WASHCost

Working Paper 10

Using GIS and SWAT analysis to assess water scarcity and WASH services levels in rural Andhra Pradesh

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WASHCost is a five-year action research project investigating the costs of providing water, sanitation and hygiene services to rural and peri-urban communities in Ghana, Burkina Faso, Mozambique and India (Andhra Pradesh). The objectives of collecting and disaggregating cost data over the full life cycle of WASH services are to be able to analyse expenditure per infrastructure, by service level, per person and per user. The overall aim is to enable those who fund, plan and budget for services to understand better costs and service levels to enable more cost effective and equitable service delivery. WASHCost is focused on exploring and sharing an understanding of the costs of sustainable services (see www.washcost.info).

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Abbreviations and acronyms

ASTER GDEM	ASTER Global Digital Elevation Model
FAO	Food and Agricultural Organization of the United Nations
GIS	Geographical Information Systems
HRUS	Hydrological Response Units
MWSWAT	Open-source SWAT model
PRA	Participatory Rural Assessment
SWAT	The Soil and Water Assessment Tool
WHS	Water Harvesting Structures
WHO	World Health Organization

Summary

Large expanses of rural India are suffering from increasing water scarcity as defined as an imbalance between water supply and demand. In these rural areas, groundwater has become the predominant source of water for irrigation and the village water supply. In comparison to surface water sources, the reliability of groundwater supply has led to many benefits for local communities. However, increased demand for water from agriculture and government extraction has lead to severe overexploitation and increasing water scarcity. An increase of water for agricultural use is often detrimental to domestic water supplies, especially those of poorer social groups.

One aim of this Working Paper is to show how relatively simple Geographical Information Systems (GIS) techniques can be used to highlight water scarcity problems for a rural area of southern India and provide important information that can be applied to decision making. It will demonstrate how that even at local level, GIS can be an effective tool. The Working Paper will also demonstrate how the SWAT model can be set up using the available data and illustrate the possibilities it presents in contributing essential hydrological information to the decision-making process.

In this paper GIS was used to analyse and document the overexploitation of groundwater in a revenue village (i.e., an administrative unit comprising of four villages) located in Andhra Pradesh, India. The outputs from the analysis show that the number and depth of agriculture wells has increased dramatically over the last three decades and that this trend has impacted negatively on domestic water supplies. The study demonstrates that GIS, and more specifically open-source GIS, can be an effective tool:

1) for analysing the severity of water scarcity and its impacts on local communities, and
2) for planning possible interventions for improving groundwater recharge and management decisions aimed at reducing groundwater overdraft.

Additionally, the SWAT model was set-up for a catchment in the revenue village to demonstrate the possibility of using this model to estimate components of water balance, such as run-off, and groundwater recharge. Knowledge of these components is essential for effective water management.

1 Introduction

1.1 Water scarcity and groundwater dependence

Large areas of rural India, particularly in semi-arid regions, are suffering from increasingly severe water scarcity. Rapid population growth, higher demand for water from urban areas and climate change are all exacerbating the problem (Bates, et al., 2008; FAO, 2012). As a result many rural households receive less than the 40 litres per capita of safe water per day recommended by the World Health Organisation (WHO, 1998), a situation that leads to significant social, economic and health related problems (Hunter, et al., 2010). Delivery of sufficient water to households in rural areas is essential for improving and maintaining livelihoods and standards of living, however, as water scarcity becomes more severe, achieving sustainable and equitable water service delivery is becoming an increasingly challenging goal (WHO, 2012). As a consequence of the above, the World Economic Forum identified a water supply crisis as the second most severe risk facing the world at the present time (WEF, 2013).

In most parts of semi-arid rural India, surface water resources, which are often seasonal and limited, are now fully exploited (i.e., basins are classified as being "closed' except in years with exceptionally high rainfall). Highly variable rainfall and frequent droughts, often influenced by monsoons and climate change, mean that surface water resources are unreliable and varies considerably from season to season and year to year (Kumar, et al., 2011). This fluctuation means that groundwater has become the primary source of water in many rural areas, both for agricultural and domestic use (WB, 2010). Groundwater extraction is made more attractive by the fact that the Indian government heavily subsidises electricity for pumps (Shah, 2012). The World Bank projected that as of 2012, groundwater would account for 65% of India's irrigated water use and 85% of drinking water supplies. This increased use of groundwater has greatly benefitted the rural population as it has enabled them to significantly increase their agricultural productivity and profitability (Shah, 2007). It is for these reasons, that subsidising groundwater is seen as an effective method of poverty reduction and for promoting rural development (Glendenning and Vervoort, 2011). In fact the development of groundwater resources has been so successful that groundwater is now the foundation to the economic prosperity of many rural water-scarce regions (Namara, et al., 2010; Wijnen, et al., 2012).

The negative consequences of widespread and unregulated use of subsidised groundwater have been the severe overexploitation of the groundwater resource and dramatic falls in groundwater levels (WB, 2010). The low cost of extracting groundwater has led to the profligate use of water, poor water productivity, lack of incentives to maintain water infrastructure and a widespread failure to allocate water to the highest value uses (Shah et al., 2008). In many places poor and inadequate management has led to intensive competition for groundwater where the beneficiaries are most likely to be households who are willing and able to construct and/or deepen wells. This means that poor and marginal farmers are at a disadvantage when trying to access groundwater, partly because their land is located in areas with unfavourable hydrogeological conditions (e.g., interfluve areas) or because they cannot afford to deepen their wells (Kumar et al., 2011). This 'arms race' of accessing groundwater has led to increased inequality in rural areas with some farmers growing rich through groundwater use while many others grow poorer as their traditional water sources dry up (Reddy, 2005). Areas underlain by crystalline basement geologies, complex hydrology or variations in groundwater levels over very short distances mean that luck plays a large role in whether farmers are successful in accessing groundwater (Kumar et al., 2011). In response to increasing water scarcity and groundwater competition, small and marginal farmers frequently invest substantial amounts of money in drilling borewells - many of which fail immediately or after a very short time. These failures leave farmers with debts they cannot afford to repay which has contributed to a very high rate of suicide among farmers in rural India (The Economist, 2010).

In many areas, the overexploitation of groundwater for agricultural use has significantly impacted drinking and domestic water supplies (Molden et al., 2007). Despite the fact that significant money has been invested in projects and schemes to improve services, water supply systems in rural areas of India remain unreliable and in reality much of the money that is spent on improving domestic water supply actually results in more intensive agricultural water use. Many households do not have piped water so rely on handpumps and public standposts for their water supply, increasing the time spent by households on collecting water (Rajeshwara Rao et al., 2010). Although some villages are part of multi-village water supply schemes or major state schemes, the majority rely only on local sources: predominantly groundwater. This piecemeal approach to water supply provision means that some areas and villages are particularly hard hit by increasing water scarcity. Areas that have low yielding aquifers are especially affected.

1.2 Water harvesting structures

The construction of Water Harvesting Structures (WHS) is one of the main responses to water scarcity and groundwater depletion within catchments. WHS are a major part of watershed development in India and are increasingly seen as essential for ensuring the sustainability of local groundwater use (Garg et al., 2012). They include structures such as check dams, infiltration tanks and contour bunds - all of which aim to slow down and capture runoff and increase groundwater recharge (Glendenning et al., 2012). The effectiveness of WHS in a catchment depends on three main factors: the efficiency of groundwater recharge; the storage capacity of the underlying aquifers; and the dynamic interactions between surface water and groundwater (Kumar et al., 2008). Understanding these three factors is essential when using WHS effectively within a catchment, but the nature and magnitude of these factors can vary considerably. Even in areas that have poor groundwater recharge efficiency and low aquifer storage capacity, WHS, are being used as the main interventions and for every WHS built within a catchment the marginal benefit decreases to a point where building extra structures makes absolutely no difference to groundwater recharge rates (Glendenning and Vervoort, 2011). Because there is poor planning and coordination, it is often the case that there are many more WHS constructed than are needed within a catchment (Kumar et al., 2008). It is therefore important to be able to estimate the appropriate number of WHS required to maximise groundwater recharge and avoid the construction of structures that are effectively delivering no benefits.

For many years the negative impacts of WHS construction were either unaccounted for or ignored (Glendenning and Vervoort, 2010). In many cases, the fragmented approach to water supply provision in rural areas means that little consideration has been given to the potentially severe impact WHS may have on water availability downstream. On the other hand it has been suggested that the building of WHS can have a positive aspect as it results in a reduction of sediment loads and an improvement in water quality (Garg et al., 2012). Generally though neither the positive or negative impacts of rainwater harvesting (RWH) are evenly distributed; often one part of the catchment can benefit through increased groundwater availability while another suffers due to receiving less runoff. This means that the construction of WHS can actually increase inequalities within catchments (Kumar et al., 2008). It can be argued that the widespread construction of RWH structures in India has been a hasty reaction to the problem of water scarcity characterised by a lack of hydrological and economic planning (Kumar et al., 2006).

Despite the widespread belief in the benefits of constructing WHS, evidence to support their local benefits is relatively limited, partly because recharge rates are so difficult to measure (Glendenning et al., 2012). Evidence also suggests that even at local level the efficiency of WHS can be poor, especially in hard rock regions such as Andhra Pradesh (Kumar et al., 2011). This is because aquifers in these areas generally have low storage capacity and during the wet season are often fully replenished by natural recharge even in the absence of WHS (Kumar et al., 2008).

1.3 Decision making and GIS

Decision making in regards to water management in semi-arid rural areas is complicated by the fact that the many different actors have a range of different agricultural, social, economic and environmental goals (Kaur, et al., 2003). Furthermore, multiple factors such as borewell construction, construction of WHS, population and economic growth, aquifer characteristics, climate change and natural climate variability influence the severity of water scarcity across rural areas. It is important that decision makers are provided with accessible and accurate information which can be easily used to inform the decision-making process. This information can be influential in planning successful interventions and making correct management choices to ultimately improve the levels of services received by poorer households.

Geographical Information Systems (GIS) is a tool that is used in a wide variety of sectors around the world, and is increasingly becoming indispensable for many businesses and organisations. GIS can be defined simply as software that allows a user to view, store, manipulate and analyse spatial data. GIS is already widely used in the development sector and for water management and there is now much greater awareness of the importance that the spatial dimension has to the majority of decision-making processes and in the role that GIS can play in providing spatial information.

GIS has a number of key characteristics that makes it an invaluable tool. Probably the most important is that it explicitly presents spatial information on maps in a way that is quick and easy to understand. It provides assistance in a range of different areas including data collection, data management and data analysis, and by representing data spatially, it provides information and insights that cannot be provided by more traditional tools such as spreadsheets. This is important because many aspects of water scarcity have an intrinsic spatial dimension, as demonstrated by fact that groundwater recharge rates and availability vary spatially over small distances. A tool that can explicitly account for this uneven spatial distribution and provide information about it is invaluable for decision makers and should ultimately lead to interventions that could potentially reduce the impacts of water scarcity.

As the number of software options has increased over the last decade the GIS landscape has changed significantly. In particular there has been a large increase in the number of open-source products available, and in the number of organisations and people using them. The power and functionality of open-source GIS tools mean that they are now viable alternatives to the more established proprietary software (Chen et al., 2010; Steiniger and Bocher, 2009). Another development is the rapid improvement of smartphones and tablets that makes it increasingly easy to use GIS on the go, presenting exciting possibilities for data collection and real-time monitoring of water services. These options mean that it can be easier for organisations to find GIS software and hardware to suit their specific needs and resources. It is also now possible to build complex spatial data infrastructure using open-source software that can play a central role in managing water scarcity (Steiniger and Hunter, 2012).

1.4 Hydrological modelling

A significant problem of water scarcity and groundwater depletion is that it is difficult to formulate effective policies while there are still numerous gaps in the knowledge of hydrological process and how different management choices will impact upon these processes (Pavelic et al., 2012). For example, quantifying the availability of water using water accounting methods is still an imprecise science and as yet there is no universal framework that can be applied to quantify water resources in any location (FAO, 2012). Much of this uncertainty is owing to the complex nature of hydrological systems and the many difficulties in accurately measuring the different components of these systems (Beven, 2012). Hydrological modelling can provide insights into the local water balance and how different management decisions and/or climate change impacts patterns of water availability and use. Many models now incorporate GIS into their structure, primarily because GIS allows a model to explicitly account for the spatial dimension of any problem. GIS is also an effective way of combining many datasets that are often of a spatial nature, such as topography, precipitation and land use. Finally, GIS can act both as a relatively intuitive interface for the model and as a tool for producing graphical outputs that are effective at communicating model outputs.

One widely-used hydrological model is the Soil and Water Assessment Tool (SWAT). SWAT is a physical semi-distributed model that runs on a daily time-step and simulates the major hydrological processes and water balance components of a model catchment (Arnold et al., 1998). SWAT is able to simulate surface and subsurface flow, sediment generation and deposition and nutrient movement and fate (Srinivasan et al., 2010). SWAT copes relatively well with three of the major challenges faced by hydrological modelling: the complexity of the natural system; the spatial heterogeneity of catchment characteristics and lack of suitable data (Gassman et al., 2007). By using GIS as a means of assembling and inputting data, SWAT is able to capture some of the spatial heterogeneity of catchments and utilise satellite data for many of the required model inputs. SWAT has gained worldwide acceptance as a model that can be applied to a wide range of hydrological conditions at various scales, and as a result there are now over 1000 published peer-reviewed articles on the model (Douglas-Mankin, Srinivasan and Arnold, 2010).

The SWAT model is a result of nearly 30 years of continuous research by the United States Department of Agriculture: Agricultural Research Service (Gassman et al., 2007). Its development has been driven by the need to assess the impact of climate change and land-use on water resources, and a need to assess which management strategies can help mitigate resulting problems (Gassman et al., 2007). It can therefore be used to quantify existing water uses and shortages and to predict how these will be altered by different impacts spatially across catchments; allowing interventions to be better targeted (Gosain et al., 2005, Douglas-Mankin, Srinivasan and Arnold, 2010).

The model has been widely applied in India for a number of different purposes, including the impact of WHS in rural catchments (e.g., Garg et al., 2012; Glendenning and Vervoort, 2011); the potential impacts of climate change (Gosain, Rao and Arora, 2011); and problems linked to sedimentation and pollution (Tripathi, Panda and Raghuwanshi, 2003). One major advantage of SWAT is that it can be applied to ungauged catchments and run without calibration, although in the majority of published studies there is at least an attempt to calibrate the model because, without it, it is difficult to apply model results to any management decisions due to the uncertainty inherent in the outputs (Srinivasan, Zhang and Arnold, 2010).

2 Methodology

2.1 Study area

The study area is the revenue village of Ungaranigundla in Dhone Mandal within the state of Andhra Pradesh, India (as shown in figure 1). A revenue village in India is a small administrative unit with defined borders normally consisting of a small number of villages and hamlets. Ungaranigundla was chosen by WASHCost as a location for a pilot study with the primary aim to collect and analyse a range of data for planning and budgeting improvements to local water, sanitation and hygiene (WASH) services provision. This was to build on earlier work carried out by WASHCost in other villages in Andhra Pradesh. One of the reasons for the pilot study was that it would focus on an entire revenue village and its surrounding agricultural areas rather than individual, isolated villages as was previously the case. It would also build on an earlier study in this revenue village which was conducted by the Andhra Pradesh Rural Livelihoods Program (APRLP) in 2003 (Rama Mohan Rao et al., 2003).

Ungaranigundla revenue village has a total area of approximately 25km2 and comprises of four villages containing 1087 households. It is situated in a semi-arid area with average annual rainfall of 587mm, but because of the monsoon rainfall, this is highly variable and unevenly distributed throughout the year. Consequently, groundwater is a vital source of water for both agricultural and domestic uses. The soil of the district is predominately inceptisols with areas of entisols and alfisols, while the underlying geology is crystalline basement (Rama Mohan Rao et al., 2003). The average elevation of the district is 430 metres with a maximum of 533 metres and a minimum of 385 metres. Figure 1 shows the land cover within the revenue village, with the dominant land use being single-crop agriculture which accounts for 60% of the total area and is predominantly rainfed. Double-crop irrigated agriculture accounts for 8% of the total area, although this fluctuates year on year depending on water availability. Other significant land uses within the village district include scrub forest/land (16% of total area) and plantation which is mainly mango trees (11% of total area), and scrub forest.

Figure 1 Map showing typical land uses in Ungaranigundla including mango plantations

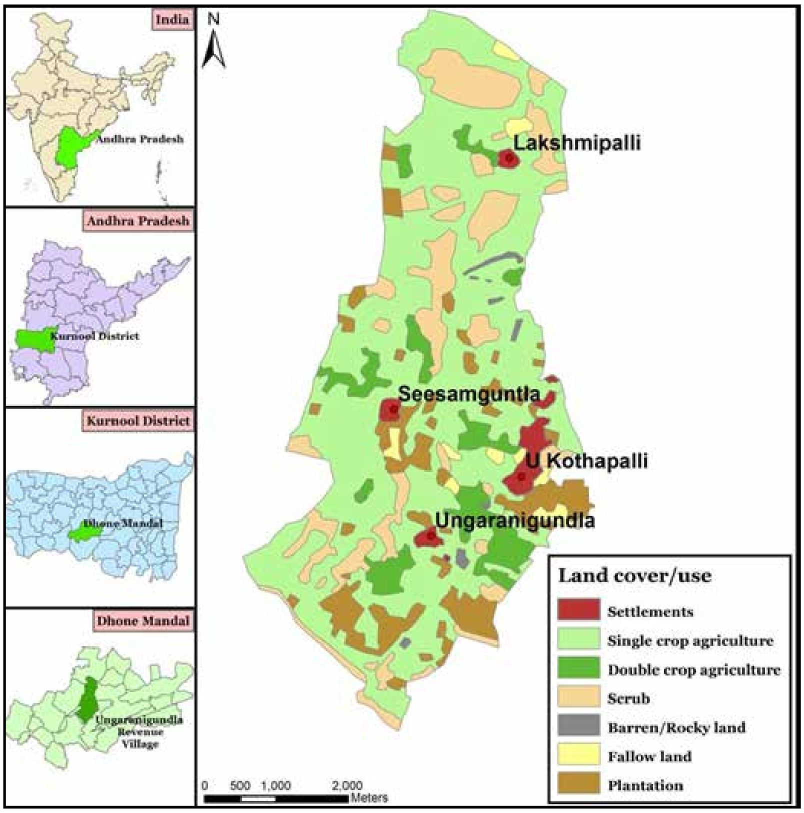


Figure 2 Map showing Ungaranigundla and local area

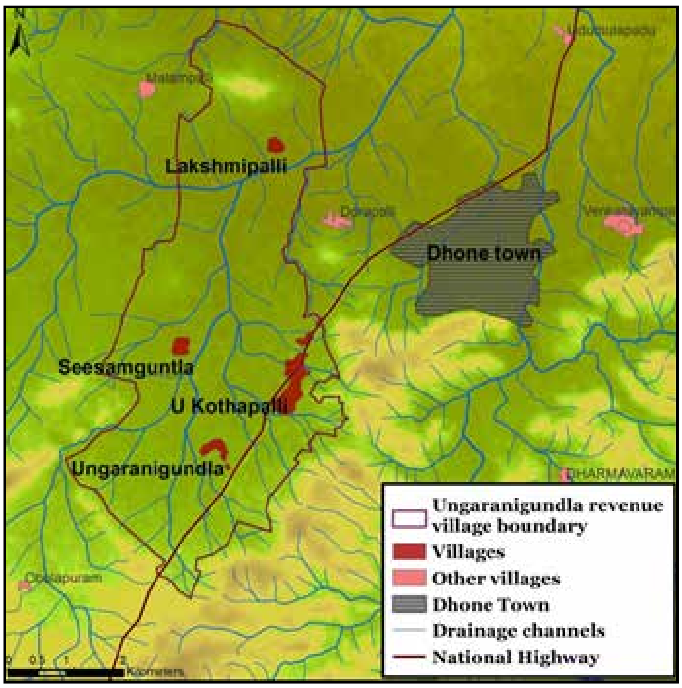


Figure 2 shows the terrain and some of the major features within the revenue village and surrounding areas. The southern part of the revenue village is surrounded by hills with a number of drainage channels flowing off these hills and through the revenue village. This means that a number of subcatchments are located almost entirely within the revenue village. Figure 2 also shows that a national highway, connecting Hyderabad and Bengaluru, bisects the revenue village. There are a number of businesses and industrial compounds, including a quarry, located along the highway. Dhone town, capital of Dhone Mandal, is located a short distance outside the revenue village (figure 2). Dhone is a rapidly expanding town of more than 60,000 inhabitants and has a major railway junction. Its close proximity to the revenue village means that Dhone has a large influence, both in terms of water resources and a range of other issues.

2.2 Data collection

In early 2012 the WASHCost project collected a large amount of socio-economic and physical data from the revenue village area. Data collection activities involved the active participation of the Gram Panchayat (local self-governments) and members of the local community. Each household was surveyed about a range of socio-economic information including which WASH services each household receives. Each village was also mapped using a total station to capture the location of all houses, other buildings and infrastructure, including that of water supply and sanitation. Additionally, a survey team mapped the location of all wells and water harvesting structures (WHS) within the district using a handheld GPS device. Detailed information was collected from the owners of each well and WHS including dates of construction, costs of construction, depth of well, number of acres irrigated and current status (i.e., working/ not working). The bulk of well and WHS surveying was conducted by members of the local community. This proved to be invaluable as it made locating wells, finding the well owners and getting the information a much quicker and more efficient process than it might otherwise have been. This meant that if a well owner could not be found during the day, a member of the survey team could speak to him in the evening and collect all the necessary information. This illustrated the advantages of participatory GIS and of involving the local community in the mapping process. Land use, or cover maps, of the district were created through the supervised classification of satellite data. Finally, consultation workshops were held with representatives from each village in the district so that the water supply problems of each village could be highlighted and potential solutions proposed. In these meetings, Participatory Rural Assessment (PRA) maps were used to help visualise the water supply and sanitation problems of their villages (shown in figure 4).

Figure 3 **Photo showing a mango plantation near Ungaranigundla village**

2.3 GIS

The purpose of the GIS analysis was to obtain a good understanding of the spatial variability in WASH services, to assess the status of water supply infrastructure within the village area and to identify areas that were under particular pressure from water scarcity. This was achieved by mapping WASH services and the type, status and distribution of water points. Given that competition for water between agricultural and domestic users is recognised to be a major problem in this area, the concentration of agricultural wells was mapped using the heat map function within QGIS software[1]. The increase in the number of wells over time was also analysed by producing and inspecting a time-series of maps. The change in the depth and type of well that were constructed over the time period was also assessed. The purpose of the GIS analysis was to also demonstrate the feasibility of using QGIS as an alternative to more expensive commercial GIS software.

Figure 4 Photo showing village consultation meeting and use of PRA map

2.4 SWAT model setup

MWSWAT[2] 2009 was used to model the hydrology of the revenue village. MWSWAT was developed by the United Nations University to provide developing countries with a tool for predictive modelling and decision support within catchments (George et al, 2007). Prior to the development of MWSWAT the only interface available for the SWAT model used ESRI's ArcGIS software. ArcSWAT is still the used by the majority of studies, however, the relatively high cost of ArcGIS software and the ArcGIS extension needed to run SWAT, makes it unaffordable for many organisations. The high cost of software has previously constrained the use of hydrological models and GIS particularly in developing countries (Chen et al., 2010). The free and open-source nature of MWSWAT helps to remove these barriers. In theory, this makes MWSWAT a good choice of model for this study.

The first issue with running the SWAT model for the revenue village was that the administrative boundaries of the village did not match up with the hydrological boundaries of the local catchments. It was necessary to either run the SWAT model multiple times for subcatchments that had the majority of their area located within the revenue village, or to run SWAT for a single larger catchment including a significant area outside the village boundary. The decision was made to run the model for the larger area because the resolution of the available data made modelling

[1] QGIS is an open-source GIS package that can be downloaded free-of-charge from www.qgis.org

[2] MWSWAT 2009 is open-source and can be freely downloaded from www.waterbase.org. MWSWAT uses the open-source MapWindow GIS as its interface, which is also freely available and can be downloaded from www.mapwindow.org (George and Leon, 2007).

the smaller subcatchments unfeasible. The most convenient way of delineating a larger catchment was to omit the northern portion of the revenue village area and the village of Lakshmipalli. As Lakshmipalli was the smallest village of the four, and slightly isolated from the rest, it was decided that omitting it was best option. Including Lakshmipalli within the model would have meant modelling a much larger catchment, of which the majority was outside the revenue village boundaries. Compared with the southern portion of the revenue village, the area around Lakshmipalli also had a much lower density of wells and WHS. Figure 5 shows the relation between the revenue village area and the catchment being modelled.

To successfully setup the SWAT model, additional data was needed beyond that collected by the WASHCost project. A 30 metre resolution Global Digital Elevation Model (ASTER GDEM) and FAO soil data in raster format were obtained for the area of interest[3] . Finally, daily rainfall data from 1996 to 2004 was obtained from the Government of Andhra Pradesh for the Indian Meteorological Department rain gauge situated near to Dhone Town, approximately 2 kilometres outside the boundary of the revenue village area.

MWSWAT structures the setup and running of SWAT into a number of steps. The first step is delineating the watershed. In this study, this was done using the ASTER DEM and a shapefile map of the drainage network which had been digitised from a topographic map of the local area. The drainage network was burned into the DEM so that the existing stream network was mirrored as closely as possible within the SWAT model and a masking shapefile was used to limit the area being processed. This reduced the time taken for the model to run this step. The drainage network was generated using an area threshold value of one square kilometre. This value was chosen because the smaller the value that was used, the more the delineated stream network diverged from the actual stream network as observed during field visits to Ungaranigundla. This was owing to the increasing inaccuracy of the DEM when trying

Figure 5 **Map showing relationship between the revenue village area the SWAT catchment**

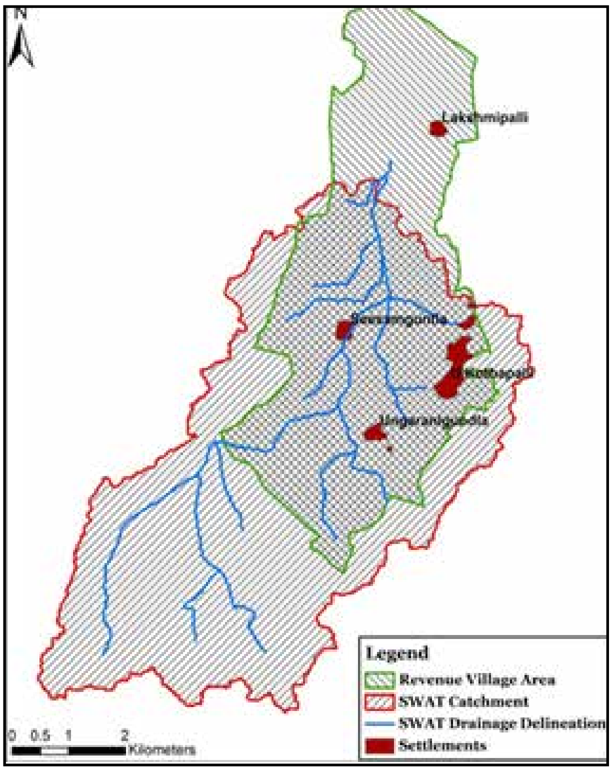
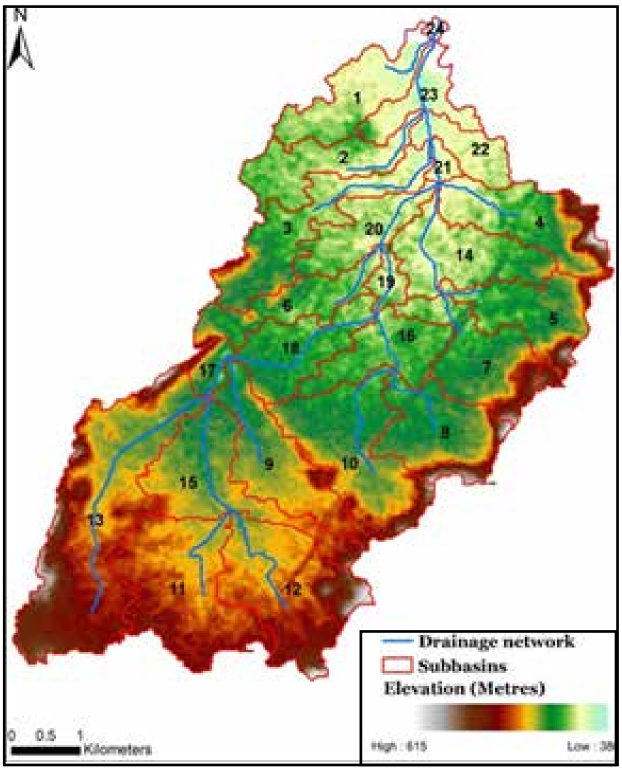


Figure 6 **Map of the SWAT catchment showing numbered Sub-basins and the drainage network**



[3]ASTER GDEM downloaded from http://gdem.ersdac.jspacesystems.or.jp/search.jsp.FAO soil data map downloaded from www.waterbase.org.

to delineate the smaller drainage channels. Because both the delineation of stream networks and the identification of sub-basins within the SWAT model are extremely sensitive to the spatial resolution of the data (Arabi et al., 2006), smaller threshold values resulted in many irregularly shaped sub-basins being created at the next step. At the threshold level chosen, the SWAT model produced 24 sub-basins (figure 6) along with the delineated drainage channels and the DEM.

The next step using the MWSWAT model is the creation of hydrological response units (HRUS). In this study, the land use and soil data was selected first. Both of these had been clipped to the required size and the land cover map reclassified to represent the global land cover classes used in SWAT. The soil that was downloaded was classified into FAO soil classes. The slope gradient percentage generated from the DEM was split into two classes of above and below 10%. Once the two datasets had been loaded and the slope classified, MWSWAT was used to create HRUS: For the purpose of this study, the 'Multiple HRU' option was used which allows the user to exclude smaller areas of land use, soil and slope by setting area percentage. The areas that fall below the threshold are distributed evenly among the remaining classes. The land use threshold was set at 20%, the soil threshold at 10% and the slope threshold at 5%. With these inputs MWSWAT created 140 HRUs within the 24 sub-basins.

The next MWSWAT step is to setup and run the model. At this stage the period of model simulation needs to be defined and the sources of weather data identified. The SWAT model needs five daily weather inputs with which to calculate the hydrologic response of the catchment. These are precipitation, minimum and maximum temperature, relative humidity, solar radiation and wind speed. In most studies precipitation and temperature are measured values from local weather stations, while the daily values for relative humidity, solar radiation and wind speed are simulated using a weather generator within the model. This is because the final three variables are not widely collected and the nearest weather station that monitors these variables is often hundreds of miles outside the modelled catchment. The weather generator takes the average monthly data for each of these variables and uses it to generate daily values (Arnold et al., 2008). The weather generator also simulates inputs for days where data is missing for the other inputs. All the data acquired from the local weather station was formatted in a text file so that it could be inputted into the model. Additionally, a gridded weather dataset of one degree grid squares, produced by the India Meteorological Department, was downloaded from the SWAT website from which the minimum and maximum daily temperature data was extracted for the study area. Data for the weather generator file, also in one degree grid squares, was also downloaded from the SWAT website. At this stage there were a number of different options to choose from when running the model. The curve number method (USDA-SCS, 1986) was chosen for calculating runoff; the Penman-Monteith method (Monteith, 1965) was chosen for calculating potential evapotranspiration, and the variable storage method was chosen as the channel routing mechanism. The model was set to run from 1 January 1996 to the 31 December 2004 with a monthly printout interval.

The final stage of MWSWAT is the visualisation of the model outputs. At this step shapefiles can be created for model data outputs for both the sub-basins and channel reaches in each sub-basin. The data for these shapefiles can be summarised in a number of ways including annual averages, monthly averages, maximum values or minimum values. In addition to visualizing SWAT outputs using the MWSWAT model, the outputs can be accessed directly within the text files that are produced by each model run. Another option for analysing the data is the SWATPlot application, which like MWSWAT is open source and freely downloadable from www.waterbase.com. SWATPlot can access model outputs for specific sub-basins and write the data to a common delineated file which can be used for further analysis of the data. SWATPlot represents a much more efficient way of accessing the required data than the text file outputs. At this stage calibration of the model should occur but owing to lack of observed stream flow this was not possible for this study. Full details of both inputs and outputs of the SWAT model can be found in the theoretical documentation (Neitsch et al., 2011).

3 Analysis

3.1 GIS analysis

Figure 7 **Map showing well location and type**

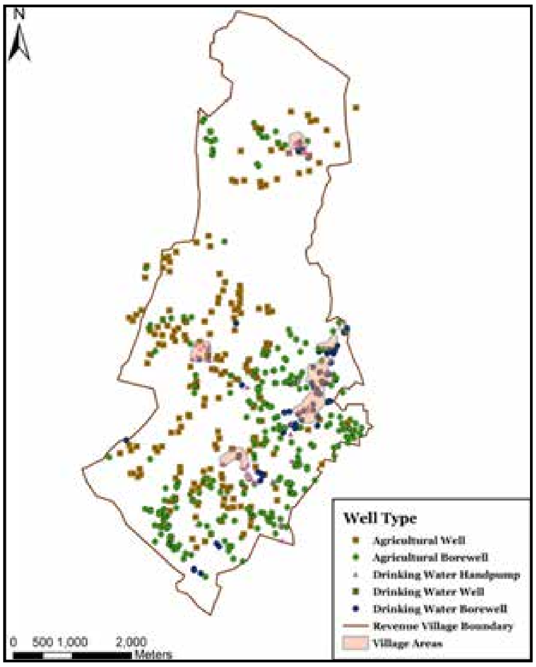


Figure 8 **Map showing well density**

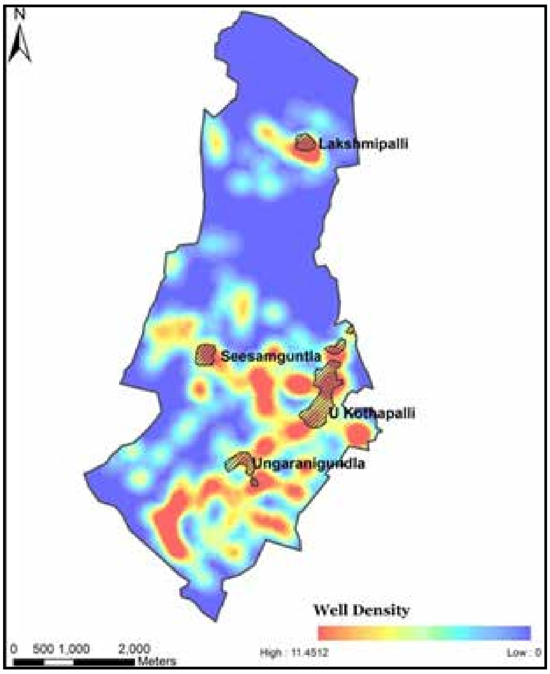


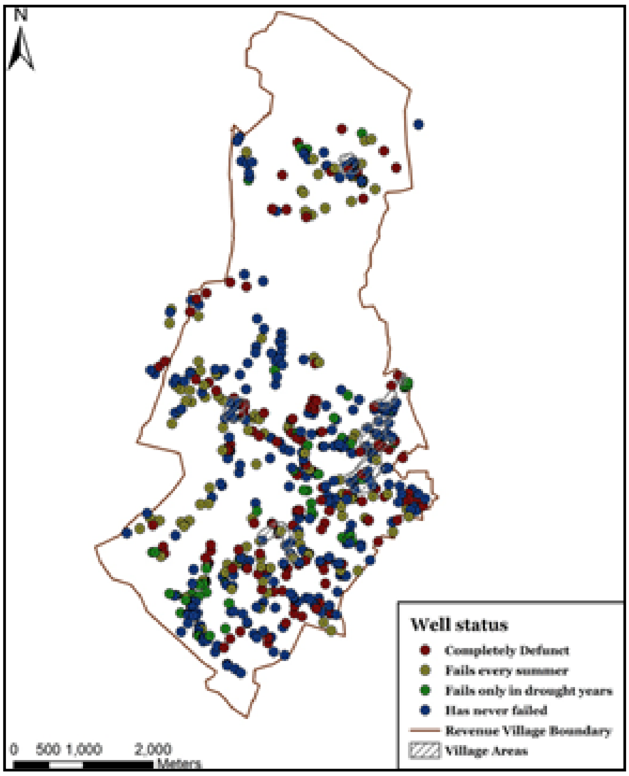
Figure 7 shows all the mapped wells located within Ungaranigundla revenue village. It shows that the concentration of wells is extremely high especially in the south of the revenue village around the villages of U Kothapalli, Seesamguntla and Ungaranigundla. There are a total of 579 wells with a well density for the entire area of approximately 24 per square kilometre. However, well density is much higher to the south of the revenue village where the concentration of wells rises to 32 wells per square kilometre. The gap between the wells surrounding the southern three villages and the wells surrounding Lakshmipalli village is partly owing to the fact that land and wells in this area are owned by farmers from villages outside the revenue village, particularly Dorapalli and Dhone Town, and were not mapped. Therefore, well density within the revenue village is actually somewhat higher than shown in figure 7. Looking at well location in relation to the land use, (figure 1), reveals interesting, if somewhat predictable results. Well density is lowest in areas of scrub where it is 11 per square kilometre. For agricultural land, well density is 19 per square kilometre for single crop agriculture, 31 per square kilometre for plantations and 33 per square kilometre for double crop agriculture. This reflects the differing water requirements of those land uses. Within settlements, well density is predictably much higher at 55 per square kilometre.

Figure 8 shows the concentration of wells mapped using a heatmap function within QGIS. Heat maps are a commonly used tool for analysing point data. The value for each point is based on the number of wells within a 250 metre radius with a weighting factor of 0.1. This weighting factor means that wells furthest from the centre have relatively less weight in the calculation of that value than wells closer to the centre[4]. Figure 8 shows the high well density in the immediate vicinity of the three southern villages and in the agricultural land surrounding these villages. Wells in the agricultural areas tend to be concentrated along drainage channels.

[4]More information on use of the heatmap function can be found at: www.docs.qgis.org/html/en/docs/user_manual/plugins/plugins_heatmap.html

Inevitably not all of the wells are fully functional. Figure 9 shows the functionality of all the wells and shows that many are either completely defunct or fail regularly. Of the total, 24% of wells are completely defunct, 19% of wells fail every summer, 11% of wells fail in drought years and 46% have never failed. In other words despite the huge number of wells constructed in the area and the large amount of money invested, less than half of them still function properly. Figure 10 is a heatmap that shows the concentration of failed wells within the revenue village and that there are also significant concentrations in the surrounding agricultural areas. In fact the only area where there has been significant well development and no concentration of failed wells is in the south-west corner of the revenue village. It is notable that this area is upstream of much of the rest of the revenue village and potentially using groundwater before it reaches the downstream wells. Figure 11 is a heatmap showing the concentration of wells with a depth greater than 70 metres, and clearly shows that these deeper wells are heavily concentrated around the four villages. It is probable that some of these wells were necessary so as to secure drinking and domestic water supplies for the villages in the face of falling groundwater. There are now over 50 wells in the revenue village with a minimum depth of 100 metres and some as deep as 150 metres. The numerous failed wells (figure 9) and the concentration of deep wells round the villages (figure 11), illustrate the efforts required by the local population to secure reliable water supply in the face of rising water scarcity.

Figure 9 **Map showing functionality of wells in Ungaranigundla**



Although construction has taken place over many decades, the high density of wells in the revenue village is the result of a rapid increase in construction in recent years. Figure 12 shows a time series of maps that illustrate how the pace of construction has increased. Between 1980 and 2012 the number of wells with the revenue village area increased from 82 to 579. This is an increase of over 600% in less than 35 years. Between 1980-2000 well construction averaged four per year, rising to 24 per year between 2000-2006, and finally to 42 per year between 2006-2012. Figure 14 illustrates the extremely rapid development of groundwater resources within the catchment and the growing dependency of the revenue village on groundwater as its primary source. The figure also illustrates the growing water scarcity of the revenue village and the increase in the number of wells constructed to replace those that had failed or stopped functioning properly. The response to increasing water scarcity has been the construction of an ever increasing number of deeper wells in a desperate attempt to capture what groundwater remains.

Figure 10 **Heat map showing failed well density**

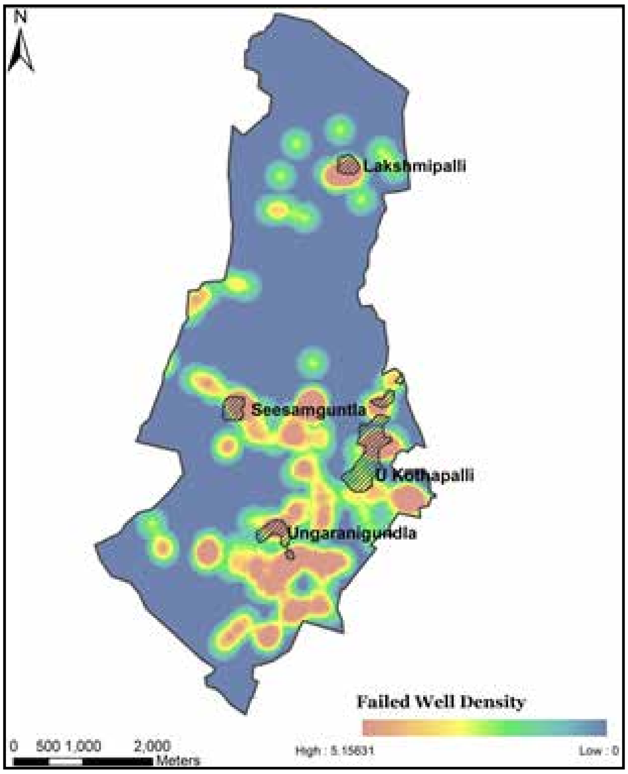
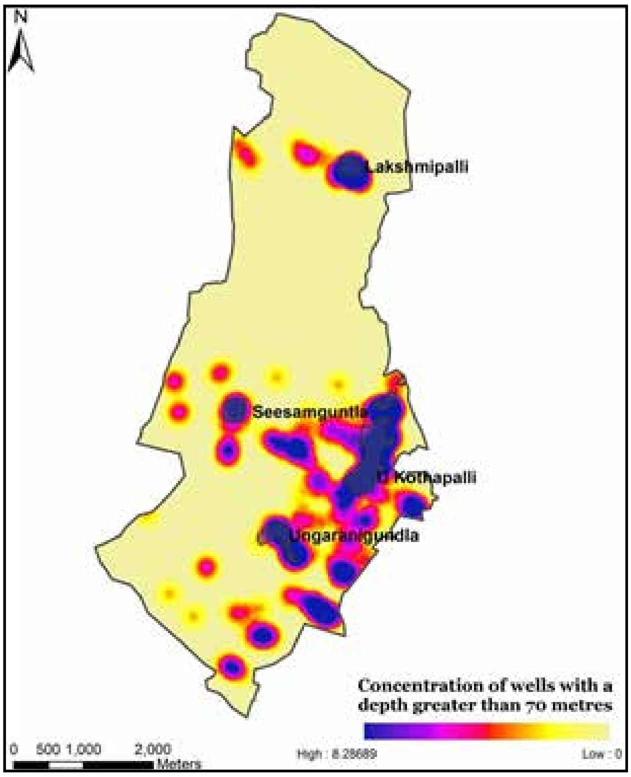


Figure 11 **Heat map showing density of wells over 70m deep**

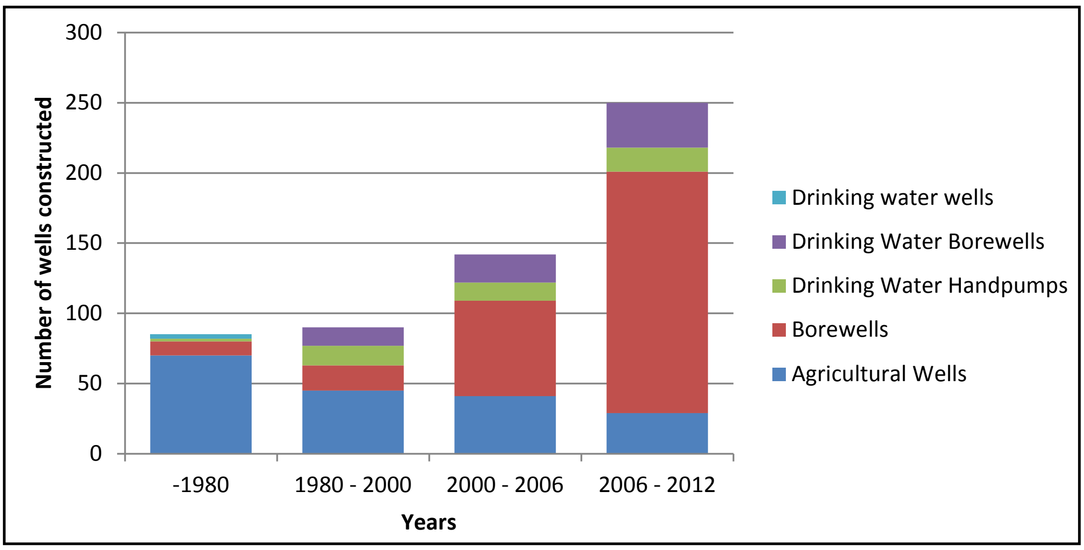


It is not just the pace of construction that has changed over the years. Figure 13 shows the type of wells being constructed has also changed over time. This trend has been necessary because traditional hand-dug wells are no longer a viable or preferred option. Up to 1980, 85% of wells constructed were agricultural wells (i.e., hand-dug open wells) while only 12% were agricultural borewells. Between 2000 and 2006, the percentage of agricultural wells constructed fell to 29% and the percentage of agricultural borewells constructed had risen to 46%. During 2006-2012, the percentage of agricultural wells built had fallen to just 12% while the percentage of agricultural borewells had risen even further to 85%. A final interesting trend (figure 13) is the increase in the construction of drinking water borewells. Between 1980-2000, 13 drinking water borewells were constructed, between 2000-2006, 20 were constructed and between 2006-2012, a total of 32 were constructed. This indicates that traditional drinking sources, such as hand dug wells, have failed because of the increase in groundwater extraction and the fall in groundwater levels.

The piped water supply for Ungaranigundla village is now supplied from three borewells situated two kilometres to south of the village (figure 15). One of these borewells is an agricultural borewell constructed in 2000 which now fails during most summers. To supplement this borewell two more were constructed: one in 2010 to a depth of 125 metres, and one in 2011 to a depth of 120 metres. It is notable that these borewells were dug upstream of the vast majority of agricultural borewells and that a new infiltration tank was constructed in an effort to increase recharge in their immediate vicinity. Figure 14 also shows that there are a number of handpumps in the village of Ungaranigundla of which the majority of ones working tend to be over 100 metres deep. Significant investment was needed to construct the three borewells, pump the water a significant distance to the village and construct a number of deeper handpumps closer to the village. Again this underlines the difficulties faced by the village in securing drinking water supplies in the face of rising water scarcity.

Figure 12 **Time series maps showing increase of wells in Ungaranigundla**

Figure 13 **Chart showing well type construction over time**



The depth of the wells has also changed over time. Figure 15 shows the average depth of wells constructed for the four time periods up to 2012. The wells constructed until 1980 had an average depth of only 9.9 metres. This is because prior to 1980 very few borewells had been constructed and surface water resources would have been less exploited. There would also have been less irrigation and more reliance on rainfed agriculture, and in all likelihood, little funds available to pay for borewell construction. The depth of wells would also have been limited by the fact that is only possible to constructed hand-dug open-wells to a certain depth. Between 1980-2000, the average depth of wells increased by 340% to 43.4 metres, mainly because of the large increase in the number of borewells being constructed and the associated draw down of groundwater levels. In the period 2006-2012, the average depth of constructed wells was 66.0 metres. In comparison to the previous period of 2000-2006, this is an increase in average depth of 28%. This indicates that not only the number of borewells, relative to other well types, increased but also the average depth of the borewells themselves. The increasing depth of wells has not resulted from a physical decrease in the amount of water but primarily due to a huge increase in demand for water, particularly for irrigation. Within the revenue village, extensive plantations of mango trees (figures 2 and 3) are using huge amounts of groundwater to the detriment of village supplies.

Figure 14 Map showing water supply infrastructure in Ungaranigundla village

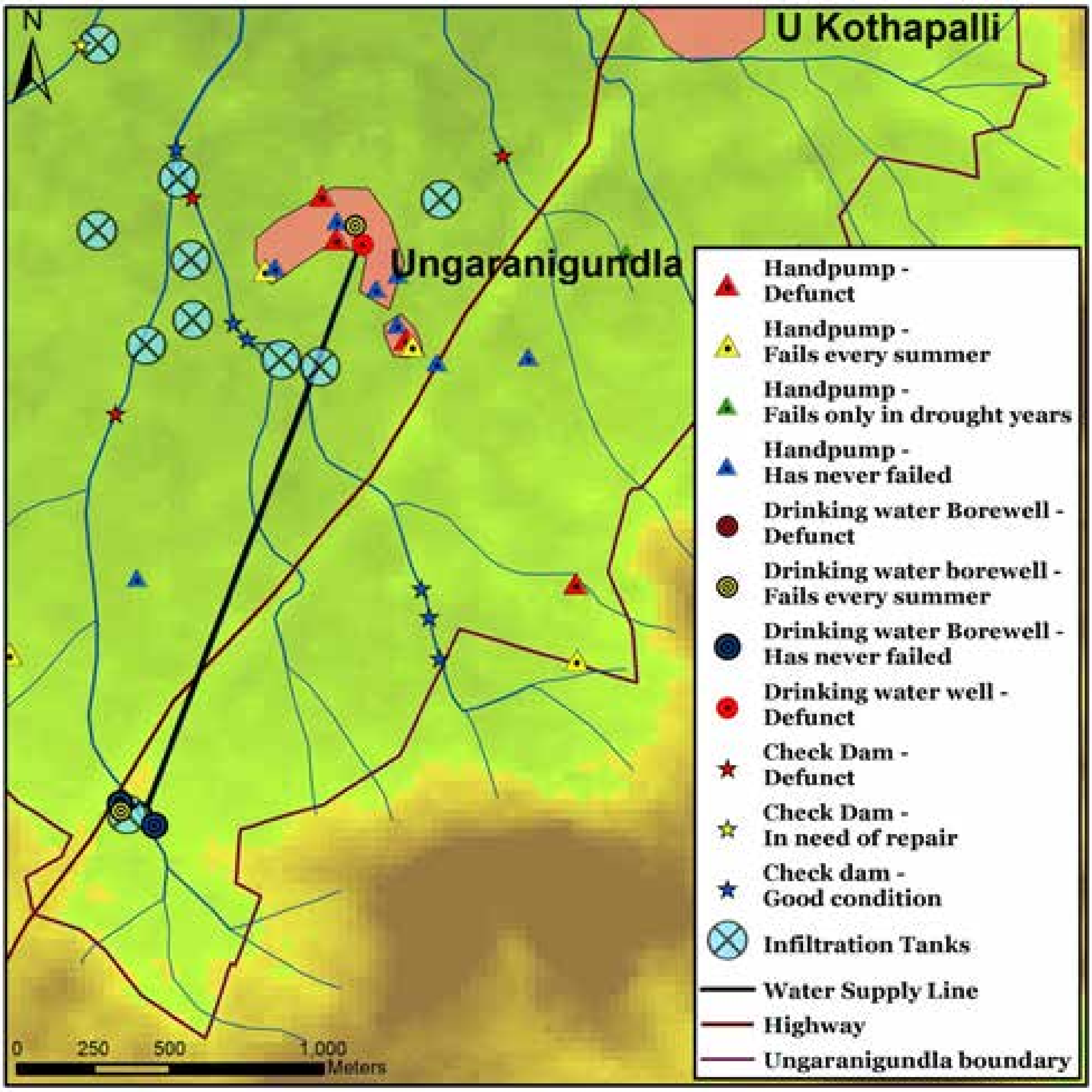
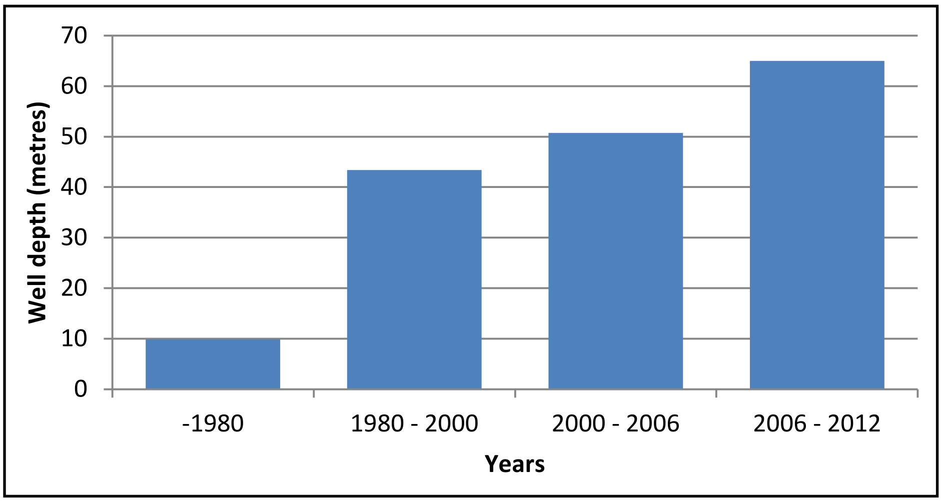


Figure 15 **Average depth of constructed wells over time**



The increase in the density, depth and number of wells illustrates the increasing pressure being put on water resources within the revenue village. One response to this has been the construction of a range of different WHS. Figure 16 shows the distribution and range of different WHS that have been constructed within the revenue village. These include 55 check dams, 42 infiltration tanks/farm ponds and six bunds spread extensively across the revenue village along drainage lines.

Figure 16 **Map showing WHS in Ungaranigundla**

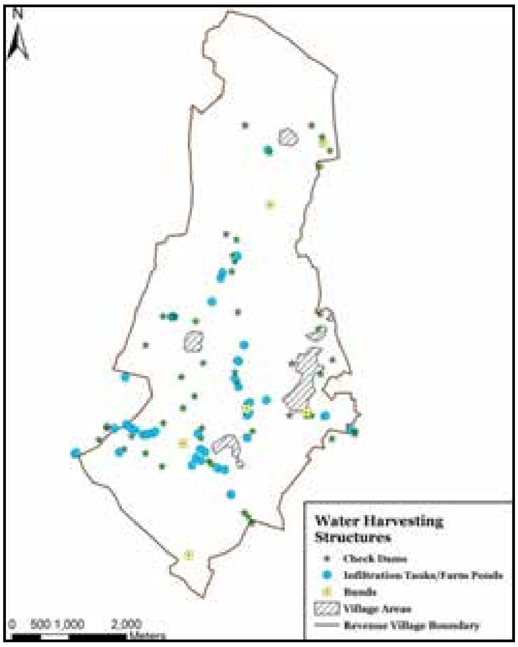


Figure 17 **Map showing status of WHS**

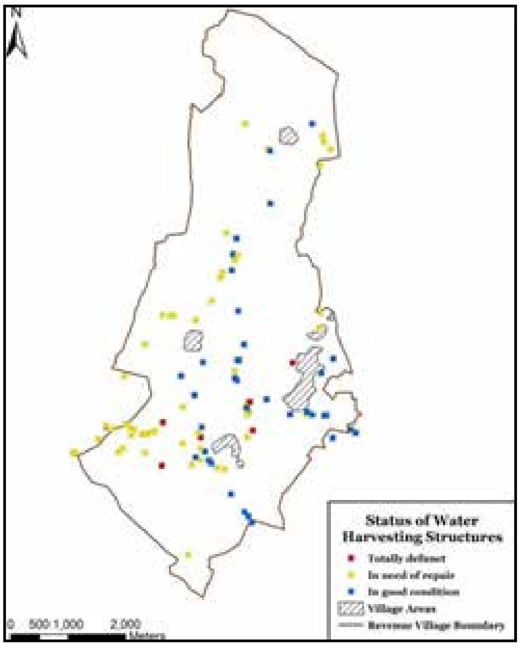


Figure 18 shows how these WHS have been constructed at different time periods, with the majority constructed after 2000. This coincided with the huge increase in the number of borewells and the increase in average depth of wells. Interestingly, the majority of check dams were constructed between 2000-2006 while the majority of infiltration tanks were constructed between 2006-2012. This suggests the possibility that by 2006 there were no more suitable locations for the construction of check dams so infiltration tanks were used in an effort to increase aquifer recharge, or ,alternatively, that a change in policies decided that it was better to invest available resources in the construction of infiltration tanks.

Figure 18 **WHS construction and type over time**

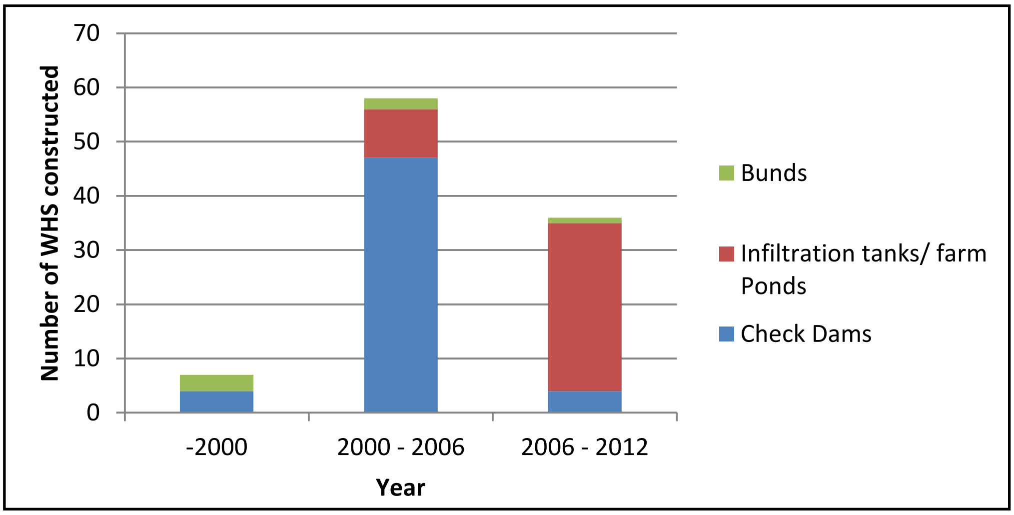
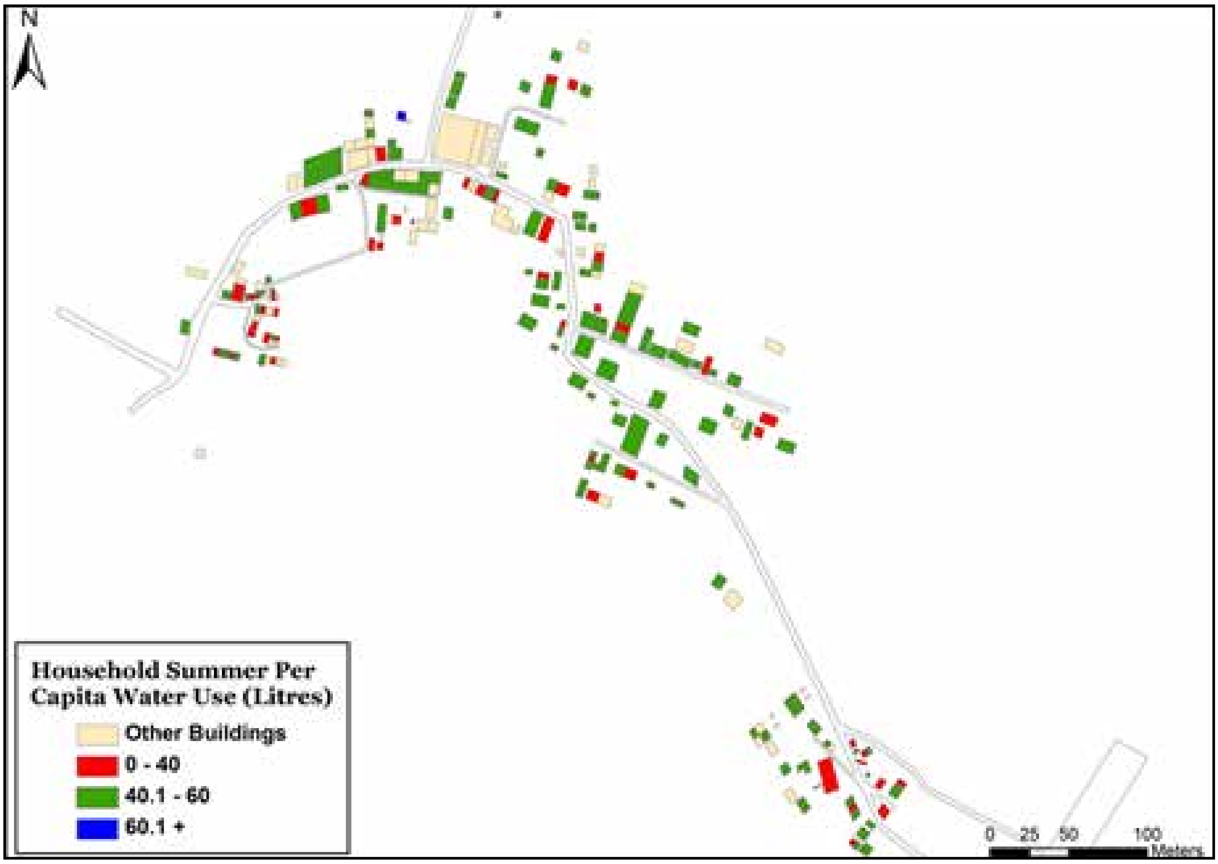


Figure 19 **Map of Ungaranigundla village showing household water use**



In total, approximately US$ 55,000 has been spent constructing water harvesting structures within the revenue village. However despite this significant investment figure 17 indicates that more than half of the WHS in the catchment are either completely defunct or are in need of repair. It is clear that the life cycle of water supply infrastructure is relatively short and little money is being invested in operation and maintenance. Instead, infrastructure is being replaced relatively frequently by new constructions.

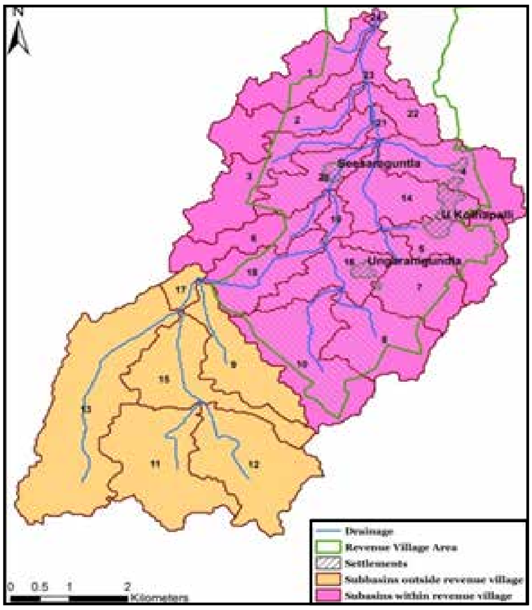
A final indication of the increasing water scarcity within the revenue village and of the impact that increased agricultural water use is having, is the amount of water being accessed for domestic use by the inhabitants of the four villages. During the summer, the daily water use for the average household per capita in the villageis 45 litres. However, as shown in Figure 19, a number of households are receiving less than the 40 litres per capita per day recommended by the UN. In total 39 households, more than one fifth of the village, receives less than this figure. This number is likely to be much higher in drought years and is likely to rise further as climate change, a rising population and an ever increasing demand from agricultural place even greater pressure on the available water resources.

Overall the 2012 assessment of water services in Ungaranigundla revenue village found that around 20% of households had water services that were less than government norms and that these households tended to be located in poorer areas of villages. The main problems reported in the village consultation meetings with inhabitants of Ungaranigundla included the failure of borewells, the failure of drinking water handpumps and generally a smaller amount of water available for all uses. The situation in Ungaranigundla village is replicated in the other three villages located within the revenue village. Other household data collected showed that households receiving less water are generally those with low income, low land ownership and from lower social/caste groups. Invariably, it is these households that suffer the most during dry years and periods of prolonged drought, and are at most risk from the increasing water scarcity. This series of maps produced by the GIS analysis present a clear picture of the increasing pressure being placed on water resources with the revenue village

3.2 SWAT analysis

As discussed in the methodology section, data limitations along with shortcomings in MWSWAT calibration procedures meant that it is only possible to have confidence in the annual values generated by MWSWAT simulations. It was necessary to collect more data to have confidence in simulations at finer temporal scales. Outputs from an eight year simulation included the following:

Figure 20 Map showing SWAT sub-basins inside and outside of the revenue village boundary



- Average annual rainfall for the period modelled by SWAT was 556mm, of which on average only 17mm or 3% of rainfall was surface runoff.
- The annual average for lateral flow contribution to streamflow was 83mm or 14% of average rainfall.
- The annual average aquifer recharge was 104mm or 19% of average rainfall.
- The average evapotranspiration from the catchment was 347mm or 62% of average annual rainfall
- The average total water yield accounting for all losses was 190mm or 34% of total annual rainfall

Figure 20 shows that 18 of the 24 sub-basins generated by SWAT are located predominantly within the boundaries of the revenue village, while the remaining six sub-basins are outside the boundaries and upstream of the revenue village. The main interests of the study centre on the SWAT outputs from these 18 sub-basins, although what happens in the other six sub-basins is also important because they contribute both streamflow and subsurface flow to the other sub-basins. Figure 21 shows the variation in evapotranspiration between the different sub-basins, from 334mm to 394mm. Figure 22 shows the average annual water yield of the sub-basins. This varies significantly from 141mm to 204mm and is highest in sub-basins 10 and four, both of which are close to areas of high well concentration.

A final output from SWAT is shown in figure 23, which displays the monthly groundwater percolation for sub-basin 10 for the entire eight year SWAT simulation. It shows that groundwater percolation only occurs for two to four months every year during the monsoon and that the total amount varies greatly between years. For example, in 1997 there is only 32mm of groundwater percolation over a four month period, while in 2002 groundwater percolation totals 148mm over a four month period. This is mainly due to inter-annual rainfall variability. During 1997 the total rainfall was 473mm while in 2002 total rainfall was 759mm. Again this demonstrates that water scarcity it not constant for the revenue village but varies from season to season and from year to year. In those years of low rainfall, groundwater recharge water scarcity is more severe and is likely to have much greater socio-economic impacts. As the SWAT outputs show, these impacts are likely to vary even at a local level within the revenue village because of the heterogeneity of hydrological processes.

Figure 21 **Average annual evapotranspiration for sub-basins**

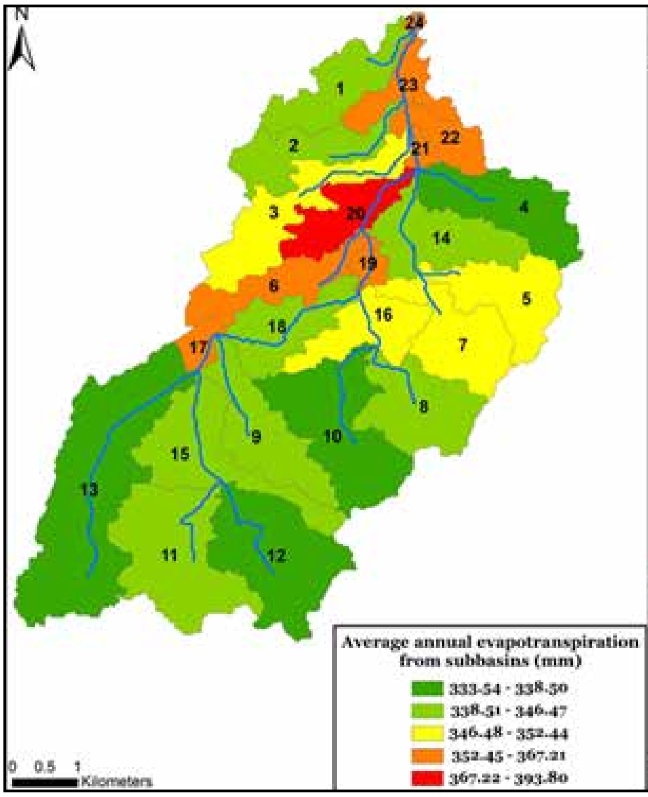


Figure 22 **Average annual water yield for sub-basins**

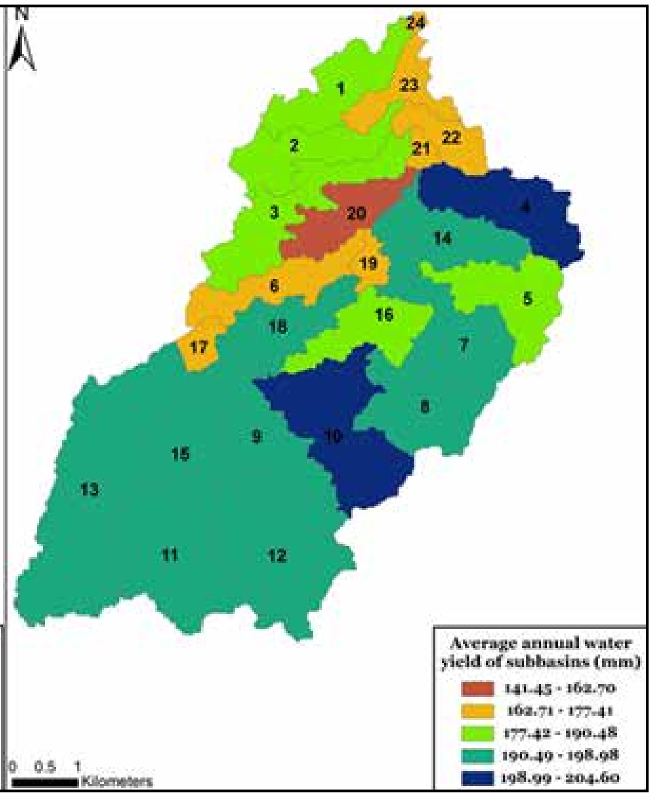
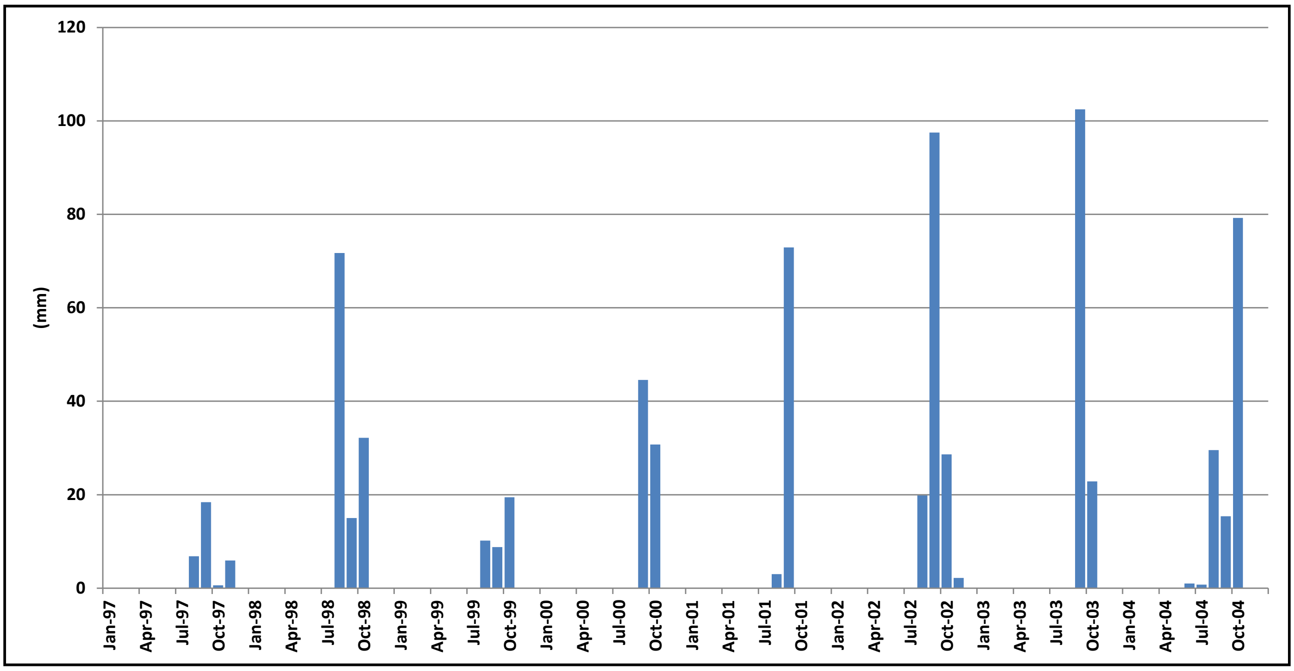


Figure 23 Monthly groundwater percolation for sub-basin 10, simulated by SWAT



4 Discussion

4.1 Water scarcity in Ungaranigundla

Despite the large investment in water infrastructure, it is clear that water scarcity is having an increasing impact on Ungaranigundla revenue village. Over-extraction of water, predominantly for agricultural use, is leading to increased pressure being place on drinking water supplies. The GIS analysis illustrates the dramatic increase in both the number and depth of wells over the last 20 years and shows that the villages have had to take ever more extreme and expensive measures to secure their drinking water supplies.

Increased focus on a demand management strategy is essential if the revenue village is to effectively combat increasing water scarcity. Supply-side schemes and construction of new infrastructure are still favoured by many decision makers, although it is now widely accepted that demand-side schemes need to play a much more prominent role if the consumptive use of groundwater and other water resources is to be sustainable. There are strong arguments that controls on groundwater use should be a prominent part of the mix and there are also examples of community management leading to more sustainable groundwater use (Garduno et al., 2009; Reddy et al., 2012). However in the end, the success of any policy or regulation that seeks to control groundwater use and increase the sustainability of water use, depends on sufficient information with which to effectively formulate it.

4.2 The use of GIS

This working paper has shown that GIS is a useful tool that can combine and analyse the available data and generate information that can be important for decision making. As demonstrated in the analysis, GIS can provide a clear picture of the overall situation and problems and help to document the impacts of water scarcity. However there are a number of ways in which this study could have used GIS more effectively.

One way is through increased participation of stakeholders and the local community. Participation that did take place proved to be beneficial, and improved the efficiency of the mapping process. For example, printing out large scale GIS maps on A0 and A3 paper that showed a range of different local information was an effective way of communicating with local stakeholders. In particular, an A0 cadastral map showing all different land parcels of the four villages was essential for identifying and surveying wells. Additionally employing local students to map wells and WHS structures went a long way to ensuring that the mapping process ran smoothly. Training them in the use of GPS units was a swift process and their local knowledge meant the survey was completed quickly and efficiently. Another example of successful participation was the creation of PRA maps by the local communities of their villages, which helped to illustrate their concerns and issues during the village consultation meetings. An area where participation could have been improved was between the GIS analysis and the creation of the PRA maps, but time and resource constraints meant that stakeholder participation in relation to this was somewhat limited. Potentially more information and knowledge could have been transferred in both directions. Incorporating more information from the PRA maps into the GIS analysis would have provided increased local knowledge and insights, while more information from the GIS analysis could have provided improved technical input to the PRA maps.

To apply GIS most effectively it is generally accepted that stakeholders and local communities should be involved as much as possible at every stage of the mapping process - from data collection to analysis to the presentation of results (McCall and Dunn, 2012). However, embedding GIS and mapping as part of the overall process and as a tool that is used in the long run can be difficult task to realize. An important part of achieving this is to ensure that there is an obvious connection between the mapping process and measurable outputs. In other words, GIS must not be a gimmick or used purely because it is expected as part of a process determined by a government or an NGO. Ultimately the best way of acquiring up-to-date and relevant data for rural areas such as Ungaranigundla is through stakeholder participation, but to ensure that this data is collected it is important that local communities are part of the entire mapping process. If they cannot see any results they will not be inclined to collect any further data, denying decision makers of an important source of data. A promising way of disseminating results is by making data and GIS outputs available online through mapping applications. However, it is important to remember that access to computers and the internet is limited in some places, and especially in those suffering most from water scarcity.

In Andhra Pradesh, one project encouraged rural communities to map their water supply infrastructure by providing them with handheld GPSs and laptops installed with a version of QGIS software translated into the local language (Kolagani et al., 2009). This example highlights another way in which stakeholders could be more involved in using GIS, rather than mainly being involved at the data collection stage, as well as another use of open-source GIS. The increasing maturity of open-source GIS, the lower cost of using it compared to proprietary software, and the ability to adapt and modify it for local conditions mean that open-source GIS has great potential as a tool for increasing the participation of local communities in the mapping process.

There is little doubt that GIS can play an important role in managing water scarcity at different scales and levels of complexity (Scaria and Vihayan, 2012), however the challenge is to apply it in ways that take advantage of the available data and local expertise. It should therefore incorporate the values and experiences of local communities, provide a platform for communication and collaboration, and deliver information and knowledge that leads to better decision making and management.

4.3 The role of modelling

It is clear from this study that local level planning and state-level policies should take better account of the changes in hydrology that have resulted from intensification of agricultural water use. A range of different factors, including local climate and geology, mean that the total amount of water available in time and space varies greatly in semi-arid areas, even within small areas such as Ungaranigundla revenue village. It is only with some knowledge of both natural hydrology and impact of different activities, such as agriculture, upon them that water resources can be effectively and fairly allocated so that different uses and users receive the water they need.

This paper has demonstrated how the SWAT model can be applied at a local level in a semi-arid rural area to provide predictions about different components of the water balance. It is clear that the SWAT model has great potential as a tool for simulating hydrological processes and water balances in part because it can be applied to ungauged catchments. And increasing amount of satellite data at progressively higher resolutions is now available online and free of charge that can be used for most of the model inputs. In addition to increased data availability and the ability to model data scarce catchments, the open-source nature of MWSWAT makes the model more accessible and adaptable for use in poorer regions and developing countries. Furthermore the increasingly dynamic communities for models such as SWAT are contributing consistent improvements to the models as well as comprehensive documentation that is making them easy to apply in situations such as documented in this paper and is increasing their potential and effectiveness as decision making tools. The results of the SWAT model in this study provide important supplementary information to outputs of the GIS analysis as it shows how hydrological process and different components of the water balance vary both spatially across the catchment (and revenue village) and temporally through time.

4.4 Improving the model

Comparisons with other studies suggest that the outputs from SWAT are similar to what is expected in this area of Andhra Pradesh (Garg et al., 2012; Rama Mohan Rao et al., 1993). Despite relatively satisfactory outputs from SWAT, in particular the modelling of the catchment water balance, a number of issues arose from the use of the model. Despite the advantages of using the open-source MWSWAT version of the SWAT model, the decision to use it rather than the more popular ArcSWAT resulted in some difficulties. Because it is newer and less popular, documentation and online resources for MWSWAT are much more limited in comparison to ArcSWAT. Additionally the fast majority of literature concerning SWAT is based on the ArcSWAT version. As a probable consequence of it being relatively new, MWSWAT contains a number of bugs that make it difficult to use. In particular, an iteration error means that the process of delineating the drainage channels and identifying sub-basins often has to be run many times over to get a satisfactory output. This can be very time-consuming when running these steps multiple times to test different data inputs and drainage delineation thresholds.

The main issues with SWAT itself was the lack of calibration and validation of the model, which raises questions about how much the model outputs can be trusted. However, effective calibration needs high quality observations of streamflow over long periods of time which is simply not available in India for the vast majority of small and medium sized catchments, such as the one modelled in this study (Moriasi et al., 2007). Even though some studies have shown that SWAT can successfully predict water balance components in the absence of calibration (Srinivasan et al., 2010) the absence of calibration limits the potential use of model outputs in planning and management decisions. Calibration of hydrological models is necessary because of their simplification of hydrological processes and catchment characteristics and because of errors in input data - all of which result in many different sources of uncertainty. Clearly sources of uncertainty need to be constrained if there is to be confidence in model outputs (Beven, 2006).

Even in the absence of flow data there are number of options that could be attempted to calibrate the model and improve confidence in the results. One solution proposed in the literature for overcoming the lack of observed data is the regionalisation of parameter values (Beven, 2012). This involves taking parameter values for gauged catchments within the same region and applying them to the ungauged catchment. Results from different studies suggest that the regionalisation of parameter values can be an adequate replacement if calibration and validation cannot be performed (Gitau and Chaubery, 2010). Another calibration option for this study would be by using satellite evapotranspiration records. Immerzeel et al (2008) demonstrated this method for the upper Bhima catchment located in South India.

Another issue with the SWAT model is deciding the parameters, or parameterisation, of catchment characteristics. The model outputs would be improved through a more local parameterisation of land cover and soil type rather than the use of the default global classification system available within MWSWAT. As shown by Garg et al (2012) it is possible to include WHS within the model through the adjustment of different parameters such as the runoff curve number. The ability to run SWAT simulations with and without WHS would provide valuable information for decision makers considering the effectiveness of the WHS structures in study catchment areas, and would provide some insight as to whether the construction of additional WHS could help alleviate water scarcity or lead to increased downstream water scarcity

When assessing the model outputs it is important to bear in mind some of the general limitations of the SWAT model. One of the main limitations is the non-spatial representation of HRUs below the sub-basin despite the spatial variability of different hydrological processes operating at that scale (Gassman et al., 2007). The larger the size of the sub-basins increases the likelihood that there is spatial heterogeneity within the sub-basin. Tripathi et al (2006) tested the impacts of different numbers and sizes of sub-basins for a catchment in eastern India and found that although runoff was little changed by having fewer and larger sub-basins there were significant impacts on the predictions of evapotranspiration, percolation and soil water content. Another limitation is that SWAT assumes that there is unlimited capacity for water to infiltrate into aquifers. This is not realistic particularly in hard rock areas such as the Ungaranigundla study area (Garg et al., 2012). A final limitation is that many of the different WHS structures are represented in the model through the adjustment of the same parameters which means that it is impossible to determine the effectiveness of individual structures (Garg et al., 2012).

A final potential improvement to the use of SWAT in this study would be the integration of SWAT with other models, particularly groundwater and economic models. This has been achieved in other studies (Gassman, P., et al., 2007). Better integration of SWAT with other models would provide a much better picture of the overall impact of management decisions and give decisions makers extra information (Douglas-Mankin, Srinivasan and Arnold, 2010). For example, because groundwater was the dominant source of water for the study area, and considering the potential problems with the conceptual representations of aquifer in the SWAT model, integration with a groundwater model would almost certainly improve outputs.

5 Conclusions

The results of the analysis in this paper reveal the acute water scarcity problem facing people living in Ungaranigundla revenue village. Intensive competition for groundwater from agricultural users is placing extreme pressure on village drinking water supplies and as a consequence many households in the villages are not receiving water services that meet Government of India norms. In an attempt to increase the sustainability of groundwater a large amount of money has been invested in WHS but the majority of these structures are either in need of repair or are completely defunct.

The paper has demonstrated how GIS can be used to provide a clear overview of problems of water scarcity facing Ungaranigundla. Time-series maps have shown the extraordinary increase in the number of borewells and their depth over the last decade or so. Heat maps have indicated where these increases have been concentrated and in what areas the concentration of failed borewells and deep borewells are highest. This is potentially useful information for managing groundwater use in the revenue village. For example, it could be used for designating groundwater sanctuary zones. GIS analysis could also form the basis for more effective community management of groundwater, through allowing different community members to easily perceive the overall situation and therefore grasp the critical need for action.

The paper has also illustrated the benefit of local participation in the mapping process. That the majority of data was collected by local students using basic handheld GPS units and a significant amount of the GIS analysis was completed using open-source software, demonstrates that there is potential for much of the methodology in the paper to be used on a larger scale by local organisations and communities. A number of studies have proved that open-source GIS is a suitable tool for use by local communities for resources management (Kolagani et al., 2009; Bunch, Kumaran and Joseph, 2012; Scaria and Vihayan, 2012) and the ability to adapted and customise open-source software to suit local needs and standards is a particular benefit. Overall this paper demonstrates that GIS has the potential to be a key tool for combating water scarcity and that the major challenge is in properly utilising it.

The second part of the analysis in this paper demonstrates how the SWAT hydrological model could be setup for a small catchment in a semi-arid, rural area. SWAT revealed how different water balance components, such as recharge and runoff, vary significantly both spatially throughout the catchment and temporally through time. Knowledge of this is important for decision making and for building adaptability into planning. However, it should be noted that the use of SWAT in this paper is very much the first step in applying the model. For the results to be meaningful and have use in terms of decision making, more work would have to be done, particularly in calibrating and validating the model and in using more local information for model parameterization. Despite this, the paper has shown that SWAT has the potential to provide the detailed and specific hydrological information at local scales that could improve decision-making significantly in the face of increasingly severe water scarcity.

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