Kaled *Anicut*. But overall these estimated $R_{ep}$ values are high when compared with the values obtained from the *Johads* and *Bandhs*, possibly due to differences in underlying stratum. This confirms the notion that the structures on the river are important for recharge. These results could also provide approximate transmissions losses from the river reaches.

![Figure 4-10: Estimated $R_{ep}$ (mm/day) from monitored *Anicuts* on the Arvari River in 2007 and 2008](image)

After the first few rainfall events, it was observed that water accumulated downstream of all three *Anicuts* on the river. This water was not flowing, and it was assumed either to
be leakage from the dams or upwelling base flow from the shallow alluvial aquifer. This water was present from July 2007 to early 2008, and again in the monsoon of 2008 to early 2009. Based on EC measurements, it appears that the water is not base flow but lateral subsurface flow from the water stored in the Anicut upstream (Figure 4-11). The EC values of the water downstream of the Anicuts are closer to the EC values of water in the storage of the Anicuts than to values in the groundwater in the nearby monitored dug wells. From this data, there is also seen an increase in salinity levels in groundwater as water levels decline. This could be from return flow from irrigated agriculture, which increases salinity in the groundwater.

Figure 4-11: Measured EC (mS/cm\(^{-1}\)) values in Anicuts and dug wells in 2008 in the focus areas of a. Kaled, b. Nitata, c. Hamirpur
Conclusions

Some general characteristics of RWH structures can be determined from the above analysis, despite uncertainties associated with the field data. In all RWH structures the higher than average rainfall in 2008, increased the total volume of \( R_{ep} \) and average daily \( R_{ep} \) depth. But recharge efficiency was similar between years and structures, which suggest that the efficiency of RWH is a function of location, size and shape rather than amount of rainfall received. This also limits the maximum daily recharge depth of the structure, which would also be related to the saturated hydraulic conductivity of the underlying stratum. Nevertheless high rainfall years influence the amount of runoff and therefore the volume of \( R_{ep} \) from a RWH structure.

4.3. Well Data Analysis

4.3.1. Recharge Estimate in Wells – Water Table Fluctuation (WTF) Method

The water table fluctuation (WTF) method is used to estimate recharge from the monitored dug well data. It requires knowledge of the specific yield \( (S_y) \) and change in groundwater levels over time (Healy and Cook 2002). The amount of recharge \( (R_{gw}, \text{mm/day}) \) can be estimated from the rise in the water table \( (\Delta h) \) over time \( (\Delta t) \) (Healy and Cook 2002; Scanlon, Healy et al. 2002):

\[
R_{gw} = S_y \cdot \Delta h / \Delta t \\
\text{Eq 4-7}
\]

A constant specific yield \( (S_y) \) was taken as 0.1, based on literature data (Table 4-6), assuming an unconsolidated geological formation. The lithology of the area is predominantly alluvium and blown sand (Table 4-7), which, according to standard \( S_y \) values (Johnson 1967), would give a similar estimate. Furthermore in the Banganga River Basin, of which the Arvari River catchment is a part, \( S_y \) in alluvial aquifers ranges from 0.07 – 0.15 (Ground Water Department Jodhpur 1999). While assuming a constant
$S_y$ can introduce errors in the recharge estimations (Sophocleous 1991), there is little other data to allow a more accurate estimation of $S_y$, such as used in other studies (Crosbie, Binning et al. 2005; Marechal, Dewandel et al. 2006; Muralidharan and Andrade 2007; Wendland, Barreto et al. 2007).

Table 4-6: Generalised aquifer characteristics for aquifers across India and most likely occurring in the Arvari River Catchment (COMMAN 2005a)

<table>
<thead>
<tr>
<th>Geological formation</th>
<th>$S_y$ %</th>
<th>$T \text{m}^3$/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconsolidated</td>
<td>5-18</td>
<td>250-4000</td>
</tr>
<tr>
<td>Semi-consolidated</td>
<td>1-8</td>
<td>100-2300</td>
</tr>
</tbody>
</table>

Table 4-7: Description of geology in areas where monitored dug wells

<table>
<thead>
<tr>
<th>Village</th>
<th>Number of monitored dug wells</th>
<th>Lithology (Geological Survey of India 1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhaonta</td>
<td>6</td>
<td>Intertrappean quartzite, conglomerate</td>
</tr>
<tr>
<td>Lalpura</td>
<td>2</td>
<td>Alluvium and blown sand</td>
</tr>
<tr>
<td>Jhiri-Lalpura road</td>
<td>3</td>
<td>Alluvium and blown sand</td>
</tr>
<tr>
<td>Jhiri</td>
<td>1</td>
<td>Alluvium and blown sand</td>
</tr>
<tr>
<td>Hamirpur-Kaled road</td>
<td>5</td>
<td>Schist and alluvium</td>
</tr>
<tr>
<td>Hamirpur</td>
<td>4</td>
<td>Intertrappean schist</td>
</tr>
<tr>
<td>Kaled</td>
<td>6</td>
<td>Alluvium and blown sand</td>
</tr>
<tr>
<td>Nitata</td>
<td>2</td>
<td>Alluvium and blown sand</td>
</tr>
</tbody>
</table>

4.3.2. Results

4.3.2.1. Well Response

Water levels in all monitored wells increased during the monsoon seasons in 2007 and 2008. The rate of increase is different for each well, which could be due to a range of
factors including: aquifer properties, number of RWH structures nearby, and the amount and intensity of rainfall in the local area. While this variability means that strong conclusions are difficult, it highlights local catchment variability, a common feature of semi-arid areas (Pilgrim, Chapman et al. 1988) and also the local recharge impacts of RWH.

Most wells had diesel pumps and these were used extensively for irrigation during the monsoon of 2007 due to the low rainfall. Consequently water levels in pumped wells decreased significantly after reaching a maximum height early in the monsoon of 2007 (which may not actually have been the maximum groundwater level because of pumping effects). This made it difficult to estimate recharge using the water table fluctuation (WTF) method. On the other hand the rainfall in 2008 was mostly sufficient for meeting Kharif crop needs, resulting in less pumping, especially in the early months of the monsoon (July – August), so the water level rises in the wells can be seen more clearly in 2008 and reached a higher level.

Data from all monitored wells, including those close to the monitored Bandhs and Johads, those close to monitored Anicuts on the rivers, and wells not close to a RWH structure, is reported. In the accompanying figures, water levels are plotted as heights above sea level (ASL) and also as relative groundwater levels, where relative height is defined as:

\[ \text{relative height} = \frac{h_t - h_{\text{initial}}}{h_{\text{max}} - h_{\text{initial}}} \]  

Eq 4-8

\( h_t = \text{height ASL (m) at time } t, \ h_{\text{initial}} = \text{initial groundwater level height ASL (m)}, \ h_{\text{max}} = \text{maximum groundwater level height (m)} \)

Using relative groundwater level heights allows easier comparison of the recharge behaviour (or rise) in wells in similar areas, and is particularly useful to examine whether any of the wells recharge faster than others.
Figure 4-12: The six monitored wells at focus area Bhaonta, a. ASL (m) groundwater level, b. Relative groundwater level height, c. Relative groundwater level height at Well BK5 and depths at Sankara Bandh and Beruji Bandh (m)

The wells at Bhaonta saw a greater response in 2008 than 2007 (Figure 4-12 a and b). There was less pumping and more rainfall, so the impact of recharge can be seen more clearly. Wells BK1 and BK2 were closest to the two large Bandhs, but were pumped in 2007. The relative response in 2008 shows a greater increase in these wells compared with BK3 and BK6 (Figure 4-12 b). In general, wells BK1, BK2, BK4 and BK5 show faster responses than BK3 and BK6. This could be due to their position in the landscape. Wells BK3 and BK6 are in a valley that runs parallel to the valley with the Bandhs, so
recharge may take longer to reach there due to different geology (Appendix 1). Well BK4 is further away from the structures than well BK3, and aquifer connectivity probably has some influence on the difference in response between these two wells. Well BK5 was the shallowest well, close to the surface in a rocky area, while BK1 and BK2 were in the agriculture land. The response from well BK5 closely mirrored the RWH structures water storage patterns of rise and fall (Figure 4-12 c.), which confirms the influence of recharge from RWH on groundwater levels. Wells BK4 and BK 6 are almost 1 km away from Sankara Bandh and 600 m from Beruji Bandh, but the influence of recharge on groundwater levels can still be clearly seen. This could be the result of large lateral transmissivity as Bhaonta is in the rockier higher elevation area and there are larger volumes of potential recharge coming from the Bandhs, particularly from Sankara Bandh (Figure 4-3).

Figure 4-13: The two monitored dug wells at focus area Lalpura, a. ASL (m) groundwater level, b. Relative groundwater level height (m)

The two wells below the Lalpura Johad had diesel pumps, which were used in both 2007 and 2008 (Figure 4-13). This makes it difficult to determine any recharge trends. Nevertheless well LP1 is situated directly in front of the Lalpura Johad and the relative response from this well was greater than at well LP2, which is further away. This suggests that recharge from Lalpura Johad has a smaller mounding influence on the
water table because it does not effect dug wells further away, whereas at Bhaonta, rises were seen in wells 6 km away. Alternatively the aquifer connectivity may be poor, with lower transmissivity, but the Lalpura focus area is in a similar landscape position and elevation to Bhaonta, so the former conclusion may be more apt.

Figure 4-14: The monitored well at Jhiri ASL groundwater level (m)

There was only one well close to the Jhiri Johad structure, which was also pumped (Figure 4-14). The response is greater in 2008 than in 2007 which could be due to less pumping and/or more recharge.
In Hamirpur all wells, which were close to the monitored Anicut on the river, similarly showed a greater relative response in 2008 than in 2007 (Figure 4-15). There was much less pumping from all wells in 2008. Wells HP2 and HP3 are directly next to each other and consequently are very similar. Wells HP1 and HP4 are closest to the river, while well HP1 is closest to the Anicut. However the response from these wells is very similar to HP2 and HP3 which are further away (Figure 4-15 b). This might indicate a fast lateral transmissivity in this area.
Figure 4-16: Response of monitored wells at Kaled. a. Groundwater level ASL (m), b. Relative groundwater level height (m), c. Relative groundwater level height (m) well KLD6

At Kaled, wells KLD1 – KLD5 are all along the river below the Anicut and display similar characteristics in response (Figure 4-16 a and b). Well KLD6 is more than 1 km away from the river and as a result the response here was slower and perhaps does not reflect the mounding influence of the Anicut nearby, but the overall recharge in the aquifer (Figure 4-16 c). Well KLD6 also indicates a higher response in 2008 than 2007. There was no pump on this well, so rise here is related to recharge reaching the aquifer in this area. This indicates that overall recharge was much higher in 2008 compared to 2007.
Figure 4-17: Response of two monitored dug wells at Nitata, a. Groundwater level ASL (m), b. Relative groundwater level height (m)

The two wells near the *Anicut* at Nitata follow each other in response (Figure 4-17). Well NT1 is above the *Anicut*, while well NT2 is downstream from the *Anicut*. Water stored in the structure percolates into the aquifer, influencing both wells. Alternatively, well NT1 might be influenced by transmission losses from water flowing into the *Anicut* storage area.

Figure 4-18: Roadside wells between Jhiri and Kaled. a. Groundwater level ASL (m), b. Relative water level height (m)
The roadside wells in Figure 4-18 are situated between the Jhiri and Kaled focus areas. These wells were not situated as close to RWH structures as the other wells and as such could be interpreted as background values of recharge. Water levels in well RD3 continue to rise when other wells nearby have already decreased (Figure 4-18 a). This well was in the valleys, not close to a RWH structure or the river, and was not pumped. The slow response of this well most likely represents lateral flow in the shallow alluvial aquifer, by transmission through the aquifer, rather than natural recharge in the area of the well itself.

Further monitored roadside wells are between Jhiri and Lalpura in the upper catchment (Figure 4-19). The wells on the roads still reflect increasing recharge in 2008, though the rate of increase is not as high as those wells close to RWH structures.

Figure 4-19: Monitored dug wells along roadside from Jhiri to Lalpura
a. Groundwater level ASL (m), b. Relative water level height (m)
4.3.2.2. Trends of Well Recharge in the Monitored Area

Figure 4-20 and Figure 4-21 show groundwater levels ASL (m) in the dug wells that have been interpolated across the surrounding area using the Inverse Distance Weighting method. This is mainly to show general trends and is not a rigorous spatial analysis. Figure 4-20 a and Figure 4-21 a are pre-monsoon levels (1\textsuperscript{st} June) in 2007 and 2008 respectively, Figure 4-20 b and Figure 4-21 b are towards the end of the monsoon (12\textsuperscript{th} September) for each monitored year. The interpolation was done within the area of the monitored wells, rather than extrapolating to the whole spatial area in the catchment (Figure 3-6). The pre-monsoon maps look very similar between years, which would be expected as local management practices results in water levels being pumped to a similar depth each year. The post-monsoon levels are higher in 2008 (Figure 4-22 b) than in 2007 (Figure 4-21 b), which reflects the greater amount of both rainfall and recharge from RWH structures in 2008 and less pumping. The maps also clearly indicate spatial variability in recharge and a general slope of the watertable towards the south east.
Figure 4-20: Inverse Distance Weighted Interpolation of monitored well heights
ASL (m) a. 1st June 2007, b. 12 September 2007

Figure 4-21: Inverse Distance Weighted Interpolation of monitored well heights
ASL (m) a. 1st June 2008, b. 12 September 2008
4.3.3. Recharge Estimates in the Groundwater Table ($R_{gw}$) – Water Table Fluctuation Method

A daily time step was used to calculate $R_{gw}$ using the water table fluctuation (WTF) method with a constant $S_y$ of 0.1 for all monitored wells. The most unaffected section of the time series was used to estimate $R_{gw}$. In 2007, due to heavy pumping, the unaffected time series for each well was very short, and for some wells not available. In 2008 however, the unaffected sections of the time series were longer as there was less pumping. The WTF method was applied mainly to the rise in dug well at the start of the monsoon season in both years. Also analysis of this section of the time series coincides with the steeper part of the groundwater rises, which means it is likely to result in more accurate estimates of recharge, because it would be less affected by lateral transmission than the latter part of the series. Not all negative change in depth is due to direct pumping. Some wells that are not pumped decrease in depth during the monsoon season, which could be due to pumping influence from wells nearby.

![Figure 4-22: Interpolation of average $R_{gw}$ (mm/day) from WTF method in a. 2007, b.2008](image)
Average $R_{gw}$ (mm/day) was estimated for each dug well monitored in each year. Due to the lack of information about the extent and properties of the local aquifer, it is difficult to extrapolate this to a volumetric increase in the aquifer. The average daily $R_{gw}$ rates (mm/day) for each year were spatially interpolated using the Inverse Distance Weighting method (Figure 4-22).

The average daily $R_{gw}$ rates (mm/day) were higher in 2008 than 2007 (Figure 4-22). Despite the uncertainty of interpolation, the general trends that can be seen show that moving down the catchment, and to lower elevations, estimated daily $R_{gw}$ increases. This might suggest flow of groundwater down the catchment is dictated by elevation. However the wells at Hamirpur and the wells south of the focus area of Hamirpur, have higher recharge rates than at Kaled and Nitata focus areas, which are further downstream (Table 4-8). This may be due to the position in the landscape. If groundwater is moving towards lower elevations, Hamirpur and the surrounds are at slightly lower elevations than Nitata and Kaled (Figure 4-23). Another interpretation is that the aquifer properties in these areas are different, and the WTF method in this study assumes a constant $S_y$ throughout the catchment. It might be possible to deduce the lateral movements from the temporal variation in well responses down the catchment. However due to spatial and temporal distribution of rainfall such an analysis is not straight forward.
Figure 4-23: Digital Elevation Model (DEM) for the area of the monitored dug wells

Table 4-8: Average $R_{gw}$ (mm/day) in the focus areas in the Arvari River catchment using the WTF method

<table>
<thead>
<tr>
<th>Focus Areas</th>
<th>Number of monitored wells</th>
<th>Average $R_{gw}$ (mm/day) 2007</th>
<th>Average $R_{gw}$ (mm/day) 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhaonta</td>
<td>6</td>
<td>4.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Lalpura</td>
<td>2</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Jhiri-Lalpura road</td>
<td>3</td>
<td>4.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Jhiri</td>
<td>1</td>
<td>NA</td>
<td>7.3</td>
</tr>
<tr>
<td>Hamirpur</td>
<td>4</td>
<td>12.4</td>
<td>23.9</td>
</tr>
<tr>
<td>Jhiri- Kaled road</td>
<td>5</td>
<td>9.6</td>
<td>13.1</td>
</tr>
<tr>
<td>Kaled</td>
<td>6</td>
<td>7.3</td>
<td>13.0</td>
</tr>
<tr>
<td>Nitata</td>
<td>2</td>
<td>10.0</td>
<td>11.5</td>
</tr>
</tbody>
</table>
4.4. Summary and General Discussion

4.4.1. Comparison of Recharge Estimates

The average daily potential recharge ($R_{ep}$ mm/day) from the monitored RWH structures was greater in 2008 than in 2007 and this increase was also seen in the water table response in the wells ($R_{gw}$ mm/day). However average daily $R_{ep}$ is much greater than average daily $R_{gw}$ for wells close to the structures (Figure 4-24). This difference could be either due to a large amount of lateral flow or due to water stored in the soil profile below the RWH storage area. This is further examined by estimating hydraulic properties of the soils in the RWH storage areas. Based on the field textures (Table 3-9) and using the soil texture triangle (Saxton, Rawls et al. 1986), field capacity ($FC$), available water ($AW$) and saturated hydraulic conductivity ($K_{sat}$) of the soil in RWH storages is obtained (Table 4-9). Using these characteristics, approximately 30% of $R_{ep}$ is held in the soil, and about 13 – 32% is $R_{gw}$ (Table 4-10). Approximately 30 – 50% of the difference could be lateral flow, as groundwater moving down the catchment. Sankara Bandh was furthest away from the wells in a hillier area, so a larger lateral flow component is more expected (Table 4-10). Larger local mounds, such as possibly under Sankara Bandh, would also increase hydraulic gradients and thus increase lateral movement of water. There is possibly less lateral flow from the Johads, Jhiri and Lalpura, due to higher storage in the soil and lower recharge values.
Figure 4-24: Comparison of $R_{ep}$ estimates from monitored RWH (mm/day) and $R_{gw}$ in monitored dug wells (mm/day) in 2007 and 2008

Table 4-9: Hydraulic properties for soil in monitored RWH structures using the soil texture triangle (cm$^3$ water/cm$^3$ soil) (Saxton, Rawls et al. 1986)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Soil texture</th>
<th>% Sand</th>
<th>% Clay</th>
<th>$FC$</th>
<th>$AW$</th>
<th>$K_{sat}$ (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sankara Bandh</td>
<td>Silt Loam</td>
<td>20</td>
<td>20</td>
<td>0.29</td>
<td>0.17</td>
<td>0.48</td>
</tr>
<tr>
<td>Beruji Bandh</td>
<td>Silt Loam</td>
<td>20</td>
<td>20</td>
<td>0.29</td>
<td>0.17</td>
<td>0.48</td>
</tr>
<tr>
<td>Jhiri Johad</td>
<td>Sandy Clay Loam</td>
<td>50</td>
<td>30</td>
<td>0.28</td>
<td>0.11</td>
<td>0.29</td>
</tr>
<tr>
<td>Lalpura Johad</td>
<td>Sandy Clay</td>
<td>50</td>
<td>40</td>
<td>0.32</td>
<td>0.10</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The high lateral flow potential also suggests that the rise in groundwater table in wells not close to RWH structures is more likely to be recharge from RWH structures than natural recharge. Natural recharge estimates from the regression developed by Rangarajan et al. (2000) for alluvial areas gives approximately 57 mm/year of natural recharge in 2007 and 104 mm/year of natural recharge in 2008 in the Arvari River.
catchment. These estimates are smaller than actual rise in groundwater, which range from approximately 200 – 300 mm in the monsoon season.

Table 4-10: Example analysis of movement of $R_{ep}$ through the soil profile on one day in 2008 (mm/day)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Average $R_{ep}$ (mm/day)</th>
<th>FC %</th>
<th>$R_{ep}$ as soil water (mm/day)</th>
<th>$R_{ep}$ – soil water (mm/day)</th>
<th>$R_{gw}$ (mm/day)</th>
<th>Average lateral flow (mm/day)</th>
<th>lateral flow %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sankara Bandh</td>
<td>55.6</td>
<td>29</td>
<td>16.1</td>
<td>39.5</td>
<td>7.2</td>
<td>32.3</td>
<td>58</td>
</tr>
<tr>
<td>Beruji Bandh</td>
<td>27.8</td>
<td>29</td>
<td>8.0</td>
<td>19.7</td>
<td>7.2</td>
<td>12.5</td>
<td>45</td>
</tr>
<tr>
<td>Jhiri Johad</td>
<td>19.5</td>
<td>28</td>
<td>5.5</td>
<td>14.0</td>
<td>7.3</td>
<td>6.7</td>
<td>35</td>
</tr>
<tr>
<td>Lalpura Johad</td>
<td>23.5</td>
<td>32</td>
<td>7.5</td>
<td>16.0</td>
<td>7.5</td>
<td>8.5</td>
<td>36</td>
</tr>
</tbody>
</table>

4.4.2. Potential Recharge from RWH in the Catchment

Based on data from the NGO, Tarun Bharat Sangh, the storage area of RWH structures is about 1.44% of the Arvari River catchment area, which is an underestimate but was used as the tested RWH density in this study. The RWH storage surface area was considered to be the same for 2007 and 2008 for the calculation presented in Table 4-11. This is erroneous because in 2008 there was more rainfall, which increased the storage surface area, but this study can not confirm by how much. The rainfall at Hamirpur was used to calculate the percentage of rainfall that becomes recharge from Anicuts/Bandhs and Johads/Talab in the catchment (Table 4-11). These structures were grouped because of similarities in size.
In 2007 around 6.6% of rainfall became $R_{ep}$, and in 2008 about 7% of rainfall became $R_{ep}$. These values are actually quite similar to the recharge efficiency estimates from the monitored RWH structures (Table 4-5). The fraction of rainfall that becomes recharge is also very similar between a dry and a wet year, which reflects the recharge efficiency of the structures.

Table 4-11: Approximate area of the catchment for different RWH structure types in the Arvari River catchment and approximate percentage of annual rainfall that becomes $R_{ep}$ in 2007 and 2008

<table>
<thead>
<tr>
<th>Structure</th>
<th>% Area of Catchment</th>
<th>% Annual Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2007</td>
</tr>
<tr>
<td>Anicut/Bandh</td>
<td>0.82</td>
<td>9.5</td>
</tr>
<tr>
<td>Johad/Talab</td>
<td>0.61</td>
<td>2.4</td>
</tr>
<tr>
<td>Total</td>
<td>1.44</td>
<td>6.6</td>
</tr>
</tbody>
</table>

4.4.3. Discussion and Conclusions

In a data sparse environment such as this area, first estimates of catchment characteristics such as recharge, flow in the river and climatic patterns are an important step towards understanding the existing hydrological processes in the catchment. This is particularly relevant for management actions that could impact catchment hydrology, including rainwater harvesting. The main outcome of this chapter is the field data from the Arvari River catchment collected in 2007 and 2008 indicating large variability in space and time.

There were significant limitations to the field data collection in the catchment. For the catchment community, measuring wells and stored water in RWH structures was a novelty, as the collected field data is the first of its kind for this area. The Arvari River catchment has very little infrastructure, with subsistence farming the main livelihood (Chapter 3). Consequently the facilities and infrastructure in the area are quite poor and this limited the field data collection. Roads were sometimes inaccessible and in disrepair. Climate and weather also constrained the ability to do field work with extreme
temperatures and intense rainfall at times. Additionally, measurements of the surface areas of stored water in RWH structures were often difficult due to inaccessibility. Nevertheless the main aim of the field work was to obtain, relatively rapidly, a large number of data points over an inhomogeneous catchment area. In the end, the overall number of observations is modest and techniques used basic and so there are measurement uncertainties. However this chapter indicates that despite these shortcomings, it was still possible to develop a relatively accurate picture of local-scale water balances and catchment-scale variability.

The focus areas were in the upper and middle reaches of the catchment. In this relatively small area, rainfall exhibited a highly variable temporal and spatial pattern, with localised events (Section 3.2.2). The 2007 season had below average annual rainfall while 2008 had above average annual rainfall. Within each year event size and distribution was very variable. This is typical of monsoonal rainfall in Rajasthan where rainfall is characterised by short intensity, localised and variable within a basin (Sharma and Murthy 1995).

The method used by Sharda et al. (2006) to estimate recharge from RWH structures was used here to analyse the data collected from the RWH structures, and results generally agree with their findings and of Badiger et al. (2002), that less than 10% of rainfall becomes potential recharge. However higher potential recharge was observed locally which would explain observations by Muralidharan and Andrade (2007). While the results are limited by the length of the time series available, this study compares a comparatively wet and dry year and this indicates variation in possible recharge. The impact of higher annual rainfall on recharge can be clearly seen in 2008, with higher rainfall resulting in more overall potential recharge. Despite this variation in rainfall the fraction of rainfall that becomes recharge was very similar between the years. Potential recharge from the structures reaches a limiting point with increasing rainfall, which is a factor of the maximum storage capacity in the structure. However, a difference in $R_{ep}$ was found between Bandhs and Johads, with an average $R_{ep}$ of 37.5 mm/day for Bandhs, and 17.8 mm/day for Johads. This may be related to the fact the observed Bandhs were located on more porous material and thus highlights the importance of careful positioning.
of the structures. Interestingly while $R_{ep}$ amounts were higher in 2008, recharge efficiencies were about the same for the two years. Efficiency is a function of infiltration and structure shape and size rather than rainfall amount. These factors also influenced the amount of rainfall that becomes recharge. For any attempt to model RWH in the catchment, it would be recommended to calibrate the model so that a similar percentage of rainfall becomes potential recharge as found in this chapter.

The analysis of the well data was difficult because of the amount of pumping, particularly in 2007. But by taking the most unaffected sections of the time series, and assuming a constant specific yield, estimates of $R_{gw}$ ranged from 7.2 mm/day to 11.3 mm/day. Recharge estimates increased moving down the catchment in elevation. The recharge values from the wells were much lower than the estimates of potential recharge from the RWH structures. This suggests that either the recharge from RWH is not reaching the aquifer, or the aquifer has large transmissivity and therefore strong lateral flow. The analysis in this chapter suggests that about 30% $R_{ep}$ is stored in the soil while at least another 30% moves laterally. As a result the water recharged becomes spreads out over a larger area depending on the size of the aquifer. Potential recharge from the structures would initially cause local mounding which dissipates across the aquifer. The latter is more likely considering the geology of the area and because RWH built by TBS only occupies 1.44% of the area. If lateral flow is significant, then the downstream impacts of reducing surface runoff upstream due to RWH could be counter-acted through the increase in groundwater levels downstream as a result of lateral flow reaching downstream areas. The length or distance of the benefits of the rise in groundwater level is not established from this study, but could be the focus of future work. Additionally more knowledge of aquifer characteristics would greatly improve understanding of the surface water – groundwater interactions.

The river flowed more frequently during the above average rainfall year of 2008, than in 2007. In both years, clustered rainfall events and larger storms were needed to generate streamflow. Based on the EC analysis no base flow was observed in the river, water below the Anicuts was assumed to be lateral flow from the storage of the Anicuts
upstream. While the analysis of recharge from the Anicuts was even more uncertain, the estimated $R_{cp}$ values were high compared with Bandhs and Johads. This confirms the local knowledge that the Anicuts provide a great amount of recharge. It also suggests substantial transmission losses from the river (Lange 2005).

RWH structures clearly have a large impact on the amount of recharge occurring in a local area, but the data collected was not sufficient to make any conclusive statements on any catchment-scale impacts. This analysis shows the dependence of RWH function on rainfall, which is highly erratic in this area, with larger $R_{cp}$ volumes in higher rainfall years. Also the size of the storage area of the structure influences the maximum daily depth of potential recharge. In all the monitored off-river structures there was no overflow, so perhaps these structures are too large. But a longer time series of rainfall and structure data would be needed to confirm this. The next step is to take the information learnt about the hydrological processes RWH influences from this chapter and apply it to a water balance model to examine the catchment scale impacts.
5. MODELLING RAINWATER HARVESTING IMPACTS IN A CATCHMENT – THE MODEL

5.1. Introduction

An individual RWH structure may not have a large effect on streamflow or aquifer storage, but the cumulative effect of many RWH structures within a large catchment would be more significant. For example, the construction of farm dams in some catchments of the Murray Darling Basin in Australia saw statistically significant reductions in the quantity of potential streamflow response (Schreider, Jakeman et al. 2002). The impact of RWH streamflow impact is important to understand due to increasing competition between water users as well as between water users and the environment. Additionally, the resulting shifts in the water balance could impact the resilience of agricultural livelihood, which means communities could be more vulnerable to shocks such as drought. Given the general lack of field data, a hydrological model is a
useful and inexpensive way of predicting and investigating management scenarios in a catchment and examining the resulting interactions between hydrological processes. A model also has the advantage of being able to investigate the effects of different management scenarios on hydrological processes at a larger scale than the field scale.

There are a many different applications for hydrological models, which largely depends on the purpose of the model and the data available, as a model is only as accurate as the data inputs (Silberstein 2006). Where large and detailed data inputs are available, the most common use of models is to calibrate and validate the model to a specific catchment, after which the impacts of different management scenarios and forecasting can be evaluated. Models can also be used as a way to test the researchers’ understanding of the processes occurring in a system, when there is no clear understanding of the process. This allows the researcher to examine the interactions between complex processes and this gives further insight into possible impacts of management decisions. From such models, future data inputs required to apply the model to a specific area can also be established. Moreover such a model could also be used to draw more general conclusions on process interaction and feedback. An example of the application of such a model is the work by Anderies (2005), which examined feedbacks in the Goulburn-Broken catchment that affect the resilience of the system.

An array of water balance models exist from simple single layer bucket methods to more complex models such as SWAT (Arnold and Fohrer 2005). Many researchers have developed their own models to simulate a specific water balance problem they are addressing, for example Portoghese et al. (2005) developed a GIS based water balance model to provide estimates of groundwater recharge in poorly gauged environments. However due to the lack of data in the Arvari River catchment, this severely limited the use of many complex models such as SWAT (Arnold and Fohrer 2005), which require long term data series inputs. The key limitation is the lack of streamflow gauging data, which means calibration and validation of a hydrological model is almost impossible. The lack of basic data is a common feature of semi-arid and arid regions in developing countries where populations are small and economic resources are limited.
communities in these areas tend to be remote and undeveloped, and expertise and investment in tools for hydrological measurement are not readily found (Sen 2008). Modelling in such areas is also difficult because climatic conditions tend to be temporally and spatially variable in these regions (Wheater and Al-Weshah 2002). Additionally the surface water – groundwater interactions, which are necessary to represent RWH hydrological processes, are limited in many models. For example the TEDI model, used to estimate small farm dam impacts in Australia, has no groundwater component. Those models that do have surface water – groundwater interactions require large amounts of data, which are not available in this case study. Due to these constraints, the aim of this chapter is to develop a conceptual hydrological model, for a catchment that is based on the Arvari River catchment data from Chapter 4, to investigate the impact of RWH at the catchment-scale.

Given the lack of calibration and validation data for any water balance model applied expressly to the Arvari River catchment, the model is designed primarily to investigate the interactions and the feedback relationships between RWH function and catchment hydrology. The model will not be an exact quantification of these impacts specific to a particular area, but a theoretical representation of potential impacts. Based on the developed model, future research and data collection can be directed more appropriately to apply the model to a specific catchment.

5.2. The Model

The model is written in R (R Development Core Team 2007) on a daily time step and is partly based on information and results from Chapter 3 and Chapter 4. For a full description of all the model parameters, which are described in detail in this chapter, see Table 5-10 in Section 5.4. The R code for one subbasin of the model is included in Appendix 2.
5.2.1. Subbasins

One way of simulating catchment hydrological processes is by considering the catchment as one lumped entity. The water balance is calculated for one unit, which is assumed to be representative of the whole catchment. With limited data and knowledge this is often the best approach. However, from the field results in Chapter 4, the catchment displays great variability in climatic and landscape conditions. As a result it was decided to divide the modelled catchment into smaller units to include some of the observed variability in catchment characteristics.

The water level responses from the dug wells in the field study in Chapter 4 reveal that RWH structures clearly affect local groundwater levels. As this model is developed to examine the impact of RWH on catchment processes, the best option would be to divide the modelled catchment into local aquifer systems, where similar hydrogeological properties exist. Unfortunately there is very little detailed information available about these properties in this area. The State Groundwater Board divided the hydrogeological properties of the Arvari River catchment into two classes: ‘hills’ for which yields are not defined, while all the other areas of the catchment are defined as ‘slate aquifers’ where the only property defined are yields of 50 – 150 m$^3$/day. Given the absence of such information, and based on the surface characteristics and the nature of the river, the catchment was divided into 3 subbasins (Figure 5-1). This assumes that the groundwater and surface water catchments align. The first division is based on separating the two rivers flowing into the dam at the end of the catchment. The longest river is divided into an upper and a lower subbasin – Subbasin 1 and Subbasin 2. Subbasin 1 is predominantly a hilly area, and represents the catchment up to the Hamirpur Anicut. Subbasin 2 corresponds to the lower elevations of the same river, characterised by less RWH and more agriculture. Subbasin 3 represents the shorter river with lower elevations and less RWH (Figure 3-11).
5.2.2. Aquifers

Based on the available hydrogeological information (Section 3.1.5), it is assumed there is an upper shallow alluvial aquifer, which is hydraulically connected to a deeper groundwater system (Gale, Neumann et al. 2002). In the model, the water that enters the deeper aquifer is considered lost from the system as most wells in the Arvari River catchment do not access this aquifer. The Arvari River catchment lies in the unconsolidated geological formations of India (Table 3-2). The field observations of the recharge response in shallow dug wells (Section 4.3.2.1) also suggest that the aquifer is close to the surface.

For each subbasin a shallow aquifer is therefore defined. For all three shallow aquifers, an initial and maximum water level describes the overall storage. Detailed aquifer properties are not known for this area, but data from Chapter 4 provide the local response...
of the monitored dug wells. Therefore the key determinant for defining the shallow aquifer limits in the model was to capture the fluctuations in the dug wells that were seen in the field results. As no baseflow was observed in the field over two years, the maximum storage in the aquifers was set sufficiently high to prevent baseflow in the model. The initial water level in the shallow aquifer was based on the average depth of the monitored dug wells on 1/1/2008, which was approximately half of the maximum storage capacity. The groundwater balance is calculated for the shallow aquifer in each subbasin, with addition from recharge from different land uses ($R$), extraction for irrigation when present ($Irr$), lateral flow between subbasins ($L$) and loss to the deeper aquifer ($Pc$) (Eq 5-1). Water lost to the deeper aquifer was calculated using a percolation coefficient, which determines the fraction of water from the alluvial aquifer lost to the deeper layer (Arnold, Allen et al. 1993). There are no field estimates, so the percolation coefficient was assumed to be quite small at 0.001.

$$\Delta GW = R - Irr - L - Pc$$  \hspace{1cm} \text{Eq 5-1}$$

$\Delta GW = \text{Change in shallow aquifer storage}$

Water in the shallow aquifer can move laterally between subbasins into other shallow aquifers. Lateral flow is described using Darcy’s Law (Anderies 2005) (Eq 5-4). Flow from the shallow aquifer of Subbasin 1 moves into the shallow aquifer of Subbasin 2. Some lateral flow from the shallow aquifer in Subbasin 2 and Subbasin 3 occurs to an assumed regional aquifer below the dam node. However the depth of groundwater below the modelled catchment is unknown ($D2$), therefore the percolation coefficient in Subbasin 2 and Subbasin 3 is increased to 0.002 to include both movement of water into a deeper aquifer and water moving laterally downstream. For the movement from Subbasin 1 to Subbasin 2, the following equation is used:

$$flow = \frac{K.A}{D3}(E1 + D2 - D1)$$  \hspace{1cm} \text{Eq 5-2}$$

$$\rho = \frac{K.A}{D3}$$  \hspace{1cm} \text{Eq 5-3}$$

$$flow = \rho(E1 + D2 - D1)$$  \hspace{1cm} \text{Eq 5-4}$$
\( K = \text{hydraulic conductivity}, \ A = \text{cross-sectional area}, \ D3 = \text{length of flow path connecting upper-lower}, \ E1 = \text{average elevation of Subbasin 1}, \ D1 = \text{depth to the water table in Subbasin 1, which fluctuates daily}, \ D2 = \text{depth to water table in Subbasin 2, which also fluctuates daily}, \ \rho = \text{parameter to describe flow unit}^2/\text{day/distance} \)

\( E1 \) was estimated from the DEM and \( D1 \) and \( D2 \) were estimated from the field data in Chapter 4. \( \rho \) was approximated, using values of transmissivity \( (T) \), where \( \rho = K.b/D \) where \( K.b \) is the transmissivity. Using \( K.b = T = \sim 250 \text{ m}^2/\text{day} \) (Section 3.1.5) and \( D3 = \sim 2500 \text{ m} \), gives \( \rho = 0.1 \).

In the model recharge from the surface in each subbasin enters the shallow aquifer one day after the actual recharge event. Cross correlation analysis between potential recharge from RWH and groundwater levels from the field data indicate there is some delay between potential recharge and actual recharge (Figure 5-2). The delay between potential recharge and actual recharge sometimes correlates over more than one day, but considering the variability within the field, and the strength of the cross correlation on the first day (Figure 5-2), a one day lag was considered acceptable.

![Figure 5-2: Cross Correlation function from potential recharge \( (R_{ep}) \) from Sankara Bandh to actual recharge \( (R_{gw}) \) at Well BK1](image)
5.2.3. Rainfall

As explored in Section 3.2.2, rainfall is both spatially and temporally variable, and is quite erratic. Rather than using the observed data from the catchment (only two years) or the long term annual data from the Alwar station (43 km from the catchment) (1901 – 2006), a stochastic model to simulate the rainfall was used to create daily realisations of rainfall for each subbasin for 12 years (Figure 5-3). Rainfall is predicted for each subbasin, thereby introducing variability in rainfall over the catchment. Rainfall is predicted using a Poisson model (Rodriguez-Iturbe, Gupta et al. 1984), where rainfall is defined as a Poisson process in time with rate \( \lambda \) (day\(^{-1}\)) (Laio, Porporato et al. 2001a; Fernandez-Illescas and Rodriguez-Iturbe 2004). The distribution of the times between rainfall events is exponential with mean \( 1/\lambda \) (day\(^{-1}\)), and the mean depth of rainfall events is defined by the parameter \( \alpha \) (mm), also based on an exponential distribution of rainfall depths.

RAINFALL MODELLING

1. Smooth function to describe annual rainfall distribution from Alwar annual rainfall
2. Add random component to annual rainfall distribution to replicate Alwar annual rainfall variability (Figure 5-6b)
3. Define \( \lambda \) for monsoon and dry season from Thanagazi daily rainfall (Table 5-1)
4. Predict \( \alpha \) for monsoon and dry season from 1. and the relationship between Thanagazi annual rainfall and monsoon season (Figure 5-3) divided by \( \lambda \)
5. Constrain \( \alpha \) to 6mm
6. Predict daily rainfall for each subbasin in the model

Figure 5-3: Stochastic rainfall modelling flow chart based on Fernandez-Illescas and Rodriguez-Iturbe (2004) and used in this model to predict daily rainfall for each subbasin

The field study collected catchment rainfall over two years, which is insufficient to develop stable statistical parameters for the rainfall model. Therefore the parameters
were calculated from the daily rainfall data at the Thanagazi station (1980 – 2006) and the annual rainfall at the Alwar station (1901 – 2002). The rainfall at Thanagazi indicates similar properties to that of the field results, but covers a longer time period (Table 5-1). As the monsoon season is the most significant period of rainfall, the data was analysed separately for the wet monsoon months (June – September), and the dry months (October – May) (Table 5-1). To account for the intra-annual variability, different $\alpha$ and $\lambda$ values were calculated for the monsoon season and the dry months.

Table 5-1: Statistical summary of Thanagazi rainfall (1980 – 2006) compared with the measured rainfall from the Arvari River catchment at Bhaonta and Hamirpur focus areas in 2007 and 2008 ($P$ = rainfall)

<table>
<thead>
<tr>
<th>Station</th>
<th>Annual Mean</th>
<th>Annual Standard Deviation</th>
<th>Annual log based mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
<td>Wet $P$</td>
<td>Dry $P$</td>
</tr>
<tr>
<td>Thanagazi</td>
<td>695</td>
<td>599</td>
<td>96</td>
</tr>
<tr>
<td>Bhaonta</td>
<td>598</td>
<td>554</td>
<td>54</td>
</tr>
<tr>
<td>Hamirpur</td>
<td>696</td>
<td>662</td>
<td>35</td>
</tr>
</tbody>
</table>

However rainfall is also variable between years. From the Thanagazi daily rainfall data, there is a strong relationship between the monsoon season rainfall and annual rainfall, which is not as strong during the dry season (Figure 5-4). Inter-annual rainfall variability is therefore influenced by the monsoon season. This observed relationship was incorporated into the rainfall model by varying the $\alpha$ values for the monsoon seasons between years to simulate the inter-annual variability.

The distribution of annual rainfall was determined from the distribution of annual rainfall from Alwar (Figure 5-5). A smooth function (based on a Fourier series approach) was used to simulate the annual variation.
Figure 5-4: Relationship between annual rainfall and monsoon season rainfall, and dry season rainfall (mm) at Thanagazi rainfall station (1980 – 2006)

Figure 5-5: Histogram of the Alwar annual rainfall distribution 1901 – 2002 indicating a log normal distribution
This function however, predicted an inter-annual rainfall variation that did not capture the distribution of the observed data at Alwar (red line in Figure 5-6 a). A random component with the standard deviation of the Alwar annual rainfall distribution was therefore added to match the observed variability (blue line in Figure 5-6 a).

The modelled and observed annual rainfall are similar (Figure 5-6 b), with an observed mean of 618 mm, and predicted mean of 609 mm, and observed variance of 29 983 mm$^2$ and predicted variance of 37 315 mm$^2$. Figure 5-6 c shows that the modelled annual rainfall distribution is similar to the observed distribution of Alwar annual rainfall (Figure 5-5), but possibly overestimating the number of low rainfall years. The red and blue points in Figure 5-6 c represent annual rainfall from the field data, which all lie within the modelled distribution.
Figure 5-6: a. One simulation of modelled annual rainfall using the Fourier Series function (red) and with a random component (blue) compared with Alwar annual rainfall (black), b. Quantile-quantile plot of one simulation of modelled annual rainfall against observed annual rainfall (mm) (with line $x = y$), c. Example of one simulation of modelled annual rainfall distribution. The coloured points represent collected rainfall during the field study from the three gauges in the catchment in 2007 and 2008 (Section 3.2.2)
The mean rain storm depth ($\alpha$) during the monsoon season and dry season was calculated by dividing the calculated annual rainfall by the number of rainfall events ($\lambda$) (Table 5-1). The parameter $\lambda$ was calculated from the Thanagazi rainfall data set, for both the monsoon season and the other months. Lastly, $\alpha$ was constrained to be greater than 6 mm as this increased the number of larger events to reflect the observed catchment rainfall (Figure 3-4).

5.2.4. Evapotranspiration

Evaporation for RWH structures is assumed to be equal to potential evapotranspiration ($PotET$). Potential evapotranspiration was predicted from the daily Alwar district data, using a similar Fourier series approach that was used to predict annual rainfall.

Due to the lack of climate information the prediction of actual evapotranspiration ($ET$) in the model is relatively simple. Evapotranspiration was based on a piece wise linear function, which has been widely used in ecohydrological water balance models (Laio, Porporato et al. 2001b; Fernandez-Illescas and Rodriguez-Iturbe 2004; Teuling and Troch 2005). In this calculation of $ET$, water loss is mainly governed by transpiration from plants. From maximum $ET$, $ET$ losses decrease linearly from $AW_{cr}$ (critical available water, where plants begin to close stomata and soil water availability becomes important) to $WP$ (wilting point) (Teuling and Troch 2005) (Eq 5-6).

$$\beta = \max[0; \min\left(1; \frac{AW - WP}{AW_{cr} - WP}\right)]$$

Eq 5-5

$$ET = f_r \cdot \beta \left(1 - \exp\left(-c_T \cdot LAI\right)\right) \cdot PotET$$

Eq 5-6

The parameter $c_T$ is the light use efficiency parameter, which was set to 0.4 (Slavich, Walker et al. 1999). $\beta$ is the soil moisture stress function (Eq 5-5). The parameter $f_r$ represents the root fraction in the layer (Teuling and Troch 2005), which was assumed to be a homogeneous root distribution in the model and set to 1. In section 5.2.5 the
derivation of $WP$ and $AW_{cr}$ is explained. Leaf Area Index ($LAI$) ($m^2$) is defined for each land use. Depending on the number of cropping seasons within the year, $LAI$ increases to a maximum of 5 m$^2$ and declines to 0.1 m$^2$ (Table 5-2). These values are based on a number of papers. In China, Li, Cui et al. (2003) found wheat had a maximum $LAI$ of 5 m$^2$. Rastogi et al. (2000) also observed a maximum wheat $LAI$ at 5 m$^2$ in India, and Tyagi et al (2003) found the peak $LAI$ for maize in a semi-arid area of India to be between 5 – 5.5 m$^2$.

Table 5-2: LAI for each Hydrological Response Unit in the Model

<table>
<thead>
<tr>
<th>Land use</th>
<th>Month</th>
<th>$LAI$ (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag1</td>
<td>July-Sept, Nov,</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Oct, Dec-Feb</td>
<td>5</td>
</tr>
<tr>
<td>Ag2</td>
<td>Oct, Dec-Jan</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Feb-June</td>
<td>0.1</td>
</tr>
<tr>
<td>Ag3</td>
<td>July-Sept, Nov,</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>March-June</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Oct, Dec-Feb</td>
<td>5</td>
</tr>
<tr>
<td>Commons</td>
<td>July-Jan</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Feb-June</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Equation 5-6 ignores soil evaporation (i.e. $ET = 0$ if $LAI = 0$). In semi-arid regions, evaporation from the soil surface is concentrated in a shallow top layer and the rapid decrease of $AW$ and hydraulic conductivity reduce evaporation strongly when $AW$ drops below field capacity (Wythers, Lauenroth et al. 1999; Lauenroth and Bradford 2006; Yepez, Scott et al. 2007). It seems clear that bare soil evaporation may be significantly reduced by such an evaporation barrier, but it is not suggested to be insignificant. Despite this, and because modelling soil evaporation would introduce further parameters, it was not directly modelled in this study. Instead, given that $LAI$ was never set to 0, some $ET$ was always occurring.
5.2.5. Soils

From the publication on soils of Rajasthan from the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), two main soils for the Arvari River catchment are defined, from which water holding capacity and $WP$ are determined (Table 3-5, Section 3.1.6). The soil descriptions are layered, but the model assumes only one soil layer, thus all horizons were incorporated. The Bansur series soil was used for the agricultural land uses in the model, while the Kanwat series is applied to the Commons land use. The Commons land use soil is much shallower and has a smaller water holding capacity than the agricultural soil, which has a field capacity of 261.19 mm. Water holding properties, such as Field Capacity ($FC$), are important properties as they determine the balance between evapotranspiration, irrigation, and recharge in each land use.

Based on the data in Table 3-5, $WP$ was defined as a fraction of $FC$, to reduce the number of parameters. As a result $WP$ was defined as 0.454 $FC$ for the agricultural land uses and 0.54 $FC$ for the Commons land use. The value of $AW_{cr}$, representing the point at which stomata close, was more difficult to define, and is essentially a free parameter. In the literature this parameter varies between 44 – 94% of $FC$ (Laio, Porporato et al. 2001a; Teuling and Troch 2005). In the model $AW_{cr}$ was defined as 0.7 $FC$ for the agricultural land use and 0.78 $FC$ for the Commons land use. Overall this means that the agricultural soil has a wider range of water availability and plants take longer to reach stress levels than the Commons soil. This would agree with the observed deeper soils under the agricultural and irrigated areas in the Arvari River catchment (Section 3.2.3).

5.2.6. Hydrological Response Units (HRUs)

Within each subbasin, Hydrological Response Units (HRU) are defined, which represent a land use with unique management factors and soil type (Arnold, Allen et al. 1993; Arnold and Fohrer 2005). Hydrological Response Units are the basic hydrological unit
for the model and have no spatial interpretation (Arnold and Fohrer 2005). The water balance is calculated for each HRU in each subbasin. The partitioning of rainfall into runoff uses the USDA-SCS Curve Number method (Section 5.2.7). All runoff is first routed into the RWH reservoirs, where a maximum depth for RWH is defined. Any water that overflows from the RWH reservoir is moved into the stream, which is then routed into the next subbasin, subject to transmission losses.

Land use information was obtained through field surveys with farmers and from government statistics for the Thanagazi block. In the Arvari River catchment, land use has changed over time. However current land use in the catchment closely reflects elevation and soil distribution (Section 3.2.3). In the hills, with higher elevations and shallow rocky soils, land is usually used for grazing with thinly covered forest areas or open land known as Commons. In the plains along the river, where the soils are deeper and richer in clay content, land use is predominantly agriculture including irrigated agriculture. Further from the river agriculture still persists, but there is less irrigation and the area for Rabi and particularly Zaid crops is reduced.

The main land uses considered in the model are Agriculture, which is divided into three by different management, Commons and RWH (Table 5-3).

Domestic and livestock water use was not considered to be significant. While mining for marble takes place within the Arvari River catchment, it was not included. This was because the model incorporates only those processes directly related to RWH, and to incorporate mining practices and related hydrology in the model was considered too complex.
Table 5-3: Description of hydrological response units (HRUs) in relation to catchment characteristics

<table>
<thead>
<tr>
<th>HRU</th>
<th>Land use</th>
<th>Landscape position</th>
<th>Elevation</th>
<th>Hydrological impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Ag1</td>
<td>2 – 3 km from river</td>
<td>On gently sloping plains</td>
<td>Relies on rainfall to increase soil moisture content.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rain-fed <em>Kharif</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ag2</td>
<td>Along river</td>
<td></td>
<td>Return flow from groundwater irrigation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Irrigated Kharif</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>and <em>Rabi</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ag3</td>
<td>On steeper rocky slopes</td>
<td>Higher elevations</td>
<td>High runoff, exposed, little vegetation (1 – 3 m trees), which are in leaf during monsoon.</td>
</tr>
<tr>
<td>Commons</td>
<td>Sparse forest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RWH</td>
<td><em>Bandhs</em></td>
<td>More concentrated in upper catchment, near/in river</td>
<td>Higher elevations</td>
<td>Stores runoff, with a high groundwater recharge component.</td>
</tr>
<tr>
<td></td>
<td>(includes <em>Anicuts</em>)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Johads</em></td>
<td>Bottom of hills</td>
<td>Mixed</td>
<td>Overflow moves downstream.</td>
</tr>
<tr>
<td></td>
<td>(includes <em>Talabs</em>)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the model, the fractional area of the total catchment for each HRU area is defined. This is based on Table 3-11 for the Thanagazi block, where the approximate area of the Commons HRU is 50%, Ag1 HRU is 35%, Ag2 HRU is 15%, and Ag3 HRU is 1.5%. The tested RWH density or fractional area is 1.44%, which is based on TBS information.
These values could be changed depending on the hydrological problem to be addressed. When irrigated agriculture or RWH area is increased, the increased area of land use is taken from the Commons HRU.

- AGRICULTURE HRU – Ag1 (Rain-fed *Kharif*), Ag2 (Irrigated *Kharif* and *Rabi*), Ag3 (Irrigated *Kharif*, *Rabi* and *Zaid*)

Field surveys and previous studies were used to understand the different farming practices in the area. Table 5-4 describes the general practices in the Arvari River catchment. Further description is in Section 3.2.4.2.

**Table 5-4: Crop seasons in the Arvari River Catchment**

<table>
<thead>
<tr>
<th>Crop season</th>
<th>Months</th>
<th>Main crops</th>
<th>Irrigation Water source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Kharif</em></td>
<td>July-Oct</td>
<td>Maize and Pearl millet. If rains are less, maize is substituted with pearl millet as this crop requires less water. Sowing after first monsoon rains (late June, early July). Almost 100% cultivable land used. For about 60% of the area, groundwater irrigation supplements rainfall.</td>
<td>Rain-fed and some areas supplemented with groundwater</td>
</tr>
<tr>
<td><em>Rabi</em></td>
<td>Nov-March</td>
<td>Wheat and mustard are the main crops, but also barley, chick peas and vegetables. Less area is cultivated than <em>Kharif</em>, due to groundwater source needed (~ 60% area) The rest is left fallow. If rainfall is good then the area of wheat planted is increased.</td>
<td>Groundwater</td>
</tr>
<tr>
<td><em>Zaid</em></td>
<td>April-May</td>
<td>Vegetables, cattle feed, some sorghum and barley. 10% cultivated area, dependent on groundwater level (less area planted due to high <em>PotET</em> and water levels are deeper so higher diesel costs for pumping)</td>
<td>Groundwater</td>
</tr>
</tbody>
</table>
All agricultural practices are simulated using the water balance approach (Figure 5-7). Rainfall, irrigation and ET influence the soil layer, which represents the layer where root activity takes place. The runoff process uses the Curve Number (CN) method and is discussed in detail in section 5.2.7. Recharge occurs when the soil layer reaches FC, and all excess input water then becomes recharge. Input into the root layer is Rainfall (P) – Runoff (RO).

\[ \text{Irr} = \text{Irrigation} \\
\text{P} = \text{Rain} \\
\text{ET} = \text{Evapotranspiration} \\
\text{R} = \text{Recharge} \\
\text{RO} = \text{Surface runoff} \\
\text{E} = \text{Extraction} \\
\text{Pc} = \text{Percolation} \\
\text{L} = \text{Lateral flow} \]

Figure 5-7: Water balance for Agriculture HRUs

Irrigation is only included for the Ag2 and Ag3 HRUs. In the model, irrigation water is taken from the shallow aquifer in each subbasin (Figure 5-7). Irrigation takes place when the soil profile is at \( AW_{cr} \) (Allen, Pereira et al. 1998), to a maximum daily depth of 150 mm and minimum irrigation depth of 100 mm. These depths were based on field observations of irrigation practices.

**COMMONS HRU**

The general simulation approach for the Commons land use is similar to the agricultural land use, but no irrigation is included, and a different curve number is used to describe runoff (Section 5.2.7). A different LAI distribution (Table 5-2) and soil type (Section 5.2.5) is also used.
• **RWH HRU – Bandhs and Johads**

In the model RWH captures all the runoff from the Commons and Agriculture land uses in each subbasin (Figure 5-8). Runoff entering RWH storage is multiplied by the fractional area of each contributing land use and then divided by the fractional area of RWH structures in the subbasin to represent the appropriate depth of water entering the storage areas. The total volume of RWH is considered as one large reservoir at the end of each subbasin (Loukas, Mylopoulos et al. 2007). The HRU for RWH was divided into two to capture the differences in recharge between the larger and smaller structures as observed in Chapter 4, where the Bandhs HRU represent Bandhs and Anicuts and the Johads HRU represent Johads and Talabs. This gives different parameter values for the two RWH HRUs, which was based on field observations for each structure type. As pointed out in section 5.2.4, ET equals PotET.

![Figure 5-8: Water balance for RWH HRUs](image)

A soil layer is not simulated in the RWH structures. Instead recharge is calculated using Darcy’s Law (Eq 5-7). Saturated hydraulic conductivity ($K_{sat}$) and depth from the surface to the aquifer ($l$) are parameters defined in the following equation:

$$q = -\frac{\Delta h}{l}K_{sat}$$

Eq 5-7

A pedotransfer function developed for India was used to calculate $K_{sat}$ (Adhikary, Chakraborty et al. 2008) where:

$$K_{sat} = 173.4^* (silt \% + clay \%)^{-1.48}$$

Eq 5-8
The resulting $K_{sat}$ from this pedotransfer function is 1534.28 mm/day, which was used for both Bandhs and Johads. Sampled soil textures in RWH storage areas (Table 3-9) were used to calculate silt % and clay %. While Johads had a deeper clay layer, which reduced $R_{ep}$ in the field, this was simulated in the model by changing the parameter of depth to the shallow aquifer, rather than $K_{sat}$.

Depth to the shallow aquifer was assumed to be 18000 mm for Johads, and 4000 mm for Bandhs, based on the average depth of water levels from the surface in wells in the field close to monitored structures. Bandhs, which also incorporate the Anicuts on the river, are therefore much closer to the groundwater table than the Johads. The maximum depth of each structure is also defined differently; storage in Bandhs is 2000 mm deep, Johads 1000 mm. This is approximately half the actual average maximum depth in the field. The half maximum depth was taken because of the difference in structure shape in the model. In the field, structure shape is almost triangular in cross-section, whereas in the model the structure shape is represented as a rectangle. Any water above the maximum depth becomes overflow and is moved into the river. The maximum depth also influences the non-linearity of potential recharge that was described in Section 4.2.2.2, where, as rainfall increases, the structure reaches a limiting capacity to induce more potential recharge. In order to interpret this effect in the model, an additional parameter ‘a’ was introduced. When calculating recharge from RWH, beyond a defined threshold of recharge, recharge is raised to the power of the parameter ‘a’, which introduces some non-linearity:

$$ (\text{threshold} - \text{threshold}^a) + (K_{sat} \cdot ((RWH.\text{storage} + \text{depth to aquifer})/(\text{depth to aquifer})^a)) $$  \hspace{1cm} \text{Eq 5-9}

All potential recharge from RWH goes directly into the shallow aquifer in each subbasin. In Chapter 4, it was noted the large difference in recharge estimates from $R_{ep}$ to $R_{gw}$, but in the model, the recharge from the fractional area of RWH spreads across the whole aquifer, so the rise in each modelled shallow aquifer reflects the field results (See Section 5.3.2 for further discussion of calibration and validation).
5.2.7. Interception and Runoff

An adapted USDA-SCS Curve Number (CN) method for India was used to estimate runoff from each land use. The CN method predicts runoff from rainfall, using a curve number, which represents potential maximum soil retention and reflects land use, antecedent moisture condition and soils (Ponce and Hawkins 1996). At the start of this research, the CN method used the adapted equations for Indian conditions (Eq 5-10) (Tiwari, Kumar et al. 1991; Zade, Ray et al. 2005). In the suggested modified equation initial abstraction ($I_a$) was set to 0.3 (Tiwari, Kumar et al. 1991).

$$Q = \frac{(P - 0.3S)^2}{P + 0.7S}$$

Eq 5-10

$Q =$ direct flow volume expressed as depth, $P =$ total rainfall, $S =$ potential maximum soil retention, $CN =$ curve number value used to estimate $S$

The translation between $S$ and $CN$ is:

$$S = \frac{25,400}{CN} - 254$$

Eq 5-11

When the model output from this study was examined, the suggested value of $I_a = 0.3$ did not produce enough runoff to reach the RWH HRU, and so recharge from RWH was well below field results. Such a high initial abstraction would be understandable in a model on an annual time step, but not at the daily time steps run in this model. On larger temporal scales, initial losses increase due to transmission and evaporation losses (Simanton, Hawkins et al. 1996). Therefore $I_a$ was changed to 0.05 (Woodward, Hawkins et al. 2003). Antecedent moisture conditions 2 and hydrologic soil group B (medium textured soils) were used to find the $CN$ for each land use. The $CN$ for each Agriculture HRU and Commons HRU was defined from the SCS tables (USDA-SCS 1985). Sharma (1987) found that $CN$ for bare crust-forming sandy soils in the Indian Arid Zone were 87 and 91 for 0.5% and 5 – 10% slopes respectively, which is greater than the USDA-SCS $CN$ of 77. Hydrologically a majority of the sandy soils in arid/semi-
arid areas have low runoff potential, but due to raindrop impact these soils form a surface crust which reduces infiltration and increases runoff. Additionally rainfall intensity is very high which also creates Hortonian overland flow. However, despite this observation, and given the absence of any firm data that the soils in the Arvari River catchment are indeed crust-forming sandy soils, the curve numbers were based on the SCS tables (Table 5-5). The chosen $CN$ values are similar to a study for south-eastern Rajasthan, where weighted $CN$ values ranged from 80 – 83 (Gupta, Deelstra et al. 1997). But it was recognised that this is a calibration parameter in the model and therefore might increase or decrease for real catchments. The agriculture HRUs have two curve numbers, one during the time when land is fallow, and the other lower $CN$ when cropped, when runoff would be lower (Table 5-5).

**Table 5-5: Land use Curve Numbers in model**

<table>
<thead>
<tr>
<th>HRU by land use</th>
<th>Curve Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commons</td>
<td>79</td>
</tr>
<tr>
<td>Agriculture Cropped</td>
<td>72</td>
</tr>
<tr>
<td>Fallow</td>
<td>77</td>
</tr>
</tbody>
</table>

Figure 5-9 shows schematically one subbasin and the inputs and outputs for each HRU, indicating the common shallow aquifer for the subbasin. Also note that all runoff is first routed into the RWH before overflowing into the stream. This approach was chosen as there was insufficient information to identify what fraction of overall runoff bypassed RWH. Once the water reaches the stream it is routed to the next subbasin and becomes subject to transmission losses.
Figure 5-9: Schematic representation of one subbasin in the model with different HRUs in the soil layer

5.2.8. Routing and Transmission Losses

There are many modelling methods to route streamflow. However with little information on channel characteristics and flow, linear routing was chosen:

\[ S = kQ \]  

Eq 5-12

\( k \) is an empirical parameter, describing the storage (S m\(^3\)) in the river reach of discharge (Q m\(^3\)/s).

In the model the routing coefficient, \( k \), was set to 5. This value indicates little spreading of the flood hydrograph, which would be typical for a semi-arid ephemeral river, such as the Arvari River. In Australia, Costelloe et al. (2005) set \( k \) to 4.5 in semi-arid channels in South-western Queensland, while in the Godavari River in India, Kshirsagar et al (1995) used \( k \) values of 2 and 8.4 with Muskinghum routing (Muskinghum routing gives more substantial storage than linear routing for the same \( k \) value).

Transmission losses are an important hydrological component of a semi-arid river system (Pilgrim, Chapman et al. 1988). However due to the limited data on streamflow, the model incorporates regressions developed by Sharma and Murthy (1994b) to calculate
transmission losses. The regression equation relates transmission loss to channel characteristics and flow volume in an arid region of north-west India (Sharma and Murthy 1994b). The study concluded that the regression could be transferred to ungauged basins. Consequently to calculate transmission losses the model uses:

\[ V_1 = 1.983 \, V_{up}^{0.73} \]  

\( V_1 \) = transmission loss for first km (m\(^3\)), \( V_{up} \) = inflow volume at the upstream site (m\(^3\))

This equation was used to calculate transmission losses per km river length. Transmission losses are then added to the shallow groundwater. Because the model works in depth only, to calculate transmission loss in each subbasin using the regression in Eq 5-13, the river length and catchment area was taken from the respective subbasin the model represents in the Arvari River catchment.

5.3. Applying the model to the real world

5.3.1. Sensitivity Analysis

Parameter sensitivity analysis is used to evaluate the magnitude of changes in parameters on the output, or to identify those parameters that exert the most influence on model results (McCuen 1973; Hamby 1994). As such, a sensitivity analysis helps to identify those parameters in the model which have the most impact or are most correlated with model output, for example streamflow volumes. From the 23 input parameters in the model, those that were considered to have the highest impact on the output of the model were chosen for a parameter sensitivity analysis. As a result the 8 parameters considered most uncertain were \( CN, I_0, LAI, PAWC, \) percolation coefficient, irrigation trigger, \( AW_{cr} \), and \( WP \). While rainfall is not a parameter, in order to understand how the spatial and temporal variability of rainfall might affect the output, this variable was included in the sensitivity analysis as well.
There are many sensitivity analysis methods, but in this case the method proposed by Lenhart et al. (2002) was used. Each of the chosen parameters was changed in magnitude from the initial value, which varied depending on a reasonable range of values, but generally the change was plus and minus 25% from the initial value. The model runs consisted of changing one parameter, for all subbasins, in the same direction. The output examined was the sum of Johad recharge and Bandh recharge ($R_{RWH}$), shallow aquifer water levels ($GW$), runoff ($RO$), ET and streamflow ($Sf$) (Table 5-7). For each output a Relative Sensitivity Index ($RSI$) was calculated (Eq 5-14) (Lenhart, Eckhardt et al. 2002; Ouessar, Bruggeman et al. 2008). While $RSI$ examines the impact of one parameter only and does not consider the sensitivity of changes in a number of parameters, it is a first step towards understanding sensitive input parameters in this model. Lenhart et al. (2002) classified each $RSI$ according to Table 5-6.

$$RSI = \frac{(y_1 - y_0)/y_0}{(x_1 - x_0)/x_0}$$  
\text{Eq 5-14}

$x_0$ = initial value of the parameter, $x_1$ = tested value of the parameter, $y_0$ = corresponding output with parameter $x_0$, $y_1$ = corresponding output with parameter $x_1$.

<table>
<thead>
<tr>
<th>Class</th>
<th>Index value</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0 &lt;= $</td>
<td>RSI</td>
</tr>
<tr>
<td>II</td>
<td>0.05 &lt;= $</td>
<td>RSI</td>
</tr>
<tr>
<td>III</td>
<td>0.20 &lt;= $</td>
<td>RSI</td>
</tr>
<tr>
<td>IV</td>
<td>$</td>
<td>RSI</td>
</tr>
</tbody>
</table>

The model is highly sensitive to changes in the rainfall input (Table 5-7), which is a stochastic input in the model. This is not surprising as rainfall is the key hydrological input into any water balance model, and impacts in some way each component of the model output. However this means that variations in rainfall across subbasins would impact the output and distribution for each model run of 12 years.
The parameters with the highest sensitivity are $CN$ and $I_a$, which for all model output had medium to very high sensitivity (Table 5-7). This is understandable as $CN$ and $I_a$ determine the partitioning of rainfall into runoff and thus are key parameters in the hydrological balance. The most sensitive model output is groundwater levels, which was sensitive to some degree for each parameter change. The sensitivity of groundwater levels is quite important in this model, as this is the key state variable that RWH is supposed to influence. Such high sensitivity would be a problem for making location specific statements given the high parameter uncertainty. However, for the purpose of investigating RWH impacts and feedbacks, this is a good outcome. Another sensitive output was $ET$, which is influenced by the soil parameters and $LAI$. Evapotranspiration and groundwater levels are also sensitive to the irrigation trigger, which influences how much water is transpired, and amount of water extracted from the groundwater. This sensitivity analysis demonstrates that accurate land use, aquifer properties and soil information would be key to understanding location specific impacts of RWH.

Table 5-7: Sensitivity of Output from the Model with Rainfall and Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$RSI - x_I$ (higher input value)</th>
<th>$RSI - x_I$ (lower input value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{RWH}$</td>
<td>GW</td>
</tr>
<tr>
<td>Rainfall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$CN$ Agriculture</td>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>$CN$ Commons</td>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>$I_a$ III</td>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>$I_a$ Commons</td>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>$LAI$ Commons</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>$FC$ Commons</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>$FC$ Agriculture</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Percolation Coefficient</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>Irrigation trigger</td>
<td>I</td>
<td>III</td>
</tr>
<tr>
<td>$AW_{cr}$</td>
<td>I</td>
<td>III</td>
</tr>
<tr>
<td>$WP$</td>
<td>I</td>
<td>I</td>
</tr>
</tbody>
</table>
This model displays similar sensitivities to that of the SWAT model (Lenhart, Eckhardt et al. 2002). In that study the most sensitive parameters were LAI and CN, and physical soil properties such as bulk density, available water capacity and hydraulic conductivity.

5.3.2. Qualitative Calibration and Verification

Calibration and validation of the model is qualitatively performed using the two years of data collected from the field and the resulting observations and conclusions from Chapter 4. Thorough calibration and validation would require many more data which is lacking in this area, and in particular groundwater and streamflow observations would need to be collected for future research. The qualitative calibration and validation was motivated in an attempt to realistically represent the processes related to RWH in the Arvari River catchment, rather than quantify them. As such, qualitative calibration brings the model in the realm of possible real catchments rather than purely theoretical.

The irrigation area was set up to mimic the field observations where the farmers were found to always maximise the use of the available groundwater. This means local farmers increase the area of irrigated agriculture based on the groundwater availability as they judge from the depths of their dug wells. Therefore a function which relates the fraction of irrigated land to post-monsoon groundwater levels was developed. The actual groundwater use is a complex function, which relates to how the farmers adjust the irrigation to water availability, and it was not attempted to model this exactly. If the shallow aquifer level is higher than 125 mm, then the defined fractional area of Ag2 and Ag3 increases 1.2 times from the originally assigned values. This function also captures shifts in crops from the more water-demanding maize, to the less water-demanding millet in Kharif, and from wheat to mustard in Rabi.

The main aim in the calibration was scaling recharge from all HRUs, which was calibrated based on field data and literature. During the calibration runs, all subbasins had the same rainfall distribution input and also the fractions of HRU area were kept constant (which includes the adjustment of the irrigated fraction as described above).
The tested RWH area was set at 1.44% of the catchment area, which was the current level of RWH in the catchment in 2005. For RWH recharge, the parameters that were calibrated were the distance to the groundwater (Eq 5-7) and the depth of the structures at which overflow takes place. From the field analysis, Bandhs had higher recharge than Johads (Chapter 4). Transmission losses on the river above Anicuts are taken into consideration in the Bandh HRU, so Bandhs were calibrated to have greater recharge (Table 5-8). In the field, the relationship between cumulative rainfall and cumulative potential recharge was non-linear. However this is not fully demonstrated in the model output, which over-estimates recharge for high rainfall (Table 5-8). This is also reflected in the percentage of rainfall that becomes recharge, which in the model ranges from 6% in low rainfall years to almost 15% in high rainfall years, but is relatively constant in the field at 7% rainfall – recharge. This demonstrates the difficulties with replicating the RWH structure shape and function in the model without the addition of many extra parameters that would increase the uncertainty of the model further. Additionally, because the field estimates are based on only two years of data, the impact of rainfall intensity and duration would also have an impact on recharge from RWH structures, which would require a longer time series of field data to understand in detail. However, when comparing the cumulative sum of rainfall against cumulative sum of recharge, the model displays some similarity in response as results from the field (Figure 5-10).

Table 5-8: Sum of field estimates of average potential recharge from RWH and model output of the same for similar annual rainfall years

<table>
<thead>
<tr>
<th>Method</th>
<th>Field estimates recharge (mm/yr)</th>
<th>Model Output recharge (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>449 mm rainfall</td>
<td>897 mm rainfall</td>
</tr>
<tr>
<td>Bandh</td>
<td>2770</td>
<td>4380</td>
</tr>
<tr>
<td>Johad</td>
<td>1950</td>
<td>2430</td>
</tr>
</tbody>
</table>
Background natural recharge estimates for the Commons HRU were calibrated based on existing literature. In Karnataka, India, weathered granites have a recharge capacity of 6 – 200 mm per year for an average rainfall value of 968 mm (Chand, Chandra et al. 2004). A developed regression equation based on tritium studies for alluvium provinces in India, where $R (\text{mm/yr}) = 0.147 \times (P \text{ mm/yr}) - 6$, was used to calibrate natural recharge (Rangarajan and Athavale 2000). Using rainfall at Hamirpur, this gives an approximate natural recharge value of 60 mm in 2007, and 126 mm in 2007. This regression was used to calibrate the Commons HRU in the model. In the original model, recharge from Commons HRU was much higher than literature estimates (Rangarajan and Athavale 2000), so the soil water holding capacity was doubled to reflect recharge estimates by increasing the $FC$. Changing the $CN$ did not reduce recharge substantially. The final Commons recharge output show reasonable comparisons to the recharge from the regression (Table 5-9). The Ag2 and Ag3 HRUs are irrigated so recharge from these units would be higher than the Commons HRU as there would be return flow from irrigation events. Marechal et al. (2006) estimated return flow from irrigated agriculture in a semi-arid groundwater basin in Andhra Pradesh, India, between 69 – 86 mm/year. The study area from this work has much lower $PotET$ than the Arvari River catchment, so higher irrigation amounts and therefore more recharge is modelled for Ag2 and Ag3 HRUs (Table 5-9). The high irrigation recharge might also be indicated by the slowly increasing salinity in the groundwater over the monsoon season (Figure 4-11).
Table 5-9: Natural annual recharge from the developed regression (Rangarajan and Athavale 2000) and the model output for different land uses

<table>
<thead>
<tr>
<th>Rainfall (mm/yr)</th>
<th>Recharge (mm/yr) from regression</th>
<th>Recharge (mm/yr) from HRUs in the model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Commons</td>
<td>Ag1</td>
</tr>
<tr>
<td>426</td>
<td>57</td>
<td>32</td>
</tr>
<tr>
<td>748</td>
<td>104</td>
<td>128</td>
</tr>
</tbody>
</table>

The response of groundwater levels in the shallow aquifer were adjusted to reflect the fluctuations seen in the monitored dug wells by changing the size of the shallow aquifer. The fluctuation in the field dug wells was multiplied by the estimated specific yield of 0.1, which gave a rise of approximately between 60 – 300 mm/year depending on rainfall and the distance from RWH structures. Figure 5-11 a shows rise at Kaled well 6 during the monsoon season of 2008. Figure 5-11 b shows the similar but slightly slower and lower response of the model output. The difference in well response in the field and the model output could be because the observed field dug wells reflect local groundwater mounding, which is not captured in the model, or specific yield is overestimated.

Figure 5-11: Groundwater levels in a. field well KLD6 2008 in village Kaled (mm ASL), b. from the model output in a similar rainfall year in subbasin 1
The model output of streamflow has an average of twenty flow days a year, depending on rainfall. Figure 5-12 b shows that the model output is similar to field estimates of observed flow over the Anciut at Hamirpur in temporal response. However the depth of modelled and observed flow is different. Subbasin 1 of the model reflects the catchment above the Anciut at Hamirpur. Using the approximate catchment area of 108 km$^2$, in 2007 and 2008 the average depth of streamflow at Hamirpur is 0.0005 mm. This depth is obviously much smaller than the predicted streamflow in the model (Figure 5-12 b). However this could be due to greater transmission losses in the field, which in the model are not captured, because transmission losses are calculated in the model using an established regression.

![Figure 5-12: a. Daily discharge over Anciuts on the Arvari River in 2007 and 2008 (m$^3$), b. Daily streamflow from model output (mm)](image)

### 5.4. Summary and General Discussion

When using any model, it is important to consider the purpose for which the model will be used. The model described here is a conceptual representation of RWH function in the semi-arid catchment of the Arvari River. An existing highly parameterised and very complex model would not have been suitable because of the large gaps of knowledge and
data related to the Arvari River catchment. This includes incomplete knowledge of aquifer properties, a lack of basic hydrological data, including long term weather observations in the catchment, soil properties and a gauging station on the river. In contrast, simpler existing models do not incorporate the hydrological processes related to RWH. As a result, a conceptual water balance model was purpose built. The model captures the relevant hydrological processes in the catchment that are influenced by RWH, which have not been captured appropriately in other models. This includes surface water – groundwater interactions and large recharge volumes from the specific land use – RWH.

Despite the aim to keep the model simple, the field results (Chapter 4) indicated that some complexity and variability was necessary to capture the processes effectively in the model. As such, the model has 23 parameters (Table 5-10). Compared to a simple model such as IHACRES (Evans and Jakeman 1998), with only six parameters, it is more complex. However low parameter models do not include the processes that are related to RWH. Simpler models, while effective for modelling streamflow output do not allow investigation of catchment internal hydrological processes. Those models that do include a reservoir model and surface water – groundwater interactions, such as SWAT (Arnold and Fohrer 2005), are far too complex (over 41 parameters) and data intensive. However the semi-distributed, deterministic model built here is similar in structure to models like SWAT. A study by Ye et al (1997) compared three rainfall-runoff models including GSFB (8 parameters), IHACRES (6 parameters), and a complex conceptual model, LASCAM (22 parameters). They found that while the simple conceptual model is adequate for monthly time periods, on a daily time step a slightly more complex model is better for prediction of streamflow in an ephemeral catchment. As the model built here was on a daily time step, in order to capture the recharge process from RWH, it is comparable to LASCAM in complexity.
Table 5-10: Model Parameters and values

<table>
<thead>
<tr>
<th>Model Component</th>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>Percolation Coefficient</td>
<td>0.001 – 0.002</td>
</tr>
<tr>
<td></td>
<td>Initial Value</td>
<td>100 mm</td>
</tr>
<tr>
<td></td>
<td>Maximum Value</td>
<td>200 mm</td>
</tr>
<tr>
<td></td>
<td>Parameter to describe flow unit²/day/distance (ρ)</td>
<td>Eq 5-3</td>
</tr>
<tr>
<td></td>
<td>Elevation of Subbasin 1 (EI)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>Groundwater level in subbasin 2</td>
</tr>
<tr>
<td></td>
<td>D1</td>
<td>Groundwater level in subbasin 1</td>
</tr>
<tr>
<td>Rainfall (P)</td>
<td>Rainfall Depth α</td>
<td>Varies with each year</td>
</tr>
<tr>
<td></td>
<td>Rainfall Length λ</td>
<td>0.5 in monsoon, 0.06 in dry months</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>Critical available water $AW_{cr}$</td>
<td>0.7 FC Agric, 0.78 FC for Commons</td>
</tr>
<tr>
<td>(ET)</td>
<td>Wilting point (WP)</td>
<td>0.454 FC Agric, 0.54 FC Commons</td>
</tr>
<tr>
<td></td>
<td>Leaf area index (LAI)</td>
<td>Table 5-2</td>
</tr>
<tr>
<td></td>
<td>Light use efficiency (-c_T)</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Soil moisture stress function (β)</td>
<td>(Eq 5-5)</td>
</tr>
<tr>
<td></td>
<td>Root fraction ($f_r$)</td>
<td>1</td>
</tr>
<tr>
<td>RWH HRU</td>
<td>Hydraulic conductivity $K_{sat}$</td>
<td>1534.28 mm/day</td>
</tr>
<tr>
<td></td>
<td>Depth to groundwater table (L)</td>
<td>18000 mm Johads, 4000 mm Bandhs</td>
</tr>
<tr>
<td></td>
<td>Maximum storage depth</td>
<td>1000 mm Johads, 2000 mm Bandhs</td>
</tr>
<tr>
<td></td>
<td>Threshold for recharge non-linearity</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>a (shape parameter)</td>
<td>0.3</td>
</tr>
<tr>
<td>HRUs (Ag1, Ag2, Ag3, Commons)</td>
<td>Curve Number (CN)</td>
<td>Table 5-6</td>
</tr>
<tr>
<td></td>
<td>Field capacity (FC)</td>
<td>Agric 261 mm, Commons 100 mm,</td>
</tr>
<tr>
<td></td>
<td>Irrigation Trigger (Ag2, Ag3)</td>
<td>When soil profile is $AW_{cr}$</td>
</tr>
</tbody>
</table>

The model described in this Chapter is similar to many other conceptual models purpose built to address a specific hydrological issue (Table 5-11). For example a similar semi-
distributed, semi-conceptual model, using linear reservoirs and with surface water – groundwater interactions, was built to examine flooding in the Okavango Delta, Botswana, though on a monthly time step (Wolski, Savenije et al. 2006). Another study uses a conceptual model due to a data poor environment in Ghana, to estimate runoff in small reservoirs, using the Thornthwaite-Mather procedure, which represents the runoff process occurring in this area. This model was calibrated by using remotely sensed reservoir storage changes, a method which could also be applied in the future to the model developed here (Liebe, van de Giesen et al. 2009). The TEDI model (Lowe, Nathan et al. 2005) and the HYLUC-Cascade model (Bishop, Calder et al. 2009) represent similar hydrological processes to estimate the impact of farm dams on catchment flows, but do not incorporate any surface water – groundwater interactions.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Number of Parameters</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 5 Model</td>
<td>23</td>
<td>Not calibrated or validated to field measurements</td>
</tr>
<tr>
<td>IHACRES</td>
<td>6</td>
<td>Limited surface water – groundwater interaction</td>
</tr>
<tr>
<td>SWAT</td>
<td>41</td>
<td>Highly complex, requires large data inputs</td>
</tr>
<tr>
<td>TEDI</td>
<td>5</td>
<td>No surface water – groundwater interactions</td>
</tr>
</tbody>
</table>

Admittedly the model in this study is only a conceptual representation of the actual environment of the case study. As a result, there is uncertainty in the representation of the landscape described in this chapter and the model output could not be applied to the field. This includes uncertainty in operations (data missing, human error), input (estimates) and hydrologic uncertainty (model and calibration). However, because the model focuses on conceptual relationships and there is limited data, uncertainty estimation is not possible. Future work would be to compare the output from this model, with other more established models and greater data input to calibrate and validate, and also whether those models are equifinal.
The sensitivity analysis identified the key data input that would have to be collected to apply this model to a real catchment. To calibrate and validate the model output data needed would be detailed streamflow data, and groundwater levels. Input data required would be long-term series of spatial rainfall and runoff measurements to calculate appropriate curve numbers. Key information for modelling of the internal processes would be: land use patterns and ET distributions, soil properties and aquifer characteristics. A longer time series of recharge estimates from RWH and natural recharge estimates would also be valuable.

R, an open source statistics and mathematics program, was useful to develop the conceptual model presented above, with a run time of 6 minutes if run for 10 years on a daily time step through the whole catchment (1.7 GHz Pentium IV machine with 1 GB RAM). While the model will produce results that are based on physical processes, they are not an exact representation of reality, but give a general indication of trends of changing land use and watershed development. The next step is to apply this model to different scenarios to examine the impacts of RWH at the catchment-scale.
6. MODELLING RWH IMPACTS IN A CATCHMENT – SIMULATION ANALYSIS

6.1. Introduction

Sustainable water resource systems are those systems that are designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity (Loucks and Gladwell 1999). However trying to apply and quantify sustainability is difficult, because systems and the ‘needs’ are always changing (Sarang, Vahedi et al. 2008). Nevertheless a number of studies have tried to quantify the sustainability of water resource systems by quantifying measures of reliability, resilience and vulnerability. The indices are based on whether a specified demand threshold is met by the water resource system (Hashimoto, Loucks et al. 1982; Loucks 1997; Zongxue, Jinno et al. 1998; McMahon, Adeloye et al. 2006;
Ajami, Hornberger et al. 2008). These indices are used in conjunction with the conceptual model discussed in Chapter 5 to examine the impacts of RWH in a catchment.

Two different aspects of the impact of RWH will be considered in this chapter. The first examines the impact of RWH on irrigated agriculture using the sustainability indices. In India irrigated agriculture is largely dependent on groundwater use. The impacts of RWH on groundwater supply and thus irrigated agriculture are therefore an important consideration. The amount of water needed to meet crop water requirements, which includes water from groundwater and rainfall, is defined as the calculation of the sustainability indices. This approach is purely anthropocentric because the threshold considers only crop water demand, and ignores environmental and ecological ‘demands’. A larger analysis examining these factors could be part of future work. The second analysis investigates the changes in the catchment hydrology through examination of changes in streamflow for different land use scenarios.

6.2. Methods

6.2.1. Sustainability Indices

Hashimoto et al. (1982) describe three criteria for evaluating the performance of water resource systems:

1. How likely the system is to fail or the frequency of failure (Reliability, \( R_E \)).
2. How quickly it recovers from failure (Resilience, \( R_S \)), and
3. How severe the consequences or extent of failure may be (Vulnerability, \( V \)).

These measures are related to Holling’s seminal paper (1973), who first described the concept of resilience as the ability of an ecological system to persist with the same basic structure when subjected to stress. In order to quantify these indices, the operational status of the water resource system needs to be described as either satisfactory (\( S \)) or unsatisfactory (\( F \)), using defined thresholds. Unsatisfactory status could be the result of
floods, droughts, or higher demands. As Loucks (1997) points out, these thresholds are subjective judgments. However by using these indices, improvements or trends in different management scenarios can be gauged in a water resource system. These indices are also easy to use (Kay 2000). For this reason they are used in this analysis to examine the impacts of RWH for different areas of irrigation and RWH using the conceptual model developed in Chapter 5.

1. **Reliability (RE)**
Reliability is the frequency or probability $\alpha$ that a system is in a satisfactory state (Fowler, Kilsby et al. 2003):

$$\alpha = \text{prob}[X_t \in S] \quad \text{where} \quad RE = \frac{\sum_{t=1}^{T} Z_t}{T} \quad \text{Eq 6-1}$$

Where $X_t$ is the system’s output state or status at time $t$, $Z_t$ is a binary measure where $X_t$ is either an element of $S$ values (output or performance of the water resource system is in a satisfactory state) or $F$ values (output or performance of the water resource system is in a failure state). The $RE$ index ranges from 0 to 1, where 1 reflects 100% reliability in meeting demands.

2. **Resiliency (RS)**
Resiliency is the probability $\gamma$ that when a system is in a failure state, the next time step is a satisfactory state (Fowler, Kilsby et al. 2003; Ajami, Hornberger et al. 2008):

$$\gamma = \text{prob}\{X_{t+1} \in S \mid X_t \in F\} \quad \text{where} \quad RS = \frac{\sum_{t=1}^{T} W_t}{T - \sum_{t=1}^{T} Z_t} \quad \text{Eq 6-2}$$

$W = 1$ if $X_t$ is element of $F$ and then $X_{t+1}$ is an element of $S$ otherwise $W = 0$. The resilience index ranges from 0 to 1, where 1 is a system with 100% resilience.


3. Vulnerability \((V)\)

Vulnerability is the maximum of the sum of the difference between the threshold (criteria \(-C\)) and the actual level \(X_t\) for any failure periods \(J_i\) (Fowler, Kilsby et al. 2003; Ajami, Hornberger et al. 2008).

\[
V = \max \left\{ \sum_{t \in J_i} C - X_t, i = 1, \ldots, N \right\}
\]

Eq 6-3

It thus reflects the severity of the failure. The vulnerability index can have a wide range depending on the difference between \(X_t\) and \(C\), but higher values indicate higher vulnerability, lower values represent a less vulnerable system.

Many studies have used these three indices to evaluate the sustainability of water resource systems. Fowler et al. (2003) modelled the impacts of climate change on the resilience of the Yorkshire water resource system. Kay (2000) applied the performance indices to the crop production index of Israel to examine Israel’s water resource system from 1949-1997. Jain and Bhunya (2008) used the indices with Monte Carlo simulations to test the performance of a reservoir in India. Peters et al. (2005) investigated how droughts are changed by groundwater systems and analysed the performance of groundwater during drought. And finally Ajami et al. (2008) used the indices to examine how hydrological uncertainties impact the management system.

6.2.2. Defining thresholds

From the literature there is sufficient evidence to show that there is a direct link between irrigation and poverty alleviation. Agricultural growth leads to overall economic growth, and irrigation is a prime catalyst for agricultural growth. Groundwater development increases irrigation area (Mukherji and Shah 2005) and is seen as a more effective way to target poverty than surface irrigation, due to its reliability and spatial availability (Wegerich 2006). There is also literature to support that where RWH is introduced, irrigated agriculture increases. In Orissa, India, a study by Srivastava et al. (2008)
confirmed that farmers increased *Rabi* and *Zaid* crops in the 2\(^{nd}\) and 3\(^{rd}\) year after RWH was established. The study found that a rain-fed farmer will shift to irrigated agriculture once the reliability of the groundwater system is established. Therefore the thresholds for the calculation of the sustainability indices in this study relate to water demand for irrigated agriculture.

In the Arvari River catchment, irrigation is supplied mainly through groundwater. However the water requirement for the first crop season (*Kharif*) is primarily met by rainfall. If rainfall requirements are not sufficient, then they are supplemented with groundwater where possible. The winter crop season (*Rabi*) is completely reliant on groundwater for irrigation. The summer season (*Zaid*) is generally 10% or less of the irrigated agriculture area and is also completely reliant on groundwater for irrigation. Because of the small area of *Zaid*, the thresholds are only defined for water required to irrigate the *Kharif* and *Rabi* crops.

In the study area the main crop grown during *Kharif* is maize. For maximum production a medium maturity grain crop requires between 500 to 800 mm of water depending on the climate. The water required to irrigate maize using the FAO crop factors, is 511.8 mm for 125 growing days (Allen, Pereira et al. 1998). The main *Rabi* crop is wheat. For high yields, water requirements are 450 to 650 mm depending on the climate and length of the growing period. For the model a threshold of 470.5 mm of water for 120 growing days of wheat was used (Allen, Pereira et al. 1998).

To meet crop water demands, the farmers rely on a combination of groundwater and rainfall in *Kharif* and groundwater in *Rabi*. The water resource system in this study was therefore based on the availability of water in the sowing months of the *Kharif* (July) and *Rabi* (November) crops. The available water in the system is defined daily as the groundwater storage combined with any rainfall in the months of July (*Kharif*) or November (*Rabi*). More months were not considered, because the initial water available at the start of each season strongly determines water availability for the rest of the season and the amount of irrigated area planted as observed in the field (Chapter 4), so any
impact of RWH would best be seen in these months. The water available in these months was then compared with the defined threshold to calculate daily values of the sustainability indices.

### 6.2.3. Simulations

Due to the stochastic generation of rainfall in the model, 30 realisations of the rainfall were applied to each land use scenario for the whole catchment (Figure 6-1). The model was run on a daily step for 12 years. The first two years of the model were discarded before the analysis as a ‘warm-up period’. A number of different land use scenarios were considered based on the area of irrigation, the area of RWH and whether irrigation or RWH is present. The percentage area of RWH land use varied at 0.5%, 1%, 1.5% and 3% and the irrigated land use percentage area was varied at 5%, 10%, 15% and 20%. Scenarios were run with and without irrigation and RWH. Results are presented as box-plots, which present the distribution across the rainfall realisations, with medians, and averaged across the subbasins.

![Figure 6-1: Histogram of annual rainfall distribution (mm) for 30 realisations of 12 year model simulations in Subbasin 2](image)
6.2.4. Droughts

In the Arvari River catchment, groundwater supply is not only affected by the irrigation demand, (represented as the area under irrigation) and recharge from RWH, but also by the amount of rainfall. While irrigation area and RWH area are determined by societal management actions, rainfall in the area is an exogenous variable. Drought is a temporary, recurring meteorological event, which begins because of a lack of precipitation and results in a lack of water availability for natural resources and human activities, particularly agriculture (Smakhtin and Schipper 2008).

Drought affects each component of the water balance differently, but the analysis here considers the impact of drought on the modelled groundwater output to meet irrigation demand. To understand the influence of annual rainfall and drought conditions on irrigated agriculture and RWH, simulations of drought were run, where a drought year was defined as below average annual rainfall. The model was run incorporating different lengths of years of below average rainfall. The indices were compared between each of the drought scenarios. For example the model was run for 12 years; 3 yrs of above average rainfall, then a below average rainfall period, which ranged from 2 to 6 years, then another 3 yrs of above average rainfall and so on until the end of the 12 year time period was reached. The first two years of the model were again discarded for the analysis.

6.2.5. Streamflow changes

With increasing RWH land use in a catchment, flow downstream may change as more runoff is stored in RWH structures. This will be examined in the model by examining differences in streamflow between different scenarios of RWH and irrigation area. In particular differences in the rainfall-runoff relationship will be analysed, including any reduction in streamflow depth and amount.
6.3. Results

6.3.1. The System without RWH

Figure 6-2 shows the results of the sustainability indices for scenarios without RWH, with 4 different irrigation areas. All indices show that as the area of irrigation increases, sustainability decreases in the system. A greater area of irrigation represents a greater crop water demand and therefore more groundwater extraction would occur, so that the threshold is not met as frequently as at a smaller irrigation area.

Reliability clearly shows the impact of the increase in irrigation area, which drops from a reliability of 0.8 at 5% irrigation, to half that at 10% irrigated area (Figure 6-2 a). This difference is not as large from the 15% to 20% irrigated area, because the reliability is already very low at 15%. Resilience again is highest for the smallest irrigated area, but as irrigation area increases, the decrease in the $RS$ index increases is not as much as the $RE$ index, because $RS$ is already low at a small area of irrigation (Figure 6-2 b). This indicates that the overall capacity of the system to withstand shocks is minimal. Vulnerability increases with increasing irrigation, and is highest at 20% irrigation, reconfirming what the other indices show (Figure 6-2 c).

The $Rabi$ season has higher reliability, resilience, and lower vulnerability than the $Kharif$ season, which is a reflection of the threshold defined for each season, which is higher for $Kharif$ than $Rabi$ (Section 6.2.2).
6.3.2. The System with RWH

When RWH is introduced in the model the indices indicate a more viable water resource system for irrigated agriculture, compared to the previous analysis without RWH. This is indicated by overall higher reliability and resilience, and lower vulnerability.
There is not much difference in reliability as irrigation increases in the *Kharif* and *Rabi* seasons (Figure 6-3). In both crop seasons, at 5% and 10% irrigation, the impact of RWH means that these scenarios are almost completely reliable. Even though reliability decreases at 15% and 20%, it is still greater than scenarios without RWH (Figure 6-2). As RWH area increases (x-axis in Figure 6-3), reliability increases, but at 15% and 20% irrigation area, as RWH increases from 1.5% to 3%, reliability does not increase further and slightly decreases, particularly at the 20% irrigation area in the *Rabi* season (Figure 6-3).

![Figure 6-3: Distribution of the reliability index with median for different areas of irrigation and RWH for *Kharif* and *Rabi* season](image)

The 5% irrigation scenario does not have a calculated resilience index, because there were no failure states from which to return to a satisfactory state (Figure 6-4). 15% and 20% irrigation areas have low resilience values (Figure 6-4). However these values are
higher than in the scenarios without RWH, so a system with RWH is more resilient than without RWH.

At 10% irrigation, in both crop seasons, the resilience index behaves quite differently to the other scenarios (Figure 6-4). This is the result of the irrigation area function in the model that mimics farmer behaviour in the field, which relates the fraction of irrigated land to the groundwater level. If water is plentiful (defined in the model as the shallow aquifer level higher than 125 mm) then the defined fractional area of irrigated agriculture increases 1.2 times. This function is thus a distinct ‘step’ function, which creates an abrupt change in the irrigation area. A smooth function would be more suitable, but due to lack of information on the exact shape of such a function, this was not attempted. In the 5% irrigation area scenario the groundwater level is always above 125 mm, and in the 15% and 20% irrigation area scenarios, the groundwater level is always below 125 mm. However at the 10% irrigation area scenario, the function impacts the resilience index. At 10% irrigation, in the Rabi season, at 0.5% RWH area, the groundwater levels are greater than 125 mm, so the fraction of irrigation area does not increase and resilience is high. However as RWH area increases, the groundwater levels increase due to increased recharge, and the irrigation area function begins to operate, increasing the irrigation area, which in turn decreases groundwater levels and thus the resilience index. At 3% RWH the irrigation area function can only increase the irrigation area to a maximum 1.2 times or 12%, so extraction can not increase further, and because of additional RWH the resilience increases. This is similarly reflected in the Kharif season at 10% irrigation area, except that the function is also operating at 0.5% RWH because of the rainfall input in this crop season, which increases storage into RWH and thus recharge.
Figure 6-4: Distribution of the resilience index with median for different areas of irrigation and RWH for Kharif and Rabi season

Vulnerability, or the extent of failure, is predictably highest when irrigation area is largest (20%). A larger area of irrigation means a larger volume of water is pumped from the groundwater. Therefore the difference between the demand required and the available water is greater, giving a higher vulnerability. At low irrigation area (5%), vulnerability is negligible, but increases with each increasing step of irrigation area. At 20% irrigation, as RWH area increases, the vulnerability distribution is similar for all RWH values. However at 15% irrigation, in both crop seasons, as RWH increases from 0.5% RWH to 1% area, vulnerability increases. And from 1.5% to 3% RWH area, the vulnerability does not improve much (Figure 6-5). This is also seen at 10% irrigation in the Kharif season, which shows a similar response for the same area for the Rabi season in the reliability analysis that is the result of the irrigation area function operating.
Figure 6-5: Distribution of the vulnerability index with median for different areas of irrigation and RWH for Kharif and Rabi season

Compared to the first analysis with irrigation and no RWH (Figure 6-2), the addition of RWH in the system increases reliability, resilience and decreases the vulnerability of the water resource system for irrigated agriculture. Within an individual irrigation scenario, as RWH area increases from 1.5% to 3%, the benefit to the system is not large and in some cases the sustainability indices actually decrease. This suggests that there is a limiting point in the area of RWH that gives a maximum benefit for recharge, beyond which the benefit is marginal. In addition the fact that farmers respond to water levels and increase their irrigation area means that some levels of RWH area have less sustainability.
6.3.3. The Influence of Rainfall

To understand the influence of variations in annual rainfall on irrigated agriculture and RWH, the indices were compared between below average and above average annual rainfall years. The long-term average from the Thanagazi station data of 705.8 mm was taken as the average for this analysis. The analysis shown here is for the Rabi season only, as the Kharif season displays a similar response. Also the Rabi season has less daily rainfall, so the impact of recharge from RWH would be the primary influence on whether the threshold demand is met or not.

In all indices, the above average rainfall years show higher sustainability than below average rainfall years. Systems with and without RWH have higher reliability with above average rainfall (Figure 6-6). However when rainfall is below average, the reliability of the system with RWH performs better than a system without RWH. This is seen most clearly at 5% and 10% irrigation scenarios; in this case, despite below average rainfall, the system has almost 100% reliability. The reliability of a system without RWH has median reliability of 80% for 5% irrigation area and 20% for 10% irrigation area (Figure 6-6 a and b). When rainfall is above average, RWH in a system gives 100% reliability up to the 15% irrigation scenario (Figure 6-6 b). In the below average rainfall scenarios when RWH is present the change from 1.5% RWH to 3% RWH sees a slight decrease in reliability (Figure 6-6 b).
Resilience is also better with above average rainfall (Figure 6-7). Again a system with RWH has better resilience than a system without RWH (Figure 6-7 b). With RWH in the system and above average rainfall, resilience can not be measured for 5%, 10% irrigation scenarios. As RWH increases from 1.5% to 3% no large improvements in the index value is seen. At 10% irrigation in the below average rainfall with RWH (Figure 6-7 b) the results are similar to Figure 6-4, which is the result of the irrigation area function operating. Groundwater levels are low at 0.5% RWH so the irrigation area does not increase, and resilience is high. From here, as RWH area increases, resilience decreases because groundwater levels rise and the irrigation area function is operating. In Figure 6-7 a, despite the absence of RWH, because of above average rainfall, groundwater levels increase, so that at 10% and 15% irrigation, the irrigation area function works, while at 20% groundwater levels are not high enough to trigger the irrigation area function, and so resilience is higher.
Figure 6-7: Resilience in *Rabi* with below average rainfall and above average rainfall a. without RWH at various levels of irrigation, b. with various scenarios of RWH and irrigated agriculture

In Figure 6-8 the vulnerability index shows that a system with RWH is better than a system without RWH in above and below average rainfall years. In Figure 6-8 b as RWH increases, vulnerability is similar for all levels of RWH.

In this analysis when rainfall is below average, the sustainability indices are not as positive as when rainfall is above average, due to lower recharge from RWH. However in below average rainfall, the indices are greater with RWH in the system than without RWH. This means RWH alleviates some of the deficit in below average rainfall years because it supplies some groundwater, though it would be less than in an above average rainfall year. This was observed in Chapter 4 in the difference in potential recharge volume between the two different rainfall years.
6.3.4. Drought Conditions and RWH Impact

RWH provides within season buffering, but may not provide longer term supply if drought occurs, because the pumping for irrigation reduces the buffer between seasons and recharge from RWH would decrease.

The overall sustainability indices for 10 year time period, with increasing series of concurrent below average rainfall years, does not show strong differences as the drought period increases. This suggests that RWH is able to provide some buffer in low rainfall periods (Figure 6-10). Overall the resilience index is low, but it shows some change, with decreasing resilience as the drought period increases, and also the reliability decreases as drought period increases, but these changes are not as large as when RWH is not present in the system in the analysis in section 6.3.1.
Figure 6-9: Sustainability indices in simulations with a. 2 year drought period, b. 4 year drought period, c. 6 year drought period

6.3.5. Streamflow Impacts of RWH

Figure 6-10 displays plots of annual streamflow as a percentage of rainfall against annual rainfall for different areas of RWH and irrigation. When irrigation is introduced, the gradient of the rainfall – streamflow relationship decreases, but streamflow still occurs at low annual rainfall. As irrigation area increases, the large streamflow events decrease. This is because the model converts the Commons HRU, with a higher CN, to irrigated...
HRUs, which has lower runoff. Therefore more water is ‘captured’ through irrigated land use, and ‘blue’ water is converted into ‘green’ water.

When RWH is introduced the gradient increases, but streamflow does not start until an annual rainfall of about 500 mm, compared with Figure 6-10 a and b, when streamflow starts around an annual rainfall of 400 mm. In the model, RWH captures runoff that would otherwise reach the stream and so the amount and frequency of water entering the stream decreases. Smaller rainfall events are captured, but larger events overflow from the RWH structures and move into the river. If the RWH area is increased (Fig 6-10 d), the percentage amount of streamflow events decrease further, but the greatest change in streamflow occurs from 0% RWH area to 0.5% RWH area (Table 6-1).

Table 6-1 also shows the large impact RWH has on streamflow, by decreasing the mean and maximum, and increasing the intercept. The mean runoff coefficient, defined as the % rainfall converted to streamflow, decreases dramatically when a small level of RWH is developed in the system.

### Table 6-1 Analysis of streamflow with different scenarios of RWH and irrigation

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Linear Model</th>
<th>Streamflow as % Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RWH % Area</td>
<td>Irrigation % Area</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>15</td>
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<td>0.5</td>
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<td>3</td>
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<td>3</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 6-10: Annual streamflow as % of annual rainfall (mm) a. No RWH or irrigated agriculture, b. 15% Irrigated Agriculture, No RWH, c. 15% Irrigation, 0.5% RWH, d. 15% Irrigation, 3% RWH, e. 5% Irrigation, 3% RWH, f. 10% Irrigation, 3% RWH
6.4. Discussion

At present irrigated agriculture in India is far more reliant on groundwater than the earlier rain-fed systems. As a result of this dependence the groundwater resource has become over-exploited in some areas, so that the groundwater buffer, which provides resilience against shocks such as drought, no longer exists (Moench 2007). Agricultural drought occurs widely in India, with about 68% of net sown area highly vulnerable. Most of this area is located in arid and semi-arid areas, where frequent and prolonged drought results in lowered groundwater levels (Mudrakartha 2007). This chapter indicates that increased recharge through RWH is an important element for providing some resilience against shocks such as drought in a groundwater irrigated agriculture system.

Under RWH scenarios irrigated agriculture is more viable than in a system without RWH. However the analysis also showed that continuously increasing RWH area does not bring additional benefits that may be expected. Instead as RWH area increases, the system reaches a limiting point, from where the benefit from RWH does not increase the sustainability indices, and in some cases decreases. This is because runoff from a catchment area is finite and more RWH means that water is just spread across more storage area. As a result, the resulting depths in the RWH structures are smaller and the recharge per structure decreases. Recharge can not increase beyond a certain limit for each structure storage area and can not be greater than $K_{sat}$. Additionally the aquifer storage capacity is limited. This relationship was seen for an individual structure by Sharda et al. (2006) and in this study (Section 4.2.2.2). It is very interesting to note that this same limiting capacity is also seen when RWH is examined at the catchment-scale. Additionally if the area of irrigation is large (in this analysis up to 20% of the catchment area), RWH many not be able to reduce the stress on the water resource system, because demand is too large.

The result from this analysis that increasing RWH beyond a certain point, does not increase the benefit to irrigation, could have serious impacts for NGOs, other agencies
and communities that invest in RWH, because the benefit to agriculture may not be worth the cost of additional RWH works at high levels of RWH development in a catchment. A greater understanding of this limiting capacity could aid in RWH development programs. This reinforces theoretical speculations about catchment-scale impacts of RWH by Kumar et al. (2006), which considered a higher degree of RWH development to reduce marginal benefits, while increasing marginal costs. That paper understood that reduction in benefit to be because of low aquifer storage capacity, lower chances of getting appropriate sites for RWH development, and the environmental costs of RWH. The model used in this study has a small aquifer storage capacity, but has also found that the nature of runoff and storage in RWH structures is an important consideration in the reduction in benefits of recharge from RWH. The model is conceptual, so before further recommendations, these results must be compared with other models that have been calibrated and validated to a specific catchment, which would require additional data.

The analysis from the model in this chapter confirms that RWH increases the viability of groundwater irrigated agriculture if short-term mild drought conditions occur. However from this analysis, longer term drought does not seem to strongly decrease the function of RWH. Kumar et al. (2006) say that RWH has extremely limited potential to provide reliable water supply, because of high rainfall variability and high PotET but the analysis from this chapter shows that while the sustainability indices decrease when drought occurs, the system is functioning better than without RWH.

Another important aspect of RWH impacts is the hydrological changes in a catchment, which were examined by comparing streamflow changes under different scenarios. The model clearly shows that when RWH is introduced, streamflow strongly decreases. Capturing local runoff upstream in RWH storages addresses problems of frequent drought and widespread poverty in upper catchments. However the ‘blue’ water investments, like irrigation canals, are generally located downstream (for example Sainthal Sagar Dam in the Arvari River catchment) and depend on large volumes of runoff (Sakthivadivel 2008). As RWH leads to an increase in water used for irrigated agriculture upstream, this will affect water availability for other downstream users,
including not only irrigators but also ecosystems, because flows, which are already highly variable in a semi-arid region, decrease. However RWH could also have positive environmental impacts as result of reduced land degradation, for example in the Arvari River catchment, more area has been re-forested since RWH development as the community recognises the importance of erosion control. There could also be improvements in water quality as runoff is slowed through the catchment, so larger sediments would filter out and the erosive power of the flows is reduced. This would require further field analysis to investigate.

The scenarios of irrigation area and RWH area highlight the link and strong feedbacks between irrigation area and RWH. The model does not capture fully the changing dynamics area of irrigation. Realistically, if groundwater levels were low, farmers might also reduce the area of irrigation, alleviating further pressure on the groundwater resource. While the model results show that RWH has a positive impact for the sustainability of irrigated agriculture, if the supply of groundwater increases due to RWH, then local demands may also increase unsustainably. This depends on how groundwater is managed, which is considered in Chapter 7.
7. MANAGEMENT OF GROUNDWATER DEMAND IN THE ARVARI RIVER CATCHMENT

7.1. Introduction

The introduction of RWH clearly has an impact on local groundwater tables (Chapter 4), and is therefore an important tool to increase local groundwater supply. However groundwater institutions, which regulate and monitor the use of groundwater, also are an important influence on the dynamics that govern the sustainability of this resource. In India, the institutional arrangements related to groundwater do not prevent unrestricted use, which is partly due to the nature of the resource itself. Aquifers are often large and invisible, which means it is difficult to exclude other users. Despite the large size, the supply is limited; consumption by one user reduces its availability to others (Ostrom, Gardner et al. 1994). These management difficulties are exacerbated by the millions of
wells that exist in India and the structure of groundwater property rights. In India groundwater property rights are attached to land, allowing land owners to extract groundwater as economically possible (Saleth 2005).

Groundwater use has exponentially increased in the last 50 years in India, but well-constructed institutions to manage this resource have not yet been developed (Kemper 2007) and the current top-down approach to manage groundwater has not been successful, with water levels declining in many states (Rodell, Velicogna et al. 2009). Giving resource property rights to communities, so that it is managed as a commonly-owned or common property resource (CPR), has been encouraged as an alternative to effectively manage resources like groundwater, particularly in developing countries (Berkes 1989; Bromley 1992; Ostrom, Walker et al. 1992; Bruns 2007; Moench 2007). But there are very few documented examples of successful commonly owned groundwater institutions, and relatively little is known about those institutions that do exist and how they govern groundwater use (Mukherji and Shah 2005). This chapter therefore examines one such CPR institution in the Arvari River catchment, the Arvari River Parliament (ARP), initiated in 1998 with the help of Tarun Bharat Sangh (TBS), the local NGO (Non-Government Organisation).

Secondary sources and a small number of structured interviews will be used to examine the ARP. The researcher interviewed a number of farmers within the Arvari River catchment during the data collection period. Inclusion criteria were based on whether they were actively participating in the ARP, via their respective Gram Sabha (village councils), whether they are living in the catchment and use groundwater. Participants were approached directly and asked if they would like to participate. Six interviews were held with members of the ARP and their respective Gram Sabhas and five interviews with groundwater users who are not members of the ARP, but owned wells that were close to RWH structures. Ethics approval was obtained for these interviews.
7.2. Inception and Rules of the Arvari River Parliament (ARP)

Since 1987, TBS has been building RWH structures with the local community. TBS works in villages after being approached by a village community for support. For each structure that is built, the village community covers a proportion of the construction costs; either monetarily or through voluntary labour. Where structures are built, TBS encourages the formation of a Gram Sabha (village council), to discuss where the structures ought to be built and how the structures would be maintained. The general results of RWH for communities in this area have been very positive. Moench, Dixit et al (2003) found that 85% of RWH structures have benefited small and marginal farmers by increasing groundwater supplies. This has allowed farmers to increase the area under irrigation and decrease their dependency on the rain-fed Kharif crops. Until 1996 there were no catchment-scale management plans in place.

In 1996, a conflict between State Government officials from the State Fisheries Department and the village of Hamirpur led to the formation of the Arvari River Parliament. In 1995, a large Anicut was built on the river reach at Hamirpur, which held a substantial amount of water. In November 1996 the State Fisheries Department gave licenses to fish in the Anicut to a Jaipur contractor. The village people opposed the contractor. The community felt that because they had built the RWH structure that held the water, the government did not have the authority to decide how that water could be used.

“When there was no water, where was the government? We requested and appealed many times to the government. But they did not listen to us; they did not do anything to provide us with water. Now, we have water because of the efforts of TBS and ourselves. All of us worked hard without any government support. Our efforts were not supported by the government even though it was the responsibility of the government. Therefore the government has no right to give fishing-contracts for our water” (from interview with Gram Sabha member, 2008).
With the support of TBS, the villagers held a *Satyagraha* (non-violent protest) against the State Fisheries Department for two months. The result was that the fishing contracts were cancelled in March 1997.

Due to this incident the community and TBS realised that others outside the community could use the water provided through RWH, which were considered the common property of each village. Consequently in December 1998, TBS called representatives of all *Gram Sabhas* of the Arvari River catchment to a meeting, where the ARP was initiated. On January 26 1999 the ARP was officially affirmed. The ARP has 110 representatives from the 72 villages of the Arvari River catchment (Kumar and Kandpal 2003).

The rules of the ARP were first set up in 1998, and focus mainly on water conservation and utilisation and forest conservation. All members agree to enforce the following informal rules:

- Water intensive crops like sugarcane, rice and cotton are not to be planted
- No one shall draw water from the river or RWH structures. But those people who gave their land for RWH structures or whose land is under water because of RWH, can take water from RWH structures and the river
- No commercial fishing is allowed in water stored in RWH structures
- Tube wells, which tap deeper aquifer, are not allowed
- Construction and maintenance of RWH is encouraged
- Land is not to be sold for mining/quarrying or any other industrial activity
- Protection and planting of forests in encouraged

These informal rules are discussed at each biannual meeting to highlight practical problems in their implementation and suggest new guidelines if needed (Moench, Dixit et al. 2003). Suggestions, if any, are debated and discussed. Members also seek guidance for resolving conflicts, if any, and report any violations of the rules listed above (Singh 2005). The informal rules are then conveyed downwards to individual villages through the elected *Gram Sabha* representatives. These are then discussed and implemented at
the village level either through social or moral pressure, depending on the activeness of each village Gram Sabha.

7.3. Review of the ARP

Despite the presence of the informal rules of the ARP, unrestricted use of groundwater still occurs within the Arvari River catchment. This is due to a number of factors including information problems about the resource size and capacity. Monitoring use of a resource that is easily accessed, yet invisible, also has high transaction costs because it would be difficult to monitor without understanding the capacity of the resource and the number of users. As highlighted earlier in Chapter 3, scientific information about hydrogeological properties or boundaries in this area is not readily available. Depending on the size of the aquifer, farmers using groundwater may not have any appropriation or provision problems until irrigation is fully established, and only then may they be motivated to work together (Schlager 2007). While all interviewees considered the amount of groundwater available a problem, they all considered that to be dependent on the amount of rainfall, rather than the area of irrigation or amount of groundwater extraction. Those interviewees who were members of the ARP believed more RWH structures ought to be built to alleviate any groundwater shortage. Decreasing or limiting groundwater extraction was not considered by anyone interviewed. The solution to limit extraction of groundwater could be to limit well building, which for people in this catchment, who are dependent on groundwater for their livelihood, might not be an attractive solution. Annual fluctuations are very strong (as seen in Chapter 4) due to the shallow aquifer system that most farmers in this area access. This reflects the amount of rainfall, so the aquifer may self-limit extraction.

The only groundwater demand rules in the ARP apply to crop choice. Crops are visible, and so it is easy to see whether other users are abiding by the informal rule to not plant certain crops. However, the interviews and other literature suggest that most people in
the Arvari River catchment are not aware of the ARP or its rules (Kumar and Kandpal 2003). From the interviews, the five farmers who were not members of the ARP and owned wells near RWH structures had not heard of the ARP. And of those, four were unaware of a Gram Sabha in their village. While the rules suggest no new tube wells to be built, there are no direct restrictions on dug well drilling or pumping. And in 2007 new tube wells seen while monitoring, and in one village three new tube wells had been installed in the last three years. There is nothing to stop well owners from deepening existing wells, digging new wells, or increasing pump capacity. The researcher also saw pumping occurring directly from the river and from the storage of the Anicut at Kaled in 2008, despite the ARP informal rule that pumping should not take place in the river or from RWH storage (with exceptions).

Enforcement and monitoring of the rules depends on the strength of the moral sanctions within the community. This depends on the activity and strength of the Gram Sabha to convey the ARP informal rules to the village community. A recent evaluation of TBS’s work found that most Gram Sabhas remained dormant after TBS had withdrawn from the village after construction of RWH. However in some villages, the Gram Sabha had taken up further activities (Kumar and Kandpal 2003). Where the Gram Sabha is most active, there has been significant impact on the management of common resources, such as forests, grazing lands and RWH construction and maintenance (Moench, Dixit et al. 2003). The most active Gram Sabhas were found in villages at the upper end of the catchment. The percentage of land under RWH in these areas is higher than other areas on lower elevations. These landscape positions also mean that RWH has had the largest impact on groundwater tables, for example in Bhaonta village, and so the community is more likely to work collectively because of the individual benefit from working together.

The ARP is evaluated against Ostrom’s factors that favour collective action (Table 7-1) (Ostrom 1990; Ostrom 1992; Ostrom 2000). These factors have been used to evaluate water institutions in a number of studies including Lopez-Gunn and Cortina (2006) and Lopez-Gunn (2003), which evaluated groundwater user associations in Spain. But the use of these factors prescriptively or interpreting them too simplistically has been debated
Cleaver and Franks (2005) consider these factors too limited with simplistic assumptions about the users, between the rules and the decision making structures. Nevertheless the design principles do outline key challenges facing the users for collective action, but are insufficient by themselves to suggest solutions. In the context of the ARP, the design factors are used to provide a framework for analysing and highlighting the challenges facing the Arvari River catchment community to manage groundwater.

As can be seen from Table 7-1, the ARP does not have many of the factors that Ostrom considers to favour collective action. While each user is heavily dependent on the resource, the boundaries are not clear. New users can only be excluded if they do not own land, as groundwater rights legally lie with the land. There is no structured monitoring of the resource or operational rules regarding the amount of groundwater extraction, so ‘free riding’ still occurs, which could further discourage collective action (Schlager 2007). When asked about the impacts of pumping, all interviewees described water levels going down locally as water is pumped, but larger or longer-term aquifer impacts were not mentioned.
Table 7-1 Analysis of ARP and the factors that favour collective action (Ostrom 1990; Ostrom 1992)

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Characteristics of the Arvari River Parliament</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearly defined boundaries</td>
<td>The ARP is defined based on surface water boundaries of the Arvari River, not groundwater boundaries. Aquifer boundaries are not clearly defined.</td>
</tr>
<tr>
<td>Salience</td>
<td>High dependency of the groundwater resource by users for their livelihood.</td>
</tr>
<tr>
<td>Participation of most users</td>
<td>Participation is dependent on the activity of Gram Sabhas, which are more active in the upper catchment. Most people in the catchment are unaware of the ARP, but there is no restriction to membership. All members are small holder farmers who use groundwater. The average age is in the mid forties, and there are very few female representatives.</td>
</tr>
<tr>
<td>Users bound by mutual obligation</td>
<td>There is no obligation between users to restrict the use of groundwater. Any restriction depends on the activeness of the Gram Sabha and moral sanctions within the village community.</td>
</tr>
<tr>
<td>Common understanding of the resource</td>
<td>The general perception of groundwater from the interviews was that pumping effects local supply, but depends on the internal routes of groundwater. Shortage of groundwater is felt to be related to rainfall. Impacts of individual use are not well understood on long term and larger scale aquifer capacity.</td>
</tr>
<tr>
<td>Graduated sanctions</td>
<td>There are no graduated sanctions. Enforcement and monitoring at village level through moral sanctions and pressure, which depends on the Gram Sabha activity.</td>
</tr>
<tr>
<td>Leadership</td>
<td>Strong local charismatic leader since inception.</td>
</tr>
</tbody>
</table>
Currently the Arvari River catchment is not facing serious supply issues in groundwater. This is because the farming practices are such that the level of irrigation does not have large or strong negative impacts on other users in the catchment. Also the resource itself encourages self-limiting behaviour in pumping. Most farmers access the shallow aquifer through dug wells, which varies significantly within a year. Consequently irrigation area fluctuates depending on the level of water at the end of each monsoon. As population grows and more area is developed for irrigation, perhaps longer term water table decline patterns could appear. However this would require reliable information, and due to the lack of monitoring in the catchment this may be difficult to determine. Nevertheless the ARP could provide a forum through which members can discuss such issues if they occur. More importantly the institution could act as a lobby and empower users to exclude other larger users of groundwater from entering the catchment, for example industrial units. Greater understanding of the resource capacity and user pumping
impacts at the catchment community level would greatly improve the ability of the community and an institution like the ARP to encourage monitoring of groundwater.

The ARP encourages the implementation of RWH across the catchment. All interviewees, when asked about the downstream impacts of RWH, said that any impact would be positive, because groundwater would move towards them in the aquifer. Strong lateral flow was also suggested in the field analysis in Chapter 4, with almost 30% of potential recharge from RWH structures moving away laterally in the unsaturated zone of the shallow aquifer. So while RWH works are carried out at the village scale, the water stock that the village would hope to access from the construction of RWH, may not be exclusive to the group of users who initiated RWH. Instead that water may move away or could even be pumped away from the control of that group, if there is no physical boundary. By encouraging RWH across the catchment, any movement of groundwater away from some users could be balanced by more RWH construction upstream. From Chapter 4 in this area the effects of RWH are largely local, and in the upper rockier areas of the catchment, wells almost 6 km away are influenced by recharge from RWH. However, the model simulations suggest that RWH impacts reach a maximum level of efficiency beyond which the benefit decreases, i.e. the cost-benefit ratio increases to a point beyond which the benefits do not warrant the cost (Chapter 6). This consequence means that demand-side management of groundwater would be better targeted to manage groundwater supply.

### 7.4. Conclusion

As highlighted in the example of the Arvari River Parliament, a community-based approach to manage groundwater in India faces serious challenges and constraints, largely because of the lack of information for resource users about the resource. Despite this, knowledge and impact of institutions at the operational level are important, particularly in India, where millions of wells exist. As Shah (2007b) points out, for
community-based institutions to work, it must serve a private purpose important to the users, otherwise they may not all participate or may even try to work against it. Currently in the Arvari River catchment that private purpose is not present, because dug well tap the shallow aquifer, which fluctuates annually and is largely dependent on rainfall and recharge from RWH (Chapter 4). But if irrigation area and population pressure increases, and more tube wells are sunk, then perhaps the need for collective action will arise, and an institution like the ARP will have more relevance. At this time the need for reliable information about aquifer characteristics and user behaviour will be important for the ARP to function effectively. If groundwater shortage does becomes a serious problem in the future, then change in livelihood patterns from the current heavy dependence on irrigated agriculture would ultimately be necessary to alleviate further extraction of groundwater.
The purpose of this thesis was to investigate the impacts of RWH, specifically designed to increase groundwater recharge, as this is important for effective implementation of watershed development programs in India. In this chapter, the key research findings of the thesis are summarised, implications for watershed development are explored, and the limitations of the study are presented. As this thesis is a step towards greater understanding of RWH, it also suggests the way forward for future research in this topic. The major contribution from this study is a methodology to systematically examine the impact of RWH development in a catchment.
8.1. General Overview and Key Findings

The thesis presented here examines the main question:

What are the impacts of rainwater harvesting (RWH) at the local and catchment scales?

The key components of this work are:

1. As a case study, local-scale impacts of RWH were examined in the Arvari River catchment in 2007 and 2008. Rainfall and water levels in RWH structures and dug wells were measured as part of an extensive monitoring approach.
2. A conceptual model was developed to specifically investigate RWH impacts at the larger catchment-scale. This model incorporates the main hydrological processes influenced by RWH, inferred from the local-scale impact study.
3. Different RWH and irrigated land use scenarios were simulated in the conceptual model to examine catchment-scale impacts of RWH on irrigated agriculture and streamflow.
4. The ability of the community-based institution, the Arvari River Parliament, to manage groundwater demand was analysed.

The case study confirmed the strong local-scale impacts of RWH on groundwater levels that has been referred to in a number of studies (Gore, Pendke et al. 1998; Sharda, Kurothe et al. 2006). The measured catchment rainfall displayed large variability, which locally influenced the storage of RWH and thus potential recharge volume from an individual RWH structure. This was particularly noticeable between rainfall years, where 2008 was a comparatively wetter year and had higher potential recharge volumes than 2007. Depending on structure size and landscape position RWH potential recharge varied. Potential recharge from RWH was highest from Anicuts on the river, and the Bandhs had a higher volume of potential recharge than Johads. In total RWH contributed about 7% of rainfall to potential recharge in the catchment, which was similar in both rainfall years, despite the difference in rainfall between years. This is due to
RWH structure shape and size, landscape position and underlying stratigraphy, which are the main factors that influence RWH performance. However this level of potential recharge did not translate into the actual recharge from the analysis of the groundwater levels in the dug wells. This is likely due to a number of elements including; local mounding of the water table beneath RWH structures, storage in the soil profile, and high lateral flow in the aquifer. This resulted in much lower actual groundwater recharge levels. There are strong annual variations in the water levels in all the dug wells, including those not close to RWH structures, particularly between the pre- and post-monsoon season levels. While this study has not quantified the impact of an individual RWH structure on groundwater levels, because of the number of structures and the few observation wells in the field study, judging by the strong local influence of recharge near RWH structures, and the small natural recharge estimates from literature, the results suggest that RWH most likely influences groundwater levels across the shallow aquifer. The results from the field study add to the knowledge base of local-scale RWH impacts in India, which are limited in the literature. The results also compare well with the few previous local scale studies of RWH such as Sharda et al. (2006). Overall the story from the field data is one of high spatial and temporal variability. However the results also clearly confirm the effectiveness of RWH performance to produce groundwater recharge.

Catchment-scale impacts of RWH are an area of research that has been little investigated. This study examines this research question through the use of a water balance model. However an analysis of existing water balance models showed that most had high complexity and large data requirements. Given the lack of information and lack of long term data series in the Arvari River catchment, a conceptual model was developed. The model incorporates the main hydrological processes relevant to RWH and those that influence catchment hydrology. This was inferred from the case study field data and local observations. The main purpose of the model was to improve the understanding of the feedbacks in the water balance related to RWH, and to explore the data inputs that would be required to apply such a model to a specific catchment. The model uses hydrological response units (HRUs) based on land uses of RWH, agriculture (including irrigated area) and Commons land use. Agricultural and Commons HRUs have a specific
soil layer, curve number for runoff and leaf area index for the plant species. Recharge for RWH is not based on the water balance method, as it is for the other HRUs, but uses Darcy’s Law. Rainfall was applied stochastically in the model. The model was calibrated qualitatively based on the local-scale field data in the Arvari River catchment. The main difficulties in simulating the hydrological processes from the field in the model were capturing the non-linearity of RWH recharge, and simulating the management practices where irrigation area is a function of groundwater levels.

The literature review and observations from the case study catchment describe a strong link between RWH area and the opportunity for increasing irrigated land use. Often RWH is implemented to augment groundwater supply, which is then extracted for irrigation. The model simulations showed that as the RWH area increases, groundwater supply increases, and thus the potential for larger areas of agriculture to be irrigated. This link was analysed using sustainability indices developed by Hashimoto et al. (1982) for different land use scenarios. The results show that irrigated agriculture is more viable with RWH than without as indicated. However as the area of RWH increases, there is a maximum limit to the benefit from RWH, as at greater RWH areas, the captured runoff is divided over a greater RWH storage area. In this study the maximum benefit limit is somewhere between 1% and 3% RWH area. This limit was also displayed in the field study for an individual structure, where for each structure a maximum recharge limit was reached. The results of the resilience index at 10% irrigation highlight the impact of increasing irrigation area when there is sufficient groundwater. Such management practices may increase crop yields, but the viability of the water resource system decreases at the optimal level of RWH found in the model. The presence of RWH decreases the impacts of short-term mild drought situations. Finally, at the catchment-scale, the model showed that as RWH increases, downstream flow decreases, and the runoff coefficient decreases strongly when a small area of RWH is introduced in the model. These conclusions have important management implications.

Implementation of RWH addresses supply-side issues of groundwater, while demand management of groundwater is reliant on the human institutions that develop rules to
manage groundwater extraction. The Arvari River Parliament was examined to see if this institution could regulate and monitor groundwater demand, but despite its efforts, unrestricted groundwater use occurs. The major limitation for this group is primarily the private purpose for the users to work collectively and secondly the lack of scientific information about the aquifer properties, including size and capacity. Any groundwater shortage issues are considered to be related to rainfall, mainly because groundwater users tap the shallow aquifer, which has strong local annual variability. As a consequence RWH is seen as a solution to groundwater shortages, rather than restricting groundwater extraction, which for most users in the catchment is their main livelihood. Nevertheless operational-level management of groundwater is an option that ought to be explored further due to the difficulties of managing this resource at larger administrative scales.

8.2. Implications

In India groundwater irrigation has helped to alleviate poverty and increase rural growth, but groundwater is being consumed unsustainably (Rodell, Velicogna et al. 2009). Groundwater decline is a serious concern, particularly for small-holder farmers which are disproportionately dependent on the resource (Gale, Neumann et al. 2002). Consequently RWH has been implemented as part of larger watershed development programs and has been initiated by communities, NGOs and government agencies across the country to augment groundwater supply. While RWH development has visible impacts on groundwater levels, very few studies have examined in detail the local-scale impacts of RWH and the hydrological processes associated with RWH. Instead RWH seems to have been implemented in a rather rapid, unplanned, and unregulated manner. For example RWH in the Arvari River catchment was driven by local demand at the village level, rather than planned at an aquifer or river catchment level. However the success of RWH work in this area is because of focus at the village-scale. In addition the ARP was set-up once the community saw the need for an integrated approach to watershed development.
Catchment-scale impacts of RWH are even less investigated and understood locally, but a growing body of scientific literature is beginning to highlight the need for such research. The thesis presented here has further highlighted these issues and increased the body of knowledge about RWH. The study gives estimates of potential recharge from different types of RWH in a semi-arid catchment in Rajasthan, and the translation of these potential values into actual groundwater rise. Communication of these outcomes to the local community is one of the follow-up priorities.

Each RWH structure has a limiting capacity to induce maximum recharge, which depends on structure size and shape, the rainfall – runoff characteristics of the catchment and hydrogeological properties of the area. In the case of the Arvari River catchment, RWH structures in the higher elevations and on the river have a larger potential recharge impact than smaller structures on lower elevations. Therefore the positioning of structures in a landscape is important when investing in RWH. In the Arvari River catchment, these components were addressed in RWH construction by villagers, whose local experience of landscape conditions guided the choice of suitable sites and structure types appropriate for their needs. However at the catchment-scale, the modelling results describe a similar limiting capacity of RWH to induce recharge beyond a certain maximum. When the area of RWH was doubled in the modelled conceptual catchment, the benefit to irrigated agriculture, using the sustainability indices, was not substantial, but the decrease in streamflow was stronger. This has important implications for NGOs, communities and government agencies who build RWH structures, because the cost of investing in RWH may not equal the benefit gained from this investment, and the downstream streamflow impacts would be more widely felt. These results deserve more consideration by applying the model to a specific catchment, and particularly examining the aquifer properties, because the case study results suggest that despite surface flows decreasing downstream when RWH is implemented, downstream users could possibly benefit from lateral flow of groundwater.
8.3. Limitations and further research

Semi-arid rural areas are generally data sparse environments and the Arvari River catchment is no exception. As a result, the field data collection was limited in scope due to the conditions and infrastructure in the catchment area and the size of the project resources. Nevertheless the results are comparable to the smaller scale and more data intensive study of Sharda et al. (2006). Consequently the thesis shows that basic field information is equally capable to provide estimates of RWH characteristics. A more detailed future field study could try to identify the minimum dataset needed to characterise local and catchment-scale impacts of RWH. It could also examine a larger area of the specific catchment, which in this study was focussed in the middle and upper reaches of the catchment. This would account for more variability in the catchment. A climate station, a river gauging station and a longer time series of data would be very valuable, as well as greater knowledge of aquifer properties and characteristics. Installation of piezometers across the catchment would alleviate some of the pumping issues associated with the dug wells in this study. Additionally soil water characteristics could be measured in RWH storage areas to better estimate soil water storage. These measurements could then possibly be used in a 2D soil-water model to calculate recharge. Rainwater harvesting may also act as erosion control by reducing runoff velocities, soil erosion, and sediment loads. This could have further ecological benefits for the catchment ecosystem as more water would be available for a longer time. Therefore runoff could be gauged by using RWH structures storage for events of rainfall, which in this study was taken on a daily time step. Also future work could examine sediment loads received in RWH structures, and the necessary maintenance times for de-silting structures could be calculated.

The model used in this thesis is conceptual so the next step would be to apply the model to a specific catchment, which has a sufficiently long data time series, including rainfall, groundwater levels, and river discharge, to allow effective calibration and validation. The results of the simulation study could then be compared to the situation in a ‘real’
catchment. Additionally the output of the model could be compared with more complex existing models if the data requirements are met. The complexity of the developed model could also be increased to address the cost-benefit questions related to RWH and irrigation development. This would mean including a crop growth model to simulate crop yields. From modelled crop yields, income generation for the community could be estimated. If such components are added, then rather than using sustainability indices, the resilience of the socio-ecological system with RWH could be analysed. A socio-ecological system would incorporate not only irrigated agriculture and the resultant income from crop yields, but also the environment including riverine ecology and environmental flows in the river. This could also possibly address issues related to sediment loads and water quality. The socio-ecological system and the feedbacks between RWH, irrigated agriculture and groundwater extraction could then be analysed. The use of remote sensing including Landsat imagery could also be used and would help in delineating land uses and could also be used to identify the number of RWH structures and storage area surface areas in different years (Liebe, van de Giesen et al. 2009). GIS would be a useful tool in developing spatial layers of such data. Terrain attributes and DEM information could also help with empirical modelling of the groundwater table.

8.4. Concluding comments

As pumping technology has changed, groundwater use has increased the accessibility of a reliable source of irrigation water for small-holder farmers across India, alleviating poverty in many rural areas. Yet the presence of millions of wells has meant that groundwater is over extracted and water levels are declining. As a result RWH has been widely implemented to raise deepening groundwater levels, but with no scientific or hydrological studies to confirm or aid in implementation.

This study has therefore examined RWH in the semi-arid rural Arvari River catchment, and then up-scaled the field results to the catchment-scale using a conceptual water
balance model developed in R to examine any hydrological impacts. This study has shown that RWH has a positive impact on groundwater recharge, but decreases streamflow downstream. Future work is needed to examine the conclusion drawn from the simulation study, that increasing RWH *ad infinitum* does not increase benefit for irrigation. Rainwater harvesting also changes blue water into green water as the irrigation area increases as RWH is implemented.

Regardless of whether or what area of RWH is implemented, the institutions that manage groundwater need to be established for sustainable use of the resource. These institutions have particular relevance because increased recharge from RWH is strongly linked with increased irrigation area, and the impact of such management practices can decrease the resilience of the system.

The heavy reliance of groundwater in many parts of India means that the examination of RWH impacts must be examined further for effective catchment development programs in India, and the results should be conveyed to the groundwater users themselves.
APPENDIX 1 – PHOTOS AND MAPS OF MONITORED RWH STRUCTURES

Photos of RWH structures monitored, local elevation ASL and distance of wells from structures. Letters with the maps and photos relate to Table 4-1.
# Subbasin 1 Variables

# Landuse Area functions
ag2 <- function(i) ifelse(year[i] >= Irrstart & (GWstore > 125) &
(Ag3.Irr(i) == TRUE), ag2.init * 1.2, ag2.init)
Luse.fr.BND <- (Luse.fr.JHD/0.4)*0.6
Luse.fr1.Ag2 <- function(i) ifelse(year[i] < Irrstart, 0, ag2(i))
Luse.fr1.Ag3 <- function(i) ifelse(year[i] < Irrstart, 0, (ag2(i)/0.9*0.1))
Luse.fr1.Ag1 <- 0.35
Luse.fr1.Com <- function(i) ifelse(year[i] < Irrstart & & year[i] < RWH.start, 0.65, ifelse(year[i] < Irrstart, 0.65-(Luse.fr.JHD+Luse.fr.BND), 0.65-
(Luse.fr.JHD+Luse.fr.BND+ag2(i)+(ag2(i)/0.9*0.1))))

# Groundwater size and initial for the UPPER AQUIFER
GW.max <- 200
GW.init <- 100

# Irrigation Parameters
Irrstop <- 2050
Irrmax <- 150
Irrmin <- 100
Ag1.Irr <- FALSE
Ag2.Irr <- function(i) {ifelse (month[i] == 7 || month[i] == 8 || month[i] == 9 ||
month[i] == 11 || month[i] == 12 || month[i] == 1, TRUE, FALSE)}
Ag3.Irr <- function(i) {ifelse (month[i] == 7 || month[i] == 8 || month[i] == 9 ||
month[i] == 11 || month[i] == 12 || month[i] == 1 ||
month[i] == 3 || month[i] == 4 || month[i] == 5, TRUE, FALSE)}
Com.Irr <- FALSE
# RWH size and initial water and yr started
RWH.start <- 2000
RWH.stop <- 2050
JHDmax <- 1000
JHD.init <- 0
BNDmax <- 2000
BND.init <- 0

# RWH recharge parameters
bnd.gw <- 4000
jhd.gw <- 18000
bnd.Ks <- 1534.28  # van genuchten mm/day (~4cm/hr)
jhd.Ks <- 1534.28  # 70% (40% s, 35% c) 1534.28
threshold <- 100
a <- 0.3

# Agriculture and Commons soil layer
PAWC.ag <- 261.2
PAWC.com <- 100
AWinit.ag <- 130
AWinit.com <- 50

# Curve Number
CN.Ag1 <- function(i) ifelse(LAI.Ag1(i) <= 0.1, 72, 77)
CN.Ag2 <- function(i) ifelse(LAI.Ag2(i) <= 0.1, 72, 77)
CN.Ag3 <- function(i) ifelse(LAI.Ag3(i) <= 0.1, 72, 77)
CN.Com <- 79
Ia <- 0.05

# Evapotranspiration
LAI.Ag1 <- function(i) {
  ifelse (month[i] == 7 || month[i] == 8 || month[i] == 9, 4, 0.1)
}
LAI.Ag2 <- function(i) {
  ifelse (month[i] == 7 || month[i] == 8 || month[i] == 9 || month[i] == 11, 4,
    ifelse(month[i] == 10 || month[i] == 12 || month[i] == 1 || month[i] == 2, 5, 0.1))
}
LAI.Ag3 <- function(i) {
  ifelse (month[i] == 7 || month[i] == 8 || month[i] == 9 || month[i] == 11,
    ifelse(month[i] == 3 || month[i] == 4 || month[i] == 5 || month[i] == 6, 4,
      ifelse(month[i] == 10 || month[i] == 12 || month[i] == 1 || month[i] == 2.5, 0.1))
}
LAI.Com <- function(i) {
  ifelse (month[i] == 7 || month[i] == 8 || month[i] == 9 || month[i] == 10,
    ifelse(month[i] == 11 || month[i] == 12 || month[i] == 1 || month[i] == 4, 0.5)
}
fr <- 1
c_T <- 0.45
s_w.ag <- 0.454 * PAWC.ag  # loam
s_w.com <- 0.541 * PAWC.com
s_star.ag <- 0.7 * PAWC.ag  # loam
s_star.com <- 0.78 * PAWC.com
# Lateral flow between Subbasins
E1 <- 457000
perc.coeff <- 0.0001
soil.GW <- 3000

# Routing
river.length <- 5 # km excluding tributaries
river.area <- 125000*10^6 # mm^2 5 km * 25 m
k <- 5

# Water Balance Functions
# Routing Function
Stream.Routing <- function(It, It1, Qt, k) {
  f <- function(Vup) (1.983*Vup^0.73)
  Vup <- rep(0, river.length)
  Tloss <- rep(0, river.length)
  for (i in 1:river.length) {
    Vup[i] <- ifelse(i==1, It1, Vup[i-1]) - f(ifelse(i==1, It1, Vup[i-1]))
    Tloss[i] <- f(ifelse(i==1, It1, Vup[i-1]))
  }
  Q <- ((It + It1 - 2*sum(Tloss, na.rm = TRUE) + Qt*(2*k-1))/(2*k+1))
  Q1 <- Q/river.area
  Q <- ifelse(Q1<0, 0, Q1)
  Tl <- sum(Tloss, na.rm = TRUE)/river.area
  Tloss <- ifelse(Tl<0, 0, Tl)
  Out <- c(Q, Tloss)
  return(Out)
}

# RUNOFF
CN.fun <- function(P, CN, Ia) {
  S <- 25400/CN - 254
  Roff <- ifelse(P*Ia*S, 0, ((P-Ia*S)^2)/(P+(1-Ia)*S))
  return(Roff)
}

# Actual EVAPORATION
E_Teuling <- function(AW, s_w, s_star, pot_ET, LAI) {
  if (AW <= s_w) {
    beta_T <- 0
  } else {
    if (AW <= s_star & AW > s_w) {
      # Add the rest of the function here
    }
  }
}

# Add the rest of the function here
\[
\beta_T \left\{ \begin{array}{l}
\frac{(AW-s_w)}{(s_{\text{star}}-s_w)} \\
1
\end{array} \right.
\]

\[
ET \left\{ \begin{array}{l}
fr \beta_T(1-\exp(-c_T*LAI)) \cdot \text{pot}_ET \\
1
\end{array} \right.
\]

Waterbalance <- function(P, ET, CN, Luse.fr, PAWC, AWinit, Irr=FALSE, LAI, s_w, s_star) {
  Roff <- sapply(P, CN.fun, CN=CN, la=la)
  if (Irr==TRUE) {
    if(AWinit <= s_star) # changed from 0.55 to s_star
      { Irra <- PAWC - AWinit
        Irrb <- ifelse(P < Irra, Irra-P, 0)
        Irrc <- ifelse(Irrb*Luse.fr > GWstore, GWstore, Irrb)
        Irrav <- ifelse(Irrc >= Irrmax, Irrmax, Irrmin)
      } else {
        Irrav <- 0
      }
    } else {
      Irrav <- 0
    }
  }
  ETcalc <- do.call(E_Teuling, list(AW=AWinit, s_w=s_w, s_star=s_star, pot_ET=ET, LAI=LAI))
  AW <- ifelse(AWinit + P + Irrav - Roff - ETcalc > s_w, AWinit + P + Irrav - Roff - ETcalc, s_w)
  DD <- ifelse(AW > PAWC, AW-PAWC, 0)
  AW <- AW-DD
  Roff <- Roff*Luse.fr
  DD <- DD*Luse.fr
  Irrav <- Irrav*Luse.fr
  Out <- c(Roff, DD, AW, ETcalc, Irrav)
  return(Out)
}

# define a function for the RWH
RWH.balance <- function(Ksat, RWHstore.init, rwh.GW, threshold, a, Input, ET, RWHmax) {
  Rep1 <- ifelse(((RWHstore.init + rwh.GW)/(rwh.GW)) < threshold, (Ksat*((RWHstore.init + rwh.GW)/(rwh.GW))), (((threshold-threshold^a)+(Ksat*((RWHstore.init + rwh.GW)/(rwh.GW))^a))))
  Rep <- ifelse(Rep1 < RWHstore.init, Rep1, RWHstore.init)
  RWH <- ifelse(RWHstore.init + Input - ET - Rep > 0, RWHstore.init + Input - ET - Rep, 0)
  overfl <- ifelse(RWH > RWHmax, RWH-RWHmax, 0)
RWH <- RWH - overfl
out <- c(RWH,overfl,Rep,ET,Input)
return(out)

# Groundwater balance
GW.balance <- function(GWstore, perc.coef, Input, Irr, G.lat, GWmax) {
  D.GW.loss <- GWstore * perc.coef
  GW <- ifelse(GWstore + Input - Irr - G.lat - D.GW.loss > 0,
                GWstore + Input - Irr - G.lat - D.GW.loss, 0)
  baseflow <- ifelse(GW > GWmax, GW - GWmax, 0)
  # correct GW for baseflow
  GW.init <- GW - baseflow
  out <- c(GW.init, baseflow, D.GW.loss)
  return(out)
}

# calc flow btw upper aquifers
# calc D1
D1 <- function(soil.GW, GW, Input) {
  D1 <- soil.GW + (GW - Input)
  out <- c(D1)
  return(out)
}

#calc D2
D2 <- function(soil.GW, GW, Input) {
  D2 <- soil.GW + (GW - Input)
  Out <- c(D2)
  return(out)
}

#calc flow btw upper aquifers
GW.flow <- function(p, E1, D2, D1) {
  flow <- p * (E1 + D2 - D1)
  out <- c(flow)
  return(out)
}

# -----------------------------------#
# Rainfall Prediction Model
# -----------------------------------#
#Rainfall Function
Precip <- function(time, alpha, lambda) {
  f_P <- round(rexp(time, lambda))
  for (p in 1:length(f_P))
    if (p == 1) {
      if (f_P[p] > 0) {
        R <- c(rep(0, f_P[p]), rexp(1, 1/alpha))
      }
    } else {
      # Additional code for handling rainfall predictions
  }
R <- rexp(1,1/alpha)
}
} else {
if (f_P[p]>0) {
  R <- c(R,c(rep(0,f_P[p]),rexp(1,1/alpha)))
} else {
  R <- c(R,rexp(1,1/alpha))
}
}
return(R[1:time])
}

#Annual rainfall analysis from Alwar
A.rain <- read.csv("alwar_yrly_P.csv")
A.annual.m <- mean(log(A.rain[,2]))
A.annual.sd <- sd(log(A.rain[,2]))
year.R <- seq(1901,2002)
N <- length(year.R)
Rain_fun <- function(year,N) {
  cos1 <- cos(2*pi*year/N)
  sin1 <- sin(2*pi*year/N)
  cos2 <- cos(4*pi*year/N)
  sin2 <- sin(4*pi*year/N)
  cos3 <- cos(6*pi*year/N)
  sin3 <- sin(6*pi*year/N)
  out <- data.frame(cos1=cos1,sin1=sin1,cos2=cos2,sin2=sin2,cos3=cos3,sin3=sin3)
  return(out)
}
Rain_mat <- cbind(Rain_fun(year.R,N),Rain=A.rain[,2])
lm3 <- lm(Rain ~ .,data=Rain_mat)

# Linear model btw annual rainfall and wet/dry season Thanagazi
rain <- as.data.frame(read.csv("thanagazi_P_stack_no1999.csv"))
P <- rain$P
Month.T <- rain$month
Month.T <- as.numeric(substr(as.Date(rain$date,"%d/%m/%Y"),6,7))
rain$wetP <- replace(rain$P,(Month.T<6 | Month.T>9),NA)
rain$dryP <- replace(rain$P,(Month.T>=6 & Month.T<=9),NA)
annual <- aggregate(rain[,5:7],list(year=rain$year),sum,na.rm=TRUE)
fit.w <- lm(annual[,3]~annual[,2])
summary(fit.w)
slope.w <- fit.w$coefficients[2]
int.w <- fit.w$coefficients[1]

# Predict ANNUAL RAINFALL for MODEL
Date <- (seq(as.Date("2000/1/1"), as.Date("2012/1/1"), "days"))
year <- as.numeric(format(Date,"%Y"))
days <- c(rep(c(366,rep(365,3)),3))
N <- length(unique(year))
Rain_mat <- cbind(Rain_fun(as.numeric(unique(year)),N),Rain=N)
p.A.rain.dry <- exp(log(runif(8,300,500) + rnorm(8,0,A.annual.sd)))
p.A.rain
days <- c(rep(c(366,rep(365,3)),3))
N <- length(unique(year))
Rain_mat <- cbind(Rain_fun(as.numeric(unique(year)),N),Rain=N)
p.A.rain.wet <- exp(log(runif(6,600,1000) + rnorm(6,0,A.annual.sd)))
p.A.rain

# lambda
lambda.w <- 0.5117967
lambda.d <- 0.05969731
lambda.d <- rep(lambda.d,N)
lambda.w <-  rep(lambda.w,N)

# alpha
A <- as.data.frame(matrix(nrow=N, ncol=2))
#A$alpha.w <- (int.w + slope.w*p.A.rain)/(122*lambda.w)
A$alpha.w <- ifelse(((int.w + slope.w*p.A.rain)/(122*lambda.w))>11,(int.w + slope.w*p.A.rain)/(122*lambda.w),11)  #rainy season has 122 days
A$alpha.d <- (p.A.rain-(int.w + slope.w*p.A.rain))/((365-122)*lambda.d)

#Predict daily RAINFALL for 3 subbasins
Rain <- as.data.frame(matrix(nrow=length(Date),ncol=4))
colnames(Rain)<- c("month","Zone1.P", "Zone2.P", "Zone3.P")
Rain$month <- as.numeric(substr(as.Date(Date,"%d/%m/%Y"),6,7))
model.w1 <- unlist(sapply(l,function(l) Precip(days[l], A$alpha.w[l], lambda.w[l])))
model.d1 <- unlist(sapply(l,function(l) Precip(days[l], A$alpha.d[l], lambda.d[l])))
wet1 <- replace(model.w1,(Rain$month<6 | Rain$month>9),0)
dry1 <- replace(model.d1,(Rain$month>6 & Rain$month<9),0)
Rain$Zone1.P <- wet1+dry1
model.w2 <- unlist(sapply(l,function(l) Precip(days[l], A$alpha.w[l], lambda.w[l])))
model.d2 <- unlist(sapply(l,function(l) Precip(days[l], A$alpha.d[l], lambda.d[l])))
wet2 <- replace(model.w2,(Rain$month<6 | Rain$month>9),0)
dry2 <- replace(model.d2,(Rain$month>6 & Rain$month<9),0)
Rain$Zone2.P <- wet2+dry2

Rain1 <- data.frame(year=format(Date,"%Y"),date=Date,
zone1=Rain$Zone1.P,zone2=Rain$Zone2.P,zone3=Rain$Zone3.P)
Date1 <- as.Date(Rain1$date,"%d/%m/%Y"
plot(Date1, Rain1$zone1, typ="l")
lines(Date1, Rain1$zone2, col="red")
lines(Date1, Rain1$zone3, col="blue")

rain <- Rain1

write.csv(rain,"zone_rain.csv",row.names=FALSE)

# Store Results of Model

Zone1.Climate <- matrix(nrow=length(Date), ncol=3)
colnames(Zone1.Climate) <- c("month","P","pot_ET")

Zone1.Out <- matrix(nrow=length(Date),ncol=20)
colnames(Zone1.Out) <-c("Roff.Ag1","Re.Ag1","AW.Ag1","etag1","irrag1","Re.Ag2","AW.Ag2","Et2","Irrav.Ag2","Roff.Ag3","Re.Ag3","AW.Ag3","et3","Irrav.Ag3","Roff.Com","Re.Com","AW.Com","ETcom","irrcom")

Zone1.RWH.Out <- matrix(nrow=length(Date),ncol=10)
colnames(Zone1.RWH.Out) <-c("JHD.depth","JHD.of","JHD.re","JHD.et","jhdinput","BND.depth","BND.of","BND.re","BND.et","bndinput")

Zone1.GW.Out <- matrix(nrow=length(Date),ncol=5)
colnames(Zone1.GW.Out) <-c("GW.init","basef","D.GW.loss","D1","GW")

Zone1.Stream.Out<-matrix(nrow=length(Date),ncol=4)
colnames(Zone1.Stream.Out) <- c("flow","volume.flow","routed","tloss")

# Define Date and Predict Potential Evaporation

Date <- (seq(as.Date("2000/1/1"), as.Date("2012/1/1"), "days"))

day <- c(rep(c(1:366,rep(1:365,3)),4),1:366,rep(1:365,2))
cos1 <- cos(2*pi*day/365)
sin1 <- sin(2*pi*day/365)
cos2 <- cos(4*pi*day/365)
sin2 <- sin(4*pi*day/365)
cos3 <- cos(6*pi*day/365)
sin3 <- sin(6*pi*day/365)

lm3 <- lm(rain$pot_ET ~  cos1 + sin1 + cos2 + sin2 + cos3 + sin3)

# Create newdata using the newdata function
year  <- as.numeric(format(Date,"%Y"))
day2 <- vector()
day2[1] <- 1
for (i in 2:length(year)) {
  if (year[i] == year[i-1]) {
    day2[i] <- day2[i-1]+1
  }
  else
day2[i] <- 1
}
# Predict pot_ET
Zone1.Climate$pot_ET <- predict(lm3, newdata=ETfit(day2))
pot_ET <- Zone1.Climate$pot_ET
plot(pot_ET, type = "l")
dm <- format(Date, "%d/%m")

# Call Rainfall
prec <- as.data.frame(read.csv("zone_rain.csv"))
Zone1.Climate$P <- prec$zone1
 Zone1.P <- Zone1.Climate$P[-1:731]
P <- Zone1.Climate$P
Zone1.Climate$month <- as.numeric(substr(as.Date(Date,"%d/%m/%Y"),6,7))
month <- Zone1.Climate$month

# Run Model
for (i in 1:length(Zone1.Climate$pot_ET)) {
  # Groundwater
  GWstore <- ifelse(i==1,GW.init,Zone1.GW.Out[i-1,1])
  # Ag1
  AWinit <- ifelse(i==1,AWinit.ag1,Zone1.Out[i-1,3])
  Zone1.Out[i,1:5] <- Waterbalance(P[i],pot_ET[i],CN.Ag1(i),Luse.fr1.Ag1,PAWC.ag,AWinit,Ag1.Irr,
                          LAI=do.call(LAI.Ag1,list(i=i)), s_w=s_w.ag, s_star.ag)[1:5]
  # Ag2
  if (year[i] < Irrstart) { Zone1.Out[i,6:10] <- rep(0,5) } else { AWinit <- ifelse(year[i]==Irrstart & day.E[i] == 1 ,AWinit.ag,Zone1.Out[i-1,8])
    Zone1.Out[i,6:10] <- Waterbalance(P[i],pot_ET[i],CN.Ag2(i),Luse.fr1.Ag2(i),PAWC.ag,AWinit,Ag2.Irr(i), LAI.Ag2(i), s_w.ag, s_star.ag)[1:5]   }
  # Ag3
  if (year[i] < Irrstart) { Zone1.Out[i,11:15] <- rep(0,5) } else { AWinit <- ifelse(year[i]==Irrstart & day.E[i] == 1 ,AWinit.ag,Zone1.Out[i-1,13])
    Zone1.Out[i,11:15] <- Waterbalance(P[i],pot_ET[i],CN.Ag3(i),Luse.fr1.Ag3(i),PAWC.ag,AWinit,Ag3.Irr(i), LAI.Ag3(i), s_w.ag, s_star.ag)[1:5]   }
  # Commons
  AWinit <- ifelse(i==1,AWinit.com,Zone1.Out[i-1,18])
  Zone1.Out[i,16:20] <- Waterbalance(P[i],pot_ET[i],CN.Com,Luse.fr1.Com(i),PAWC.com,AWinit,Com.Irr, LAI.Com(i), s_w.com, s_star.com)[1:5]
# JHD
if (year[i] < RWH.start) { # no RWH built
    Zone1.RWH.Out[i,1:5] <- rep(0,5) # all values are 0
} else { # RWH have been built
    JHDstore.init <- ifelse(year[i]==RWH.start & day.E[i] == 1,JHD.init,Zone1.RWH.Out[i-1,1])
    JHDinput <- (Zone1.Out[i,1]*Rof.JHD.Ag1(i) + Zone1.Out[i,6]*Rof.JHD.Ag2(i)
                 +Zone1.Out[i,11]*Rof.JHD.Ag3(i)
                 +Zone1.Out[i,16]*Rof.JHD.Com(i))/Luse.fr.JHD
    Zone1.RWH.Out[i,1:5] <- RWH.balance(jhd.Ks, JHDstore.init, jhd.gw, thresholdj, a,
                                      JHDinput,pot_ET[i],JHDmax)
}

# BND
if (year[i] < RWH.start) { # no RWH built
    Zone1.RWH.Out[i,6:10] <- rep(0,5) # all values are 0
} else { # RWH have been build
    BNDstore.init <- ifelse(year[i]==RWH.start & day.E[i] == 1,BND.init,Zone1.RWH.Out[i-1,5])
    BNDinput <- (Zone1.Out[i,1]*Rof.BND.Ag1(i) + Zone1.Out[i,6]*Rof.BND.Ag2(i)
                 +Zone1.Out[i,11]*Rof.BND.Ag3(i)
                 +Zone1.Out[i,16]*Rof.BND.Com(i))/Luse.fr.BND
    Zone1.RWH.Out[i,6:10] <- RWH.balance(bnd.Ks, BNDstore.init, bnd.gw, thresholdb, a,
                                          BNDinput ,pot_ET[i],BNDmax)
}

# Groundwater
GWinput <- ifelse(i==1, 0,Zone1.Out[i-1,2]+Zone1.Out[i-1,7]+Zone1.Out[i-1,12]+Zone1.Out[i-1,17]+
                 Zone1.RWH.Out[i,3]*Luse.fr.JHD + Zone1.RWH.Out[i,8]*Luse.fr.BND+
                 Zone1.Stream.Out[i,5]*Luse.fr.BND) +
    Zone1.GW.Out[i,1:3] <- GW.balance(GWstore,perc.coeff,GWinput,sum(Zone1.Out[i,c(10,15)]),
                                      G.lat,G.W.max) [1:3]
    Zone1.GW.Out[i,4] <- D1(soil.GW,G.W.max,Zone1.GW.Out[i,1])

# Stream
Zone1.Stream.Out[i,1] <- ifelse(year[i]>=RWH.start, Zone1.RWH.Out[i,2]*Luse.fr.JHD +
                                Zone1.RWH.Out[i,7]*Luse.fr.BND+
                                Zone1.RWH.Out[i,11]*Luse.fr.BND
                                +Zone1.RWH.Out[i,16]+Zone1.GW.Out[i,2])
    # Routing for Zone 1 (volume)
    Qinit <- ifelse(i==1,1,Zone1.Stream.Out[i-1,3])
    It1 <- ifelse(i==1,100,Zone1.Stream.Out[i-1,2])


COMMAN (2005b). Managing Groundwater Resources in Rural India: the Community and Beyond, British Geological Survey Commissioned Report, CR/05/35N.


Savadamuthu, K. (2002). Impact of Farm Dams on Streamflow n the Upper Marne Catchment, South Australia, Department of Water Resources.


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