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Contents

1 Acknowledgments

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2 Executive summary

The motivation for this study lays in a desire to assist stakeholders and policy makers in India come to terms with the impacts of climate change and the responses they could use to adapt to it. The State of Andhra Pradesh[1] had instituted a far reaching Watershed Development (WSD) program in the late 1980s, which was touted as an initiative that solved many of the on-going water scarcity problems by providing access to water to the poor dry land farming sector. This strategy later became conflated with the problem of climate change and believed by some to also act as a solution to the problem. However, the problem with harvesting water through the WSD projects is that it competes with the water available to the intensive large irrigation schemes, something the government had heavily invested in prior to the WSD program.

Developing plausible future scenarios and adaptation responses to future climate change involves a large number of uncertainties. This suite of uncertainties makes climate change adaptation a typical 'wicked problem'. In order to assess some of the uncertainties, a catchment[2] wide approach (centring on the Musi catchment of the Krishna basin) was combined with a Scenario Planning approach to develop stakeholder elicited adaptation responses to predicted climate futures. At the core of the Scenario Planning approach applied in this project lies the design of adaptation responses to the three climate change scenarios and concomitant evaluation of the water security and economic performance of the resulting scenario-response combinations. An iterative multi-tier stakeholder consultation process carried out over a period of three years yielded a set stakeholder prioritised adaptation options, which includes *changing cropping patterns, increasing watershed development and improving irrigation efficiency.*

This range of adaptation responses was then subjected to a rigorous hydro-economic evaluation to determine their hydrologic (water security) and economic performance (cost-effectiveness). The analysis is based on three downscaled members (Q_0, Q_1 & Q_{14}) of the climate ensemble derived by downscaling the A1B emission scenario from the Hadley Centre Global Climate Model. The climate predictions were used as forcing data for the groundwater and surface hydrology models to determine the climate impacts on water resource availability and subsequent assessment of water security. This analysis was carried out for three 30-year time periods (2010-2040; 2041-2070 & 2071-2096).

The hydrologic impacts arising from the three climate scenarios vary significantly. While the Q_{14} climate scenario results in increasing river discharge, the Q_1 scenario shows a decrease in river discharge. The early-century results show that the future average annual streamflows will decrease by 24% and 14% for Himayat Sagar and Osman Sagar storages, respectively. However, during the mid-century period the future average annual streamflow would increase by 31% and 70% for Osman Sagar and Himayat Sagar, respectively.

The water security performance shows that variations occur between responses and between time periods. At an aggregate system level, the crop diversification option shows the best aggregate water security performance at 80% reliability level (6104 MCM) for the period 2011-2040, compared to improving efficiency (5486 MCM), watershed development (4144 MCM) and a busness-as-usual (do-nothing) scenario (4680 MCM). It is important to stress that there are large variations in performance among the various demand centres within the catchment. In addition, the policy of unlimited supplemented supply to the Musi catchment from the Nagarjuna Sagar Project implies that water

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[1] *During the life of this project, the State of Andhra Pradesh was subdivided into two states: Andhra Pradesh and Telangana. In this report we refer to the two states as Andhra Pradesh.*

[2] *The words catchment and sub-basin are used interchangeably throughout this report.*

shortages occurring in the catchment translate into reduced security in the two major irrigation systems supplied by this project: NGJS-LC and NGJS-RC. As a result of the WSD program of the GOI, water security improves largely at the expense of water security in the irrigated command areas.

Of equal importance in the performance evaluation of the selected response options is their economic performance. The economic analysis shows that increased reliability and water security comes at a cost, especially with respect to the water foregone during wet periods. For the Musi catchment it was estimated that the system would be run at its most financially optimum level if it set reliability rates at approximately 35%, and if it is run at more than 85% the costs of increased reliability outweigh the benefits. Across the catchment, three regions (the NGJS-LC and NGJS-RC and the region around Hyderabad city) tend to be the places where changing water policies and climate change have the greatest financial impact. WSD has placed a financial burden on the existing large scale irrigation systems in the Musi catchment. Improving WSD, while not placing a great financial burden on the State, does little to improve the water supply situation across the catchment. Improving irrigation efficiency, while improving water security, does come at a significant cost, one which does affect the distribution of water and benefits greatly. Changing cropping patterns not only provides the highest overall water security but is also the most cost effective adaptation policy.

Adaptation of water resources management to climate change involves catchment specific considerations of the hydrology, social, economic, environmental and institutional and political reality of the catchment. The most enduring legacy of this project is the generic-adaptive framework that was developed, tested and applied in the Musi catchment, which can be applied to any catchment in an adaptive manner. The framework developed in this project can form the basis for up scaling the framework to the Krishna basin level. However, scaling up the application of this framework to the Krishna basin level poses new problems and challenges as it involves multi-state jurisdictions and diverse water management policies. This is the obvious future progression of this research.

Glossary of Terms

AVHRR	Advanced Very High Resolution Radiometer
BAU	Business as usual
CDF	Cumulative distribution function
CV	Coefficient of variation
FGD	Focus discussion group
GCM	Global climate model
HS	Himayat Sagar reservoir
IITM	Indian Institute for Tropical Meteorology
IMD	Indian Meteorological Department
IWMI	International Water Management Institute
KRB	Krishna Basin
MCM	Million cubic meters
MODFLOW	Groundwater Model
NDVI	Normalized Difference Vegetation Index
NJSP	Nagarjuna Sagar Project
NJSP – LC	Nagarjuna Sagar Project Left Canal
NJSP – RC	Nagarjuna Sagar Project Right Canal
OS	Osman Sagar reservoir
PRECIS	Providing REgional Climates for Impact Studies
QUMP	Quantifying Uncertainties in Model Predictions
REALM	Resource Allocation Model
RCM	Regional climate model
TERI	The Energy and Resources Institute
SWAT	Soil and Water Assessment Tool
WSD	Watershed Development

3 Background

The long term impacts of climate change and watershed development (WSD) on water security in many river basins worldwide, including the Krishna and the Murray-Darling basins, are expected to be large. Climate change and WSD are expected to have a significant impact on the hydrologic behaviour of the catchments. The Krishna river basin is closing as a result of the combined impacts of vast irrigation development over the past 50 years and extensive WSD programs, both promoted by the Indian Government. It is predicted that by the end of the century, India will experience a 3 to 5°C increase in temperatures and a 20% rise in summer monsoon rainfall (Kumar et al. 2006), while Gosain et al. (2006) suggested that in the Krishna basin, a 20% decline in precipitation can be expected.   A corresponding decrease in runoff is predicted to vary from 30 to 50% in the Krishna Basin. As a consequence of these dire predictions achieving the desired level of agricultural growth the Government expected would be a challenge.

The agricultural sector in India represents 35% of the Gross National Product (GNP). The agricultural economy of rural India is heavily dependent on the summer monsoons. When the summer monsoons fail, or are excessive, the economic losses can be large and widespread. In the State of Maharashtra, a single drought (in 2003) and a flood (in 2005) absorbed more of the State budget ($3.6 billion) than the entire combined expenditure (of $3.2 billion) on irrigation, agriculture and rural development, between 2002 and 2007 (World Bank, 2008). Climate change is expected to increase the frequency of extreme events and therefore the development of adaptation measures to reduce vulnerability to them is crucial.

The losses from not adapting to climate change in the Krishna and Murray Darling basins were expected to be massive. In an earlier ACIAR funded project (LWR/2003/026) it was estimated that if stream flows were reduced by 20% in the Musi catchment (a sub-basin of the Krishna) over the next 40 years would lead to a net discounted loss to society of A$205 million, with agriculture accounting for A$190 million of these losses. In the same catchment, it was found that inflows to reservoirs between 1980 and 2002 had already fallen by 40%, leading to imports of irrigation water from adjacent catchments needed in order to meet urban demand. The cost of importing water has been estimated to be $A650 million and has led to reduced water security for agriculture in both the Krishna and adjacent catchments. In Australia, Garnaut (2008) reviews the various studies of the impacts of climate change on the agricultural sector. The sector was expected to experience significant economic impacts from climate change, including a reduction in economic returns in the Murray-Darling Basin of between $A0.8 billion and $A1.2 billion (depending on the level of greenhouse gases emitted).

Few would argue with the proposition that global climate change is one of the most complex and important issues confronting the world today. The IPCC (2007) reviewed the scientific evidence, while Stern (2007) and Garnaut (2008) warned of the dire economic consequences that may arise should actions to reduce carbon emissions not be taken. Garnaut (2008) argued that a quantitative assessment of the vulnerability to climate change is essential to improve the policy making response. Stern (2007) suggested that the effects of climate change were expected to be greatest in the developing world, and that India may well be greatly affected. Initial climate modelling indicated that the physical and economic impacts on Australia and on the developing world (particularly India) will be severe, and of particular concern to both these countries are the impacts climate change will have on water security.

Research on climate change adaptation centres on quantifying the risks associated with alternative adaptation scenarios, including a do-nothing option. However, the costs of reacting to and rectifying the problems that arise from climate change can be high. There are always risks associated with the alternative adaptation policies that could be undertaken, including the possibility that the specific problem it was designed to rectify, does not arise. Consequently, this research is designed to inform policy makers of the course of action that will minimise the overall risks, maximise the benefits and/or reduce the impacts and costs of climate change.

Watershed development (WSD) has been shown to significantly affect the hydrology of catchments and ultimately water security (Gosain et al. 2006). A complicating factor in dealing with climate change from a water resource management perspective is the current Indian government policies that promote and subsidise watershed development. These policies were designed to increase agricultural output and reduce poverty (Joshi et al. 2005). Reacting and adapting to climate change and WSD entail local costs and externalities that need to be quantified.

Different strategies imply different costs and different levels of effectiveness at ensuring water security at different times and locations. An assessment of the costs and outputs (effectiveness) requires some idea of the government's objectives and possible policy approaches to the problem. Once these issues are resolved, assessing the effectiveness in terms of the costs involved in each adaptation strategy can be undertaken to a certain degree of accuracy.

It could be argued that Australia is one region which would appear to be already experiencing significant impacts from climate change. The average surface air temperatures have increased by 0.9°C since 1950. Precipitation has declined along the East and West coasts of the country (Murphy and Timbal, 2008). Analysis of future scenarios suggests that the average temperatures are projected to increase by between 1 and 5 °C by 2070. Average precipitation is likely to decline in parts of Australia, which will affect water resources and agriculture (CSIRO and BOM, 2008). The climate model reported by the IPCC give reasonably consistent predictions of temperature rises for the Murrumbidgee region, but there is considerable disagreement in rainfall projections. It has been suggested in these models that the number of droughts per decade (currently 3) is predicted to change to the range 1-5 in 2030 and 1-9 in 2070. Evaporation in 2030 is expected to be 1-13% higher as temperatures increase by 0.2-1.8 °C and the number of very hot days with temperatures over 35°C is estimated to increase from 20 to 21-34 days.

Watershed development can profoundly modify the surface and subsurface water fluxes of the water cycle. Additional water capture structures retain water that is used for irrigation and promote groundwater recharge. To understand and quantify the impact of WSD and climate change at the sub-basin scale, a modelling effort needs to be directed towards understanding the groundwater-surface water interactions and the ability to predict the impact of these two key forcing variables.

Adaptation strategies may vary in the future according to national, state and regional priorities. This analysis will be used to predict future impacts arising from an extensive stakeholder consultation process comprising key water management authorities, civil society and the farming community. This process was closely informed by current national and state water policy priorities. In this analysis the trade-offs between multiple uses of water (economic and environmental) will be observed at different spatial and time scales in the basin using the multifunctional criteria outlined by Malano and Davidson (2009). The impacts of the stakeholders selected adaptation strategies are analysed with a focus on water security for agriculture and their economic performance.

4 Objectives

The overriding objective in this project were to assess the impacts of watershed development and climate change on the long term water security for agriculture in the Krishna river basin. This assessment provides the basis to ascertain whether WSD and other strategies can support future food production in light of what might arise from a changing climate. More specifically, in this project the objectives were to:

- compile and synthesize the current understanding of historical climate change in the Krishna and Murrumbidgee basins and model future regional climate change scenarios;
- assess the combined impact of watershed interventions and climate change projections on surface and groundwater hydrology at different spatial scales;
- develop a framework for identifying stakeholder defined adaptation scenarios in the context of relevant policies;
- integrate the hydrological outputs to create a coupled hydro-economic methodology that is capable of assessing response strategies to the combined impacts of climate change and watershed development at basin and sub-basin level.; and
- facilitate cross-learning of methodologies and adaptation strategies to climate change between India and Australia.

To achieve these aims, the following objectives were pursued:

Objective 1: To compile and synthesize the current understanding of historical climate change in the Krishna and Murrumbidgee basins and model future regional climate change scenarios

Activity 1: Collection and compilation of climatic data (sub-basin and basin levels) Analyse historical data to assess past climate changes.

Activity 2: Development of high resolution climate scenarios using Regional Climate model.

Activity 3: Conduct sensitivity and uncertainty analysis of various climate projections from the regional climate model.

Activity 4: Analyse the frequency of droughts and floods and the onset and advance of monsoons in the Krishna basin and changes in climatic patterns.

Objective 2: To assess the combined impact of watershed interventions and climate change projections on surface and groundwater hydrology at different scales

Activity 1: Collection and compilation of hydrologic and water demand data (sub-basin and basin levels).

Activity 2: Remote sensing analysis of land use, evapotranspiration and watershed structures of study basins.

Activity 3: Develop and couple distributed surface and groundwater hydrological models.

Activity 4: Assess the impact of storage structures, land use and climate change on stream flows and groundwater (sub-basin scale).

Activity 5: Model aggregate water availability, demand and security under climate change scenarios at sub-basin and basin levels.

Objective 3: Development of a framework for identification of stakeholder defined adaptation scenarios in the context of relevant policies

Activity 1: Institutional mapping and review of water resources policies and programmes being promoted in the basin.

Activity 2: Study of socio-economic aspects and water utilisation patterns at sub-basin and basin levels.

Activity 3: Develop a framework for identifying adaptation scenarios.

Activity 4: Use of water modelling outputs to demarcate regions of water stress both upstream and downstream (sub-basin and basin scales).

Activity 5: Undertake stakeholder consultations to identify and characterize key water management issues that will be affected by climate change (sub-basin and basin scales).

Objective 4: To integrate the hydrological outputs from objectives 1 and 2 and create a coupled hydro-economic methodology to assess response strategies to the combined impacts of climate change and watershed development at basin and sub-basin level

Activity 1: Enhance an existing coupled water allocation-economic model to assess adaptation responses (sub-basin and basin scales).

Activity 2: Develop a methodology for evaluating hydrological and economic changes that result from different adaptation scenarios (sub-basin and basin scales).

Activity 3: Assess the hydrologic and economic trade-offs that occur between upstream and downstream users, due to future watershed development (sub-basin scale).

Activity 4: Assess the long term implications of climate change and watershed adaptation policies on water security (sub-basin and basin scales).

Activity 5: Isolate the suite of feasible strategies and inform policy makers to develop adaptation measures with respect to the impacts of climate change and WSD on water security.

Objective 5: To facilitate cross-learning of methodologies and adaptation strategies to climate change between India and Australia

Activity 1: Select appropriate irrigation areas in the Murrumbidgee catchment for comparison of climate change impacts and adaptation policies.

Activity 2: Analysis of climate change responses in selected areas of the Murrumbidgee catchment.

Activity 3: Comparative analysis of approaches to climate adaptation policies and potential outcomes in Australia and India.

Activity 4: Dissemination of methodologies for selection and evaluation of adaptation approaches to climate change impacts in Australia and India.

5 Methodology

The broad conceptual framework used in this project is based on the integration of a range of modelling tools that once assembled and integrated are used to support a scenario planning approach and then ultimately inform policy makers. This framework consists of two critical parts: a) Integration of all elements of the water cycle with economic outcomes, and b) integration of research outputs into an evidence based policy formulation agenda that involves the key project stakeholders. A depiction of the two-dimensional integration process and the links to individual objectives of this project is shown in Figure 1. In order to understand the methods used in this project, it is first necessary to understand the nature of the climate adaptation problem being dealt with. This then becomes a precursor to discuss that methodology needed to address the problem and the need to find a way to test a wide set of scenarios (each of which has to be developed). Once developed the critical variables in this analysis (i.e. water security and cost-effectiveness) need to be identified and the study area described. From this base, the individual modelling elements and methods that represent the desires of stakeholders, the climate, the ground and surface hydrology, the allocation of water and its economic components can be developed. It should be noted that further details on the approaches taken to model this system are presented in the Appendices (see Section 11).

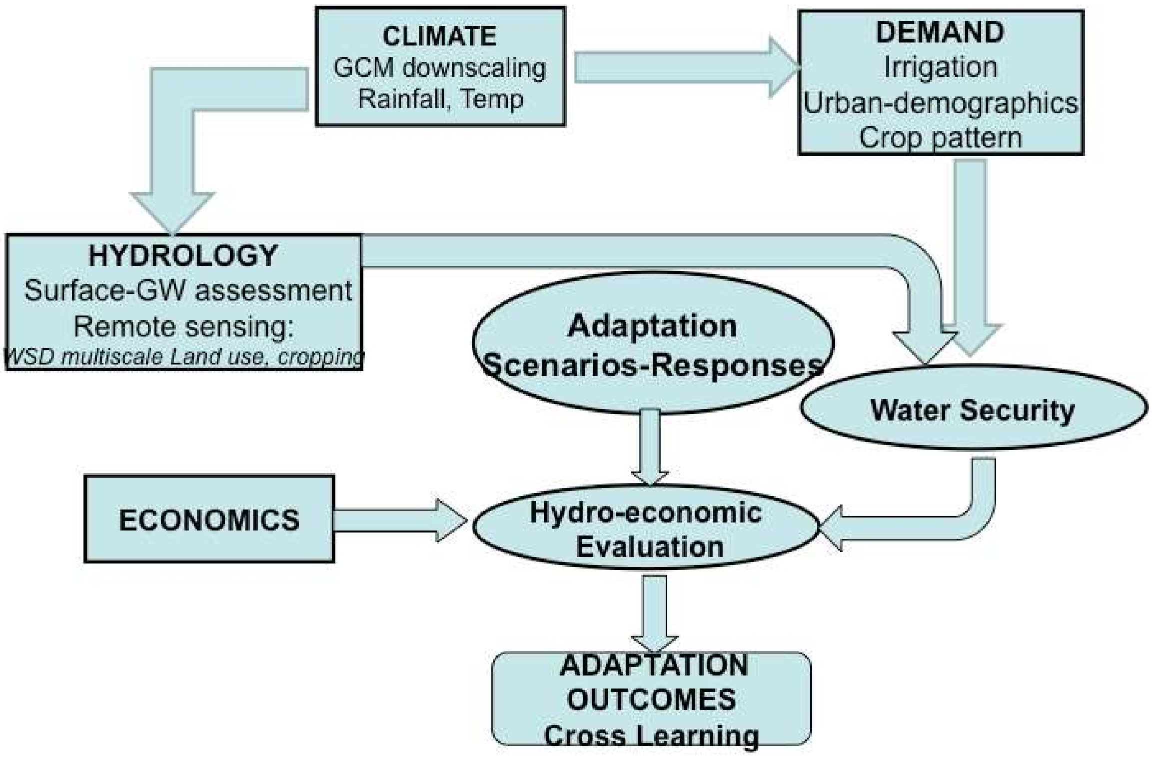

Figure 1. Conceptual project map

The nature of the problem

Developing plausible future scenarios and adaptation responses to future climate change involves a large number of uncertainties. This suite of uncertainties makes climate change adaptation a typical ‘wicked problem’. These uncertainties can be classed into several groups including C*ognitive, strategic, institutional, knowledge imperfection, problem* *instability, multi-causality and interdependences* (Malano, 2010). As water resource systems are highly complex, it is difficult to identify all the causes and effects of water management problems or solutions. A particular causative factor that may remain undetected can nonetheless have severe impacts on the behaviour of the system. This would be the case with many aspects of WSD, such as the nature of impacts of the program on the livelihood of rural people, and vice versa, the impact of farmers or the impacts of WSD on larger system scales. The nature of the problem addressed in this research is to develop an approach that policy makers and stakeholders can use to order and assess the uncertainties associated with climate change and the adaptive responses to it.

The overall research framework

The problem of water resource adaptation to climate change is characterised by uncertainties and instability, which requires an approach that can accommodate flexibility and adaptive capacity for decision-making. Such an approach will allow for corrective measures over time if the scenarios and responses envisaged in the initial stage of the project take a different form at some future stage. This necessitates an approach that integrates the different relevant disciplines needed to address the challenges facing the water management sector.

There are many types of future problems with different degree of uncertainty and severity of consequences, if they occur. Climate change adaptation in water resource management exhibit a classical combination of *high uncertainty-severe consequence.* Scenario Planning (Schoemaker, 1995) is an appropriate and useful tool when futures are subject to high uncertainty and the consequences can be severe. Van Notten (2006) defines "scenarios" as *"a consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action"*. Typically, Scenario Planning has been used to make business decisions under conditions of 'high uncertainty' by trying to capture a range of possible futures and develop responses designed to cope with these possibilities. This is normally done by developing objective narratives that describe the future possibilities after distilling a wide range of possible imagined scenarios into a few well-defined *scenarios*. In this project the selection of future *plausible climate scenarios* are combined with a range of *responses* that are then subjected to a rigorous hydro-economic evaluation to determine their hydrologic (water security) and economic performance (cost-effectiveness).

The research approach taken for this project consists of an integrated-multidisciplinary framework aimed to evaluate a range of adaptation responses to expected climate futures for the Musi Catchment, Andhra Pradesh. At the core of this strategy is a stakeholder consultation process geared to elicit plausible and agreed responses to future climates in the region (Figure 1).

Why Use Scenario Planning?

A problem characterised by uncertainties and instability requires an approach that can accommodate flexibility and adaptive capacity for future decision-making. Such an approach will allow for corrective measures over time if the scenarios and responses envisaged in the initial stage of the project take a different form at some future stage.

There are many types of future problems with different degree of uncertainty and severity of consequences, if they occur. Depending on the combination quadrant between these two parameters, either deterministic planning or scenario planning can be more appropriate. The four combinations of uncertainty and consequence determine the best approach to undertake the relevant planning:

- *Low uncertainty – severe consequence:* Future is predictable although

consequence can be severe. In this case, deterministic planning can be applied.
- *Low uncertainty – minor consequence:* Future is predictable and consequence is not severe. Decision making can start without much consideration of the future.
- *High uncertainty - minor consequence*: Despite future being uncertain and more than one future is possible, deterministic planning can be applied although if severity of consequence moves towards the middle, scenario planning can be a better option.
- *High uncertainty – severe consequence:* this is the classical combination where scenario planning is necessary. This project fits into this category.

Flexibility and adaptive capacity means that “no-regrets measures” must be taken at the appropriate time depending on the manifestation over time of the plausible impacts of climate change or WSD. ‘No regret’ measures are measures that turn out to be of benefit no matter how or if the predicted climate changes impacts materialise.

In light of the uncertain characteristics of climate change and WSD development and the difficulty in identifying “no-regret” measures at the beginning of the adaptation cycle, it is important to establish the key criteria by which alternative responses can be evaluated under a Scenario Analysis framework. These are:

- Assess whether the strategy meets the best –economic, environmental and social- objectives under the current state of knowledge and uncertainties about the future, and;
- Adopt an adaptive policy framework to account and incorporate continuous changes in the biophysical and policy environments

Such a framework can only be developed and implemented if there is an on-going partnership between stakeholders and decision makers, supported by robust research evidence. There are five critical parts to this framework, each with its own suite of techniques and methods (Figure 1). They are a stakeholder analysis, climate modelling, an assessment of the land use using GIS, an assessment of the surface and ground water hydrology the modelling of water security and a cost effectiveness analysis.

Key variables of interest- Water security, scenarios and responses

In this project, of interest is how water security is affected by both climate and the responses to it (like WSD). In this study water security is defined to mean water reliability. “….. *the expected availability of water at a specified level of probability of exceedance*” Conversely, water security risk is the probability associated with obtaining the same volume of water or less. That means the number of years (in 100) that a select quantity of water is provided to the catchment as a whole or to a specific demand centre, in particular. In saying this, it is possible that the water reliability could well differ across the catchment between nodes. In addition, while the focus is on the agricultural demand for water, there is a need to consider all the elements of the catchment system such as urban, industrial and environmental demands. In other words, while the impacts of a growing Hyderabad city must be included in the analysis, the outputs for that node are not included in the results.

This modelling assessment process is designed to evaluate a range of scientifically defensible stakeholder driven biophysical, social and economic adaptation strategies, rather than seeking a single preferred (optimal) alternative. This approach assumes that the decision on the adoption of preferred adaptation alternative remains with Government and other entities charged with policy formation and implementation. The modelling framework developed in this project is generic in nature and is designed to evaluate alternative policy options for their water security economic performance. The framework is also adaptive and can be applied to other catchments where sufficient data is available to populate the models.

The study area

The Krishna Basin is the fourth largest river basin in India in terms of annual discharge (at 65 km^3) and the fifth largest in terms of surface area (at 258,948 km^2). The basin traverses through three large states – Karnataka, Maharashtra and Andhra Pradesh. The river supplies 73 million people with their water needs. This basin is interesting as it is nearly closed, crosses jurisdictional boundaries, experiences both spatial and sectorial demand pressures for more water and suffers from a number of environmental pressures. The acute water shortages in the basin are leading to interstate conflicts on the allocation and use of the resource.

The project focused on one sub-basin of the Krishna basin: The Musi Catchment. The Musi River, a principle tributary of the Krishna River in India, originates in the Anantha Hills around 90km west of Hyderabad. The Musi River catchment supports a population of around 10 million people in an area of approximately 11,000 km^2. The climate of the Musi sub-basin is typical of the semi-arid rain-fed conditions found throughout the Deccan Plateau. Summers are hot and winters are temperate.

In this project, the Musi catchment has been segregated into four dryland regions (zones 1 to 4), three irrigation regions (Musi Medium, the NGJS-LC and NGJS-RC systems) and two river diverters (the Musi Anicut and the Wastewater irrigation system). The catchment also includes components for Hyderabad City and industrial use. In addition, there is a need to account for the water that comes from outside the catchment, not only including the highly influential Nagajuna Sagar system, but also the water that is imported from the Godavari catchment. Details of the study area can be seen in Figure 2.

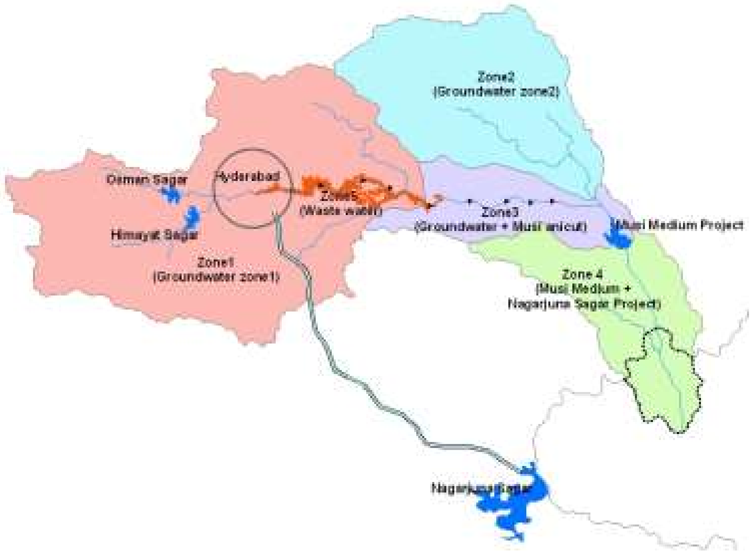

Figure 2. The study area.

The Musi sub-basin is subject to both south-west and north-east monsoons. The mean annual rainfall of the catchment is 760 mm and is unevenly spatially and temporally distributed. The land use consists of agriculture, forest, and urban, barren and rocky areas. The major crop in the sub-basin is rice followed by vegetables, ground nuts (*Arachis hypogea)*, cotton, chillies, sugar cane, jowar (*Sorghum bicolor*), bajra

(*Pennisetum glaucum*), maize (*Zea mays)* and gram (*Vigna mungo)*. Economic activities in the catchment are diverse and include pharmaceutical industries, metallurgy, information technology, electroplating, oil mills, lead extraction/battery units, pharmaceutical, leather, textile, paper, soap and jewellery industries. At present, areas within the Musi sub-basin are already facing a water shortage with allocations in the catchment not being able to meet the demand from major demand centres.

Designing adaptation responses

The stakeholder consultation process involves the development of constructive and productive relationships over the long term with people interested in an issue. It results in a relationship of mutual benefit and enables the identification of trends and emerging challenges, which are currently or will in the future be of concern. In this project, the stakeholder consultation process represents a core element of the research framework (Figure 1). It is designed to elicit a set of key adaptation responses to the expected future climate scenarios.

Initially relevant stakeholders were identified and classified into one of four tiers: central government, state government, district government and the local community (comprising mainly of farmers as the fourth tier). These stakeholders were identified on the basis of their roles and responsibilities in relation to agricultural water security in the study area.

To identify relevant stakeholders an institutional mapping exercise was undertaken to reveal the concerned departments and designation for consultation process. For the state level consultations the broader area of Krishna Basin comprised of three states (Andhra Pradesh, Karnataka, and Maharashtra) were selected. For more focussed study, Musi sub-basin was selected and the three districts (Mahboobnagar, Rangareddy and Nalgonda) all which are part of Musi sub-basin were studied in more detail. In these districts a number of villages with contrasting features were identified, based on the criteria:

- Water abundant *vis-a-vis* water scarce;
- Where agriculture was rain-fed only *vis-a-vis* canal irrigated, irrigated by ground water;
- Affluent/prosperous *vis-a-vis* poor/subsistence based;
- Farmer suicides have occurred in the past *vis-a-vis* no farmer suicides in the past; and
- Government schemes were being implemented *viz.-a-viz.* no government schemes implemented.

The process of consultation is illustrated in Figure 3. In the Musi catchment various rounds of interactions were held with the three relevant tiers stakeholder groups (excluding the broad state level tier). In the initial round, stakeholders were asked to respond to a set of ‘what-if-scenarios’ presented to them (Appendix 11.B). These scenarios were based on the available literature review of the assessment of climate change impacts, including rise in temperature and decrease in water availability and increased variability, in general. Through this process around 50 adaptation responses were received from all the stakeholders, which were then organised into four major categories: Technical; regulatory; institutional; and financial.

This process was used to engage stakeholders in the project from the beginning and helped build the relationships amongst participants and understand the existing policy and programs in the region in the context of agricultural water security. These consultations were also held at the larger spatial scale of Krishna Basin and covered all important institutes in the three states of Karnataka, Maharashtra and Andhra Pradesh.

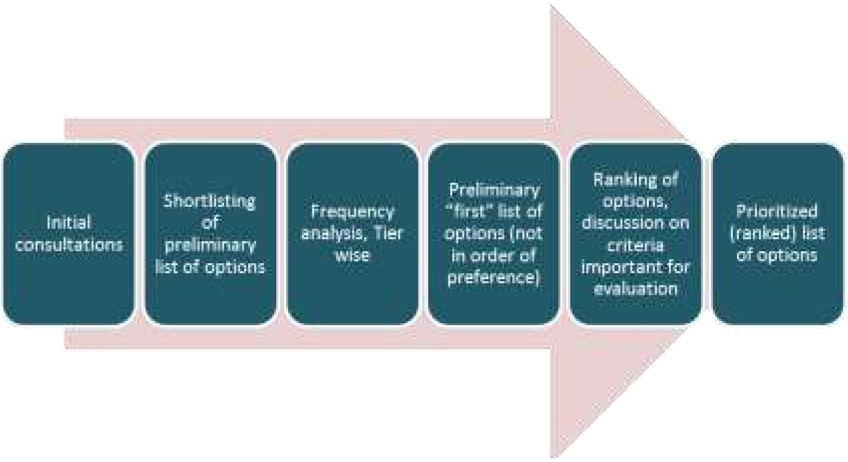

Figure 3. The stakeholder consultation process

At subsequent rounds of the consultation process stakeholders were exposed to the modelling outputs received from the assessments of the hydrological and groundwater modelling exercises performed under different climate change scenarios. These results were presented in a simplified manner to the stakeholders in order to help them understand the complexities involved and so they could provide responses in the form of potential adaptation options. From all the tiers, multiple adaptation options were collected and these were shortlisted, based on a frequency analysis of their occurrence. Further, a prioritization exercise was undertaken with the stakeholders using different approaches to rank and weight the adaptation options. This analysis yielded scores for ranking the criteria that were then normalized. The criteria included costs, co-benefits, people benefitted, the scale of impact, the time of implementation, institutional barriers, social acceptability and technical know-how. Finally four adaptation options were selected from the prioritized adaptation options.

Integrated Modelling Framework

The modelling framework adopted in this research is consistent with the concept adopted for assessment of the climate adaptation responses (Figure 1). The framework consists of three main components (Figure 4):

- Resource assessment (surface and groundwater resources);
- Estimation of water demand; and
- Water security modelling to evaluate the hydrologic performance of alternative climate scenarios and adaptation response combinations.

The first step towards developing a water allocation model is to take account of the current resource situation, its distribution both spatial and temporal and the recent trends. This was achieved by detailed modelling of the catchment's hydrology using data and hydrologic modelling tools. The SWAT hydrologic model (Arnold et al. 1998) was used to model the surface hydrology of the Musi catchment, while the MODFLOW groundwater modelling framework was adopted to simulate the groundwater behaviour under various scenario-response combinations. The REALM (Resource Allocation Model) model

(Perera et al, 2005) was adopted to assess the level of water security associated with each scenario-response combination.

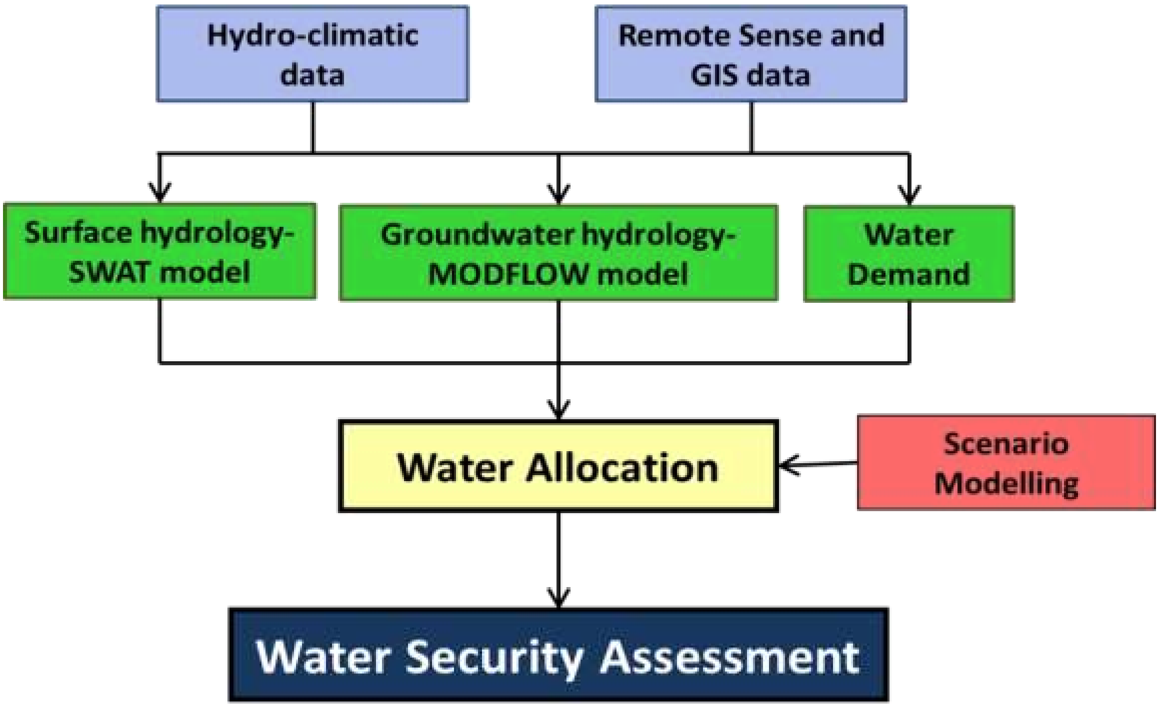

Figure 4. The integrated modelling framework

Climate modelling

The objective in this component of the analysis is to predict the possible future climate scenarios. The impact of climate change is examined using high resolution climate change simulations over the Krishna Basin. Climate change projections for rainfall and temperature are made for three future time slices 2011-2040, 2041-2070 and 2071-2098 using the regional climate model – PRECIS. The Indian Institute of Tropical Meteorology, Pune, carried out the PRECIS simulations at 50 km x 50 km horizontal resolution for the period of 1961-2098. Three members from a 17 member Perturbed Physics Ensemble (PPE) generated using Hadley Center Coupled Model (HadCM3) for the QUMP (Quantifying Uncertainties in Model Predictions) project (Murphy et al, 2004 and Stanford etal, 2005), are used to drive high resolution regional climate model PRECIS.

As the summer monsoon contributes more than 70% of annual rainfall in the Krishna river basin, summer monsoon characteristics like the onset of monsoon as well as the excess/ deficit monsoon years are analysed for the three time slices. The southernmost grid in the Krishna basin (75.355ºE, 13.45ºN) where the summer monsoon sets in is selected using the normal onset date chart by IMD (www.imd.gov.in). The criteria used to define the onset over the selected grid is that if daily rainfall at this grid is greater than 2.5 mm for consecutive three days, the first day is identified as the onset date.

Similarly the excess and deficit rainfall years are analysed to investigate the frequency and the quantum of rainfall received as well as any possible changes in these features in future, under a global warming scenario. The excess/deficit rainfall years are identified using the following criterion: If the area averaged seasonal rainfall over the basin is less than (greater than) mean-std. dev. (mean + std. dev.), the year is defined as a deficient (excess) year.

GIS and land use

The Krishna River Basin is one of India's largest waterways that supply water to approximately 73 million people. The basin is overall gently rolling or flat except for the hilly forests in central-northeast of the basin and the mountains in Western Ghats. The annual rainfall is on average 850 mm/year, however it gradually varies from relatively dry downstream in the east (~500 mm/year) to mountainous upstream regions in the west (up to ~2000 mm/year). There are two major cropping seasons in the basin: monsoon-rainfed (Kharif) in June-November and irrigation-dependant Rabi in December-March. For the purpose of this analysis, ET in December-May is lumped to represent the Rabi season. In the GIS and remote sensing part of this project, methods were developed to estimate evapotranspiration using vegetation indices combined with meteorological observations, and to classify land use and land cover classes using multi-temporal visible and infrared images collected by satellite instruments (on-board the Moderate Resolution Imaging Spectro radiometer, MODIS, and the Advanced Very High Resolution Radiometer, AVHRR).

Global twice-a-month composites of the Normalized Difference Vegetation Index (NDVI) retrieved from AVHRR in combination with the ground-based meteorological observations (air temperature, relative humidity, wind speed, and sunshine duration) of the Indian Meteorological Department (IMD) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) were used as input into a modified Penman-Monteith model with biome-specific canopy conductance (Teluguntla *et al.,* 2013). Final ET estimates are 0.1-degree (approximately 10-km) gridded monthly average values from July 1983 to December 2006. Since June is the first month of the Kharif season, the June 1984 value was used to fill a gap in June 1983. The annual ET, which was used to calculate the long-term ET trend, were estimated from 1983 (June 1983 – May 1984) to 2005 (June 2005 – May 2006).

This research developed a new methodology to classify land use using cropping patterns in the Krishna basin. Individual snapshots of visible and infrared imagery exhibit similarity between different crops and pasture lands from which unique cropping and phenological patterns can be utilised to discriminate land use and land cover types in more detailed categories. This analysis resulted in the production of yearly land cover maps with 12-6 classes using unsupervised classification method applied to 16-daily (MODIS, 250-m resolution) ~ monthly (AVHRR, 10-km resolution) time series of satellite imagery. The final annual land use and land cover maps were produced at two separate resolutions: 250 m over the Musi sub-catchment and 10 km over the whole Krishna River Basin. The higher resolution (250 m) land use maps were used as input to the hydrological modelling at the Musi study catchment while the coarse resolution (10 km) maps were used for the whole basin scale ET mapping.

Mapping technology for rice paddies still remains in its infancy despite flooded rice paddies covering a great portion of agricultural land use in much of Asia. The above land use classification method was extended to include more complex rice paddy mapping algorithm. The algorithm takes advantage of the unique spectral pattern of rice paddies, showing a strong water signal followed by steep increase of chlorophyll signal occurring during the rice transplanting season, a time window of approximately 2-3 weeks. The Australia-India Land Surface Parameterisation Experiment (AILSPEX) supported the development of the algorithm, which included a two intensive field campaigns conducted in 2011-2012 as part of the project. As a result, the inclusion of the rice paddy maps in the ET algorithm greatly improved the accuracy of KRB-scale ET estimates.

Integrated surface-groundwater modelling

The main objective of the hydrological modelling component of the project is to assess the impacts of future climate change adaptation responses and watershed development on the catchment's water cycle. The water cycle (which includes surface, groundwater resources, demand and water use fluxes), is driven by two main forcing variables: climate and watershed development (land use and hydrological structures). The hydrologic modelling component of a wider integrated modelling framework (one that is informed by the climatic modelling and remote sensing analysis and includes both surface and ground water elements in it) is intended to provide the water cycle responses to these drivers. These will be later become inputs into the water allocation model and economic analysis.

The approach that was used to validate and evaluate the conjoint surface and groundwater models is given in Figure 5. At first, surface and groundwater models were developed for the of the Musi catchment. The surface hydrology model Soil Water Assessment Tool (SWAT) was calibrated at two gauging stations using observed streamflows, while the groundwater model (MODFLOW) was setup to include all the hydrologic and hydro-geologic variations across the Musi catchment. The groundwater flow model was calibrated against groundwater levels by perturbing the natural recharge from direct rainfall and artificial recharge from irrigation return flows, watershed development (WSD) structures and lakes.

Once both models were calibrated and validated separately, the recharge estimated by both models was compared to establish a measure of confidence in the performance and consistency in simulating the surface and groundwater hydrology models. The two models were then used to analyse several climate sequences arising from the regional downscaling of the GCMs for the Krishna river basin.

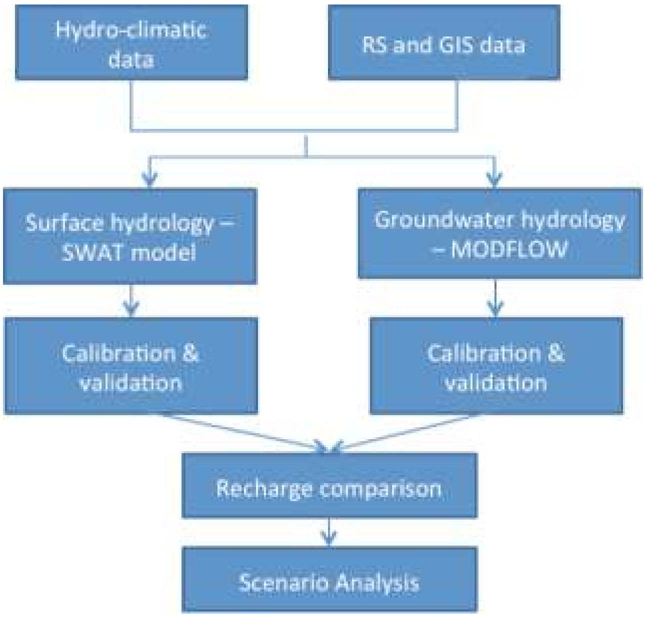

Figure 5. Conjunctive modelling of surface-groundwater

Surface hydrology model

Arc SWAT has been selected as the hydrological modelling tool for the Musi catchment. It uses a Arc GIS – Arc View extension and has a graphical user input interface to the **SWAT** model (Arnold *et al.*, 1998, Arnold and Nancy, 2005). The SWAT model is a process-based continuous hydrological model that can be used to assess the impacts of land use and hydrological structures on stream flows. SWAT use data on spatial variability in land use, soil and climate to capture human induced land and water management practices in a given catchment. The main model components are: climate, hydrology, erosion, plant growth, nutrients, pesticides, land management, channel and reservoir routing.

Surface runoff and infiltration are estimated either from daily rainfall using modified SCS-CN (USDA-SCS, 1972) method or the Green-Ampt infiltration, while the Muskingum method is used carried out the channel routing. The model estimates potential evapotranspiration using any of three methods: the Hargreaves method, Priestley-Taylor method or the Penman-Monteith method. SWAT simulates plant growth by using a generic crop growth model which first calculates plant growth under optimal conditions and then computes the actual growth under stresses arising from water, temperature, nitrogen, and phosphorous deficiency.

Data pre-processing in Arc SWAT involve three steps: watershed delineation, hydrological response units (HRU) and a weather data definition. Based on the stream network the model divides the watershed into sub basins. These sub basins are further sub-divided into HRU's, which consist of homogenous land use and soil characteristics. The HRU's represent percentages of the sub-basin area that are not spatially identified.

Initially, the model was calibrated and validated using historical forcing data (daily rainfall, maximum and minimum air temperature). Rainfall data from 10 precipitation stations were used in setting up the model. Once the model was calibrated and validated, the model was run using the PRECIS climate simulation data covering the period 1960-2096 under three QUMP simulations (Q_0, Q_1 and Q_{14}). These model outputs were then analysed and comparisons were made for the periods 1980-2010, 2011-2040, 2041-2070 and 2071-2096.

Man-made hydrological structures can be represented in the SWAT model as a reservoir. SWAT can only accommodate a single reservoir at the outlet of each sub basin. To overcome this constraint, the hydrological structures in each sub-catchment were aggregated into a single structure with an equivalent estimated storage area. The volume–area relationship to estimate the storage volume was calculated using data collated from a field survey of structures. The single reservoir is implemented at the outlet of each sub-basin to harvest the runoff equivalent to the storage volume. The impact of hydrological structures on stream flow is analysed by running the model with and without any structures and comparing the output stream flows. In this analysis, the structure volume was assumed constant throughout the simulation period.

Groundwater hydrology

Hard rock aquifer systems provide groundwater resources that are vitally important for the millions of smallholder farmers in India who derive their livelihoods from these water resources. It is anticipated that uncertainties and future water crisis will be more likely in the hard rock aquifers due its low storage capacity and adaptability (Gosain et al., 2006).

The limited storage capacity of hard rock aquifers means that increasing demand and associated stresses due to rising population, increased industrialization and agricultural intensification are more strongly felt than in alluvial aquifers. However, the low storage capacity also means that groundwater levels in hard rock aquifers respond quickly to changes in recharge and discharge (Surinaidu et al., 2013).

The groundwater flow model for the entire Musi basin (11,257 km^2) was developed using a spatially discretised 1.0 km^2 grid resolution that uses the finite difference based groundwater flow simulator MODFLOW implemented using the Visual Modflow 2011.1 graphical interface. The basin was divided into eight sub-watersheds (WS1 to WS8) according to the National Watershed Atlas of India (NWAI) methodology to estimate water fluxes at the sub-basin scale.

The subsurface environment was characterized and conceptualised by compiling and analysing available geological, geomorphology, fracture density, bore well geologic logs and hydrograph observations data (Surinaidu et al., in prep.). Although the aquifers are highly complex due to discontinuities and anisotropy induced by the fracture networks in the fractured or weathered layers, this complication can be overcome at a larger scale by making equivalent porous medium (EPM) approximations, resulting in the catchment being conceptualised as a two layer aquifer system with total aquifer thickness varying from 30 to 46 metres.

The Government of Andhra Pradesh well census data and irrigation statistics were used to estimate groundwater pumping supplemented by pumping duration and rate from previous groundwater investigations in the basin (Massuel et al., 2013). The pumping rates vary spatially depending on land use pattern on different geomorphologic units and pumping well density. The total number of wells in the catchment used in the groundwater model increased from 68,000 in 1989 to 210,000 in 2010. The total recharge assigned to each of the 8 sub-watersheds was based on the contributions from direct rainfall recharge, irrigation return flows and artificial recharge. These historical trends of groundwater pumping and recharge and their relationship with rainfall from 1989 to 2010 were used to project future pumping and recharge.

It was assumed that WSD structures have increased linearly relative to current structures by a factor of 2 between 2011-40, by a factor of 3 between 2041 and 2070 and by a factor of 3.5 between 2071 and 2096. This also implies that net recharge from WSD structures have increased proportionally. It is also assumed that one filling of structures occurs for rainfall events greater than 25 mm which translates into a total of nine fillings in wet years and four fillings in dry years based on daily rainfall analysis in the catchment.

The Musi River forms part of the MODFLOW simulation river package. The river bed elevations are taken form DEM data and topographic maps. The western and south eastern edges of the basin were set as a specified head boundary condition calculated for each time step as a function of the piezometric gradient.

Water security modelling

The aim in this component of the analysis was to assess how the quantities and security of water in the catchment are affected by changes in the climate and by the responses that were identified in the stakeholder analysis. *Water security*[3] is the product of combining water resources availability and water demands imposed on the resource across the whole of the catchment taking into consideration all the water uses and related infrastructure. The total water demand imposed on the system includes all competing uses of water including agriculture, environmental and urban-industrial demand. Variations in future climate are also expected to impact on water demand for agriculture and other uses. The modelling of water security is based on the integration of resource availability and water demand through a network allocation model. The Resource Allocation Model (REALM) was used for this purpose. More detailed description of the model is provided in George et al. (2011) and Perera et al. (2005). The REALM water security modelling assessment relies on outputs from the surface and groundwater availability assessment and a combination of all demands imposed on the catchment system – agriculture, urban and industrial (Figure 4).

In the Musi sub-basin, the water allocation model integrates all water sources internal and external to the catchment including the Nagarjuna Sagar project and Singur and Manjira projects, which lie outside the Musi. Despite lying outside the catchment, the Nagarjuna Sagar project is considered an integral part of the system as it is the main source of water supply to Hyderabad city since 2004 and also supplies water to irrigate the lower part of Musi sub-basin. In total, eleven supply structures and fourteen demand centres are included in the model (Figure 6) The main storages are Osman Sagar, Himayath Sagar, Manjira, Singur, Nagarjuna Sagar, Musi medium, wastewater, Musi Anicut and four groundwater nodes. The main demand centres are Hyderabad urban, industry,

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[3] *Water security in this study is defined as the expected availability of water at a specified level of probability of exceedance. Conversely, water security risk is the probability associated with obtaining the same volume of water or less.*

wastewater irrigation, Suryapet urban, Musi Anicuts, Musi medium irrigation area, Nagarjuna Sagar left and right canals, the Krishna delta and four groundwater irrigation nodes. The model requires the definition of supply priorities according to current institutional arrangements in the catchment. These specify that the first priority is to meet urban demand followed by industrial demand and then agriculture.

The model considers groundwater usage as a supply source that is set to extract water up to a sustainable yield established through groundwater modelling of the Musi catchment using the MODFLOW model.

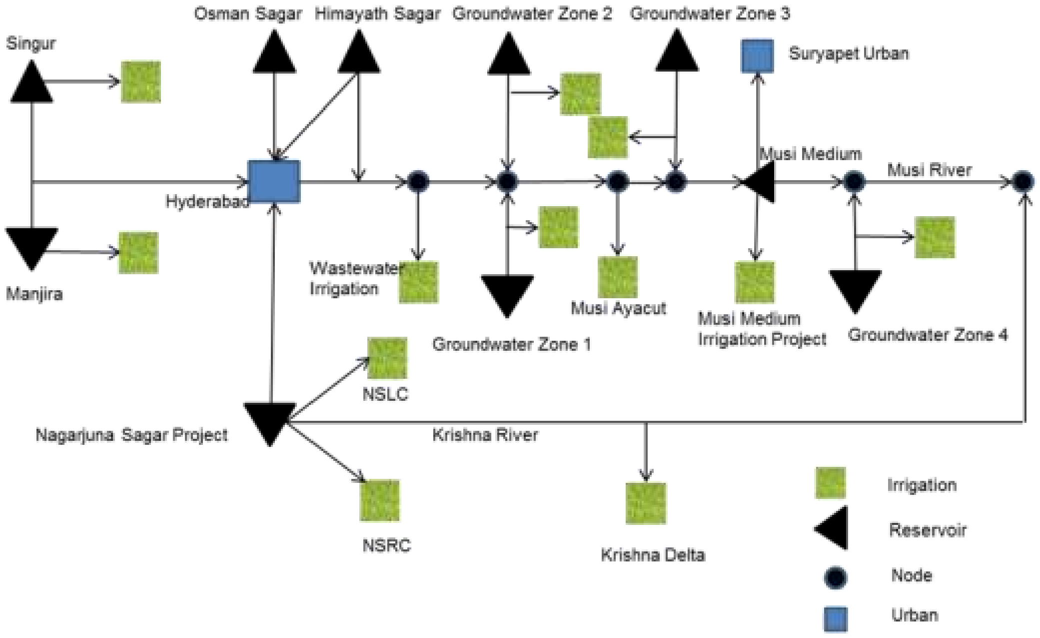


Figure 6. Schematic of water allocation model for the Musi system

Cost-effectiveness of adaptation

A hydro-economic modelling effort was undertaken to assess the impacts various climate scenarios and adaptation responses have on agricultural water users. The aim in this assessment was to evaluate the cost-effectiveness of either maintaining or improving the degree of water reliability in various nodes in the catchment (see Davidson et al forthcoming). While the ‘effectiveness’ is measured in terms of the level of reliability (i.e. the quantity of water required to maintain supplies for a given level of reliability), the costs include not only those associated with an adaptation response, but more importantly the net costs of maintaining a desired level of reliability. To put this another way, maintaining a degree of reliability involves holding water back for future use making it unavailable for use in a current period. The hidden costs of holding water back need to be accounted for and included as a counter to the benefits obtained from a certain level of reliability (which are also accounted for as it is the ‘net’ costs that are of interest), along with the costs of an adaptation strategy. A more detailed discussion of the concepts of water reliability and security is presented in Appendix 11.C.

A complex process is involved in gathering the data needed to undertake this analysis. A climate model feeds into a model of the surface and ground water in the catchment. This model then provides inputs into an allocation model (REALM), which is used to determine the flow duration curves and quantities of water reliably supplied to different nodes in the Musi catchment at different levels of reliability. The average values of water used at different nodes in the catchment was derived from Hellegers and Davidson (2010). The costs of each adaptation strategy were derived from the 2030 Water Resources Group (2009) report, *Charting our Water Future*.

For the sake of brevity in this component of the research it is assumed that:

- Population and water demand growth is fixed at 2% per annum. To assess the impacts of population growth on this catchment see George et al (2011 a, b).
- Water reliability, the policy objective in this study, is set at 80%. In other words, averagely over the whole system policy makers desire water to be supplied at 80% reliability. To further understand the impacts of changing reliability on the Musi catchment see Davidson et al (forthcoming). An 80% reliability rate was chosen was found that on average if the system is run at 80% reliability, the benefits will just outweigh the costs of running the system. In other words, it will break even.
- One of only three future climate scenarios will occur, resulting in a dry, wet and average season. These scenarios coincide with those mentioned above.
- One of three ‘responses’ are considered; a change in cropping patterns from rice to more water efficient crops across the catchment, making a 10% improvement to water efficiency in the irrigated zones, and developing WSD at twice the current rate in the dryland zones.
- Responses and climate change impacts are all assessed independently.

The capacity to evaluate the hydrologic and economic performance of each scenario and/or response combination is critical to assist decision making in water management adaptation to climate change. The evaluation of scenario-response combination in this project is based on their water security and cost-effectiveness relative to the Business-As-Usual (BAU) baseline. This involves valuing water in the Musi catchment for each scenario-response combination. Values are important because they add another dimension to the dual-criteria upon which decisions are made. The hydro-economic performance of combinations resulting from three climate futures and three responses (efficiency improvement, crop diversification and watershed development) for nine zones within the Musi catchment were evaluated (see Figures 2 and 6).

6 Achievements against activities and outputs/milestones

Objective 1: *To compile and synthesize the current understanding of historical climate change in the Krishna and Murrumbidgee basins and model future regional climate change scenarios*

No.	Activity	Outputs/ milestones	Due date (adjusted date)	Status and comment
1.1	Collection and compilation of climatic data (sub-basin and basin levels). Analyse historical data to assess past climate changes	• Project Inception (Project Team)	Jan 2010 (May 2010)	COMPLETED MAY 2010. All the participants in the project attended this workshop, along with representatives of the other ACIAR cluster funded projects in India. In this workshop a detailed project plan was developed and methods for integrating the various components of this project together, both internally and externally with other related ACIAR projects were established.
		• Collation of historical data (PC,A)	Feb 2010 (June 2010)	COMPLETED JUNE 2010. Historic climate data were collated from IMD. The collated data consist of interpolated data on rainfall, maximum and minimum temperature, RH, solar radiation and wind speed of all grids in the Krishna Basin. Station data were obtained for few stations.
		• Preliminary analysis of climatic data (PC, A)	March 2010 (July 2010)	COMPLETED JULY 2010 Results were presented at the project team meeting in Sept 2010. The team suggested some additional analysis on the dates of onset of monsoon. In the Musi catchment, seasonal rainfall was found to be increasing and monsoon season temperatures show a significant rise that is similar to the rest of the Krishna basin.
		• A report on historical changes in both basin (PC,A)	May 2010 (Sept 2010)	COMPLETED OCT 2010 Detailed climate data analysis was completed in Dec 2010 and results were discussed at progress review meeting in Feb 2011. A report is attached
1.2	Development of high resolution climate scenarios using Regional Climate model	• Developing the climate model scenarios (PC)	July 2010 (Nov 2010)	COMPLETED DEC 2010 The QUMP global simulations, comprising of 17 versions of the fully coupled version of HadCM3 from Hadley Centre were collated.
		• Calibration and validation (PC)	Sept 2010 (Jan 2011)	COMPLETED JAN 2011 The 17 simulations were compared with historical data and three best

				simulations of historical climate were selected for further downscaling (Qo, Q_1, Q14).
		• Downscaling the output to sub catchment level (PC)	Oct 2010 (Feb 2011)	COMPLETED MARCH 2011 The PRECIS simulations corresponding to the IPCC-SRES A1B emission scenario were completed for the three selected QUMP scenarios. The downscaled climate outputs were available for 357 grids in the Krishna Basin.
		• Generating future scenarios (PC)	Nov 2010 (March 2011)	COMPLETED APRIL 2011 High resolution (50km x 50km) climate outputs were generated for the period 1961-2098. The outputs consisted of rainfall, maximum and minimum temperature, relative humidity, solar radiation and wind speed.
		• Time series of climate data (PC)	Dec 2010 (April 2011)	COMPLETED APRIL 2011 Climate output was made available at 50 km by 50 km grid scale to all project partners in April 2011 (Three scenarios)
1.3	Conduct sensitivity and uncertainty analysis of various climate projections from the regional climate model.	• Robust model (PC) • Uncertainties identified (PC) • Identify sensitivity of different model parameters (PC)	January 2011 (May 2011)	COMPLETED JUNE 2011 Simulations from the downscaled ensemble Q_0 showed a 2% to 6% decline in precipitation in the period 2020/30, followed by an increase in rainfall towards the middle of the next century. Q_1 is the driest scenario which shows consistent decline in precipitation. Rainfall variability is expected to increase as this century progresses and rainfall deficient years are likely to be more severe. The output from the climate model is manipulated to use in the hydrologic models.
1.4	Analyse the frequency of droughts and floods and the onset and advance of monsoons in the Krishna basin and changes in climatic patterns	• Probability of drought and flood occurrence (A, PC)	Feb 2011 (June 2011)	COMPLETED JULY 2011 The simulations for A1B scenarios over the Krishna basin do not indicate any significant change in the frequency of deficient years in the future, compared to the model baseline. However, the deficient years may be more severe towards the 2080s, compared to the baseline period.
		• Information of shift in monsoon start date (A, PC)		COMPLETED JULY 2011 Detailed analysis on onset and advance of monsoons is completed. South-west monsoon arrives first in the southern parts of the basin around the 7th June. No clear-cut boundary is seen between withdrawal of the southwest monsoon and the onset of the north-east monsoon. The monsoon finally withdraws from the

				basin by end of October.
		• Report on climate change impacts on rainfall, temperature and frequency of occurrence (A,PC)		COMPLETED JULY 2011 Detailed report on climate change impact analysis is completed in July 2011 and was discussed in progress review meeting in 2012.

PC = partner country, A = Australia

Objective 2: *To assess the combined impact of watershed interventions and climate change projections on surface and groundwater hydrology at different scales*

no.	**Activity**	**outputs/ milestones**	**due date (adjusted date)**	**Status**
2.1	Collection and compilation of hydrologic and water demand data (sub-basin and basin levels)	• Collation of watershed data (PC, A)	July 2010 (Nov 2010)	COMPLETED JUNE 2011 A detailed field survey was carried out to collate the data on WSD structures. This data set was used to develop volume-area relationship of each type of hydrologic structures (Check dam, percolation pond, mini-percolation tank etc.). This data together with statistical data collected from government departments was used to set up the hydrologic model.
		• • Collation of Remote sensing data (A, PC) ● ● ● ● ● ●	July 2010 (Nov 2010)	COMPLETED DEC 2010 AVHRR and MODIS data for RS has been collected and collated. (Appendix A). Cloud-free images of Landsat-5 and Landsat-7 that included the Hyderabad lysimeter station were collated for the years 1998 and 2000 to calibrate the remote sensing product with the lysimeter data
		• Field experiments for ground truthing (PC, A)	Sept 2010 (Jan 2011)	COMPLETED AUGUST 2012 Detailed field experiments for ground truthing were carried out in Feb 2011 and August 2012. Field measurements were taken at 42 sampling locations on 16 different land uses. The ground data collected include 12-band reflectance measurements by CROPSCAN (model MSR16 by CROSCAN, Inc.), surface

				skin temperature, soil temperature values at the top 1 cm, 5 cm and 10 cm, vegetation height, soil moisture content at the top 5 cm by the theta probe soil moisture sensor (model ML2 by Delta-T Devices Ltd.
		• Surveys to understand groundwater pumping information (PC,A)	Oct 2010 (Feb 2011)	COMPLETED JUNE 2011 A detailed survey on groundwater pumping was carried out in the upper Musi catchment and a watershed development structures dataset was also collated. The groundwater pumping data collected for a small sample size is then extrapolated to use for the Musi catchment.
2.2	Remote sensing analysis of land use and evapotranspiration of study basins	• Remote sensing analysis to assess the impact of watershed development and land use change (A)	July 2011 (Nov 2011)	COMPLETED DEC 2011 The analysis using MODIS and AVHRR data to assess land use change was completed in March 2011. The analysis shows that land use has changed significantly in areas where irrigation development has occurred.
		• Remote sensing analysis to estimate distributed ETo (A)	July 2011 (Nov 2011)	COMPLETED DEC 2011 Monthly time series of ET maps over the Krishna River Basin have been produced from 1983 to 2001 using AVHRR satellite imagery and spatially distributed monthly ET estimates at 1-km resolution from 2000 to present in the Musi catchment were completed. This information can be used for additional hydrologic model validation.
2.3	Develop and couple distributed surface and groundwater hydrological models	• Develop a coupled surface-GW model (A, PC)	Sept 2011 (Jan 2012)	COMPLETED AUGUST 2012 A semi-distributed surface hydrological model was developed for the Musi catchment using the SWAT software. Initially, the model was calibrated and validated using historical forcing data (daily rainfall, maximum and minimum air temperature). Rainfall data from 10 precipitation stations were used in the model. A MODFLOW groundwater model was developed for the catchment. The model coupling was not done due to difficulty in getting the coupled model source code from SWAT developers. But the model outputs of both SWAT and MODFLOW were compared for consistency.
		• Linking remote sensing data with hydrological model (surface and ground water (A)	Oct 2011 (Feb 2012)	COMPLETED SEPTEMBER 2012 Land use, soil and DEM were used to develop the hydrologic model. The actual ET estimated by using remote sensing was compared with SWAT estimated ET at the HS catchment. The WSD structures dataset reported by the government statistics was verified by sampling Google maps.

		- Understood the interaction between surface and ground water (A, PC)	Dec 2011 (April 2012)	COMPLETED APRIL 2013 The recharge estimated by SWAT and MODFLOW at two sub basins were compared. Further analysis was carried out during the scenario model runs, which provided a more complete understanding of the spatial surface-groundwater interactions. Such an understanding has been critical in capturing the spatial availability of both resources.
		- Model calibration & validation (A)	Mar 2012 (July 2012)	COMPLETED APRIL 2013 The surface hydrology model was calibrated by adjusting the SWAT parameters manually such that the resulting stream flows at the downstream produce should match the observed inflows at two gauging stations. The groundwater model was calibrated and validated using observed water level data. Surface hydrology and groundwater models were calibrated individually and the recharges estimated by both models were compared. Further testing of the coupled models was carried out prior to their use to simulate adaptation responses which showed the models are performing adequately. The models were coupled asynchronously due to incompatibility of the two models to be coupled synchronously.
2.4	Assess the impact of storage structures, land use and climate change on stream flows and groundwater (sub-basin scale)	- A hydrologic modelling framework integrated with climate model (A)	Feb 2012 (June 2012)	COMPLETED APRIL 2013 The hydrological modelling framework was completed and integrated and use of the model for scenario analysis had commenced. The SWAT model was used to estimate the future streamflows, using the projected rainfall and meteorological data for the Q_0, Q_1 and Q_{14} QUMP scenarios generated using the PRECIS model.
		- Assess the impact of climate change on surface-GW hydrology (A)	March 2012 (July 2012)	COMPLETED APRIL 2013 Analysis of CC impacts in the Musi catchment has been undertaken for the three QUMP scenarios. Results are presented in surface hydrology section of this report. (Appendix B). Potential evapotranspiration (PET) showed an increasing trend throughout the time slices analysed for all the three scenarios. The streamflow doesn’t show any specific trend for different periods and for three scenarios.

		• Assess the impact and WS development on surface-GW hydrology (A)	March 2012 (July 2012)	COMPLETED MAY 2013 The surface hydrology model was run with reservoirs and without reservoirs for the period from 1995 to 2098 in order to assess the impact of WSD on inflows. It was observed that stream flows have reduced due to the impact of hydrological structures in the catchment.
		• Analysis of scenarios (A,PC)	July 2012 (Nov 2012)	At this point in the project we have modelled and analysed the four adaptation responses identified by the stakeholder consultation for climate scenario Q_0. This is deemed to be a middle range climate scenario. The surface-groundwater model outputs are used to analyse the level of water security. The outputs are used to carry out the economic analysis to determine their economic performance using a cost-effectiveness approach.

OBJECTIVE 3. *DEVELOPMENT OF A FRAMEWORK FOR IDENTIFICATION OF STAKEHOLDER DEFINED ADAPTATION SCENARIOS IN THE CONTEXT OF RELEVANT POLICIES*

no.	**activity**	**outputs/ milestones**	**due date of output/ milestone**	**Progress to date**
3.1	Institutional mapping and review of water resources policies and programmes being promoted in the basin.	• Database of existing policies and programs (PC) • Stakeholders identified (PC, A)	Sep 2010 (Jan 2011)	COMPLETED JAN 2011 A database of existing policies and programs were collated in Feb 2011. Details are presented in first annual report (Appendix C). COMPLETED JAN 2011 A detailed mapping of stakeholders was developed for all the four stakeholder tiers.
3.2	Study of socio-economic aspects and water utilisation patterns at sub-basin and basin levels	• Data collection and analysis reports (PC) • Development of a socio-economic database (PC) • Data validation (PC)	Dec 2010 (April 2011)	COMPLETED APRIL 2011 Documentation and analysis of socio-economic aspects in Krishna basin states was completed.

3.3	Develop a framework for identifying adaptation scenarios	• Framework ready (A, PC) • A list of adaptation scenarios developed (PC, A)	Dec 2011 (April 2012)	COMPLETED APRIL 2012 A comprehensive framework was developed on the basis of stakeholder consultation and literature review COMPLETED APRIL 2012 A list of adaptations options was prepared which was presented at the stakeholder workshop held in Feb 2012 for consideration and discussion.
3.4	Use of water modelling outputs to demarcate regions of water stress both upstream and downstream (sub-basin and basin scales)	• Water stress region identified (PC, A) • Linking allocation models with socio economic data (A, PC)	July 2011 (Nov 2011)	Consultations with farmers has been conducted in water stress regions of Andhra Pradesh and Maharashtra to characterise these areas. These consultations also allowed us to refine the elicitation of the final scenario responses.
3.5	Undertake stakeholder consultations to identify and characterize key water management issues that will be affected by climate change (sub-basin and basin scales)	• Scenarios developed and documented (PC, A)	March 2012 (July 2012)	COMPLETED JULY 2012 Identification of concerned stakeholders and site selection was completed followed by the first round of consultation in Krishna basin states at institutional level, district level and village level in all three states has been completed. A set of 50 scenarios are initially identified. Refining of these scenarios in the order of importance is in progress Subsequent stakeholder consultations were completed at four different tiers spread across government (Central, State, District and Village), academics farmers as well as households. Adaptation options to be taken forward for modelling were finalized during the project workshop held in Pune, India on 24, September, 2012. A further round of consultations were maintained with stakeholders (Tier 2 (State Level) and Tier 3 (District Level) in February 2013. In this consultation, preliminary climate and hydrologic modelling results were presented and feedback received from stakeholders. The consultation process and outcomes were presented at a project cluster meeting held at Walamtari, Hyderabad on 14 March 2013.
3.6	Project socioeconomic conditions – taking into account some critical parameters	• Detailed scenario analysis (PC, A)	Dec 2012 (April 2013)	Modelling scenario results were discussed with stakeholders on an on-going basis together with potential socio-economic and hydrologic implications.

3.7	Suggest measures to modify policies that effectively capture the risks	- Risk assessment done (PC, A)	Dec 2013	The water security risk assessment which forms part of the hydrologic analysis was in progress at this point. A full assessment of risk was planned to be carried out upon completion of the water security analysis for each adaptation response. -

OBJECTIVE 4: *TO INTEGRATE THE HYDROLOGICAL OUTPUTS FROM OBJECTIVES 1 AND 2 AND CREATE A COUPLED HYDRO-ECONOMIC METHODOLOGY TO ASSESS RESPONSE STRATEGIES TO THE COMBINED IMPACTS OF CLIMATE CHANGE AND WATERSHED DEVELOPMENT AT BASIN AND SUB-BASIN LEVEL*

no.	activity	outputs/ milestones	due date of output/ milestone	Progress to date
4.1	Enhance an existing coupled water allocation-economic model to assess adaptation responses (sub-basin and basin scales)	- Enhance the existing water allocation model (A)	Aug 2012 (Dec 2012)	The Water Allocation model REALM was at this point being setup with preliminary hydrologic data from SWAT and MODFLOW models for the purpose initial testing. REALM will be subsequently populated with hydrologic data from the selected adaptation scenarios. Following the initial setup, the REALM (Resource Allocation Model) was recalibrated and tested to represent current infrastructure and cropping conditions in the catchment. The model was used to simulate and examine the level of water security associated with each combination of climate scenario and adaptation responses. A full set of adaptation responses for climate scenario Q_o had been completed at this point in the project with plans to complete the modelling and analysis of all combinations of climate scenarios and adaptation response in the month of February 2013.
		- Development of economic model (A)	Sept 2012 (Jan 2013)	COMPLETED JUNE 2014 An economic model was developed in which the cost effectiveness of various policy innovations can be measured. This model was used to assess the costs of various levels of water reliability arising from different adaptation strategies and from different climate scenarios. The model was tested and complied with economic theory.

		• Linking the economic model with allocation model (A) • Model(s) verified using historical flows and water balance (A) • Uncertainty analysis in water allocation models (A)	Oct 2012 (Feb 2013)	Data from a number of a number of scenario-response combinations were generated from the REALM allocation model. This data was run through the economic model and preliminary results were derived. This tasks was completed for the hydrologic models (SWAT, MODFLOW & REALM) at various stages of the project described above. The economic model is not subject to this verification as it is not applicable. Uncertainty analysis forms part of the overall water security analysis carried out for each combination of climate scenario and adaptation responses. Uncertainty was assessed using the full range of climate and hydrologic model predictions together with their impact on the level of water security
4.2	Develop a methodology for evaluating hydrological and economic changes that result from different adaptation scenarios (sub-basin and basin scales)	• Methodology developed (A) • Ability to use methodology and models (A) . •	Sept 2012 (Jan 2013) Oct 2012 (Feb 2013)	The methodology for evaluating hydrological and economical changes has been documented and was published in the MODSIM conference in 2011. Methodology has been tested with the first model runs using baseline climate scenario and 3 adaptation responses - Baseilne, improved irrigation efficiency and crop diversification - The ability of the models and methodology was demonstrated by an adequate performance of the modelling suite in delivering the initial set of scenario results.

		• • A tested methodology available for detailed assessment (A)	Dec 2012 (Apr 2013)	Assessment of the scenario results consists of hydrologic and economic assessment. The tested methodology was used to assess a combination of climate change scenarios and adaptation responses. This assessment allowed for a full test of the methodology which was shown to be adequate for further similar assessments.
4.3	Assess the hydrologic and economic trade-offs that occur between upstream and downstream users, due to future watershed development (sub-basin scale)	• Assessment of economic impacts of watershed development (A, PC) • Assessment of economic losses in the command (A, PC) • Trade off analysis (A, PC)	Jan 2013 (May 2013) Feb 2013 (Jun 2013) Feb 2013 (Jun 2013)	Preliminary analysis has been undertaken and cost-effectiveness ratios have been developed for middle range climate scenario (Q_0) and three adaptation responses – Baseilne, improved irrigation efficiency and crop diversification - The economic assessment of each scenario-response combination clearly indicates their relative performance in relation to BAU. This ratio can be used to determine whether economic losses may occur with any of these combinations. The comprehensive scenario-response analysis shows various trade off that occur between water security and actual cost-effectiveness for each adaptation strategy. This assessment framework has shown to be particularly suited for this trad-off analysis.
4.4	Assess the long term implications of climate change and watershed adaptation policies on water security (sub-basin and basin scales)	• Adaptation policies modelled (A) • Water security assessed (A) • Assessment of risk and uncertainty (A)	July 2013 (Nov 2013) Aug 2013 (Dec 2013) Sept 2013 (Dec 2013)	A full set of adaptation responses has been evaluated for climate scenarios Q_0, Q_1 & Q_{14} as described earlier. Water security is one strand of the assessment process outlined above. Water securit has been assessed for the full set of scenario-response attached to all three climate scenarios. Risks and uncertainty were assessed for all scenario-response combinations as part

				of the water security analysis. Water supply-probability analysis for each combination was completed with selected level of security used to make the hydro-economic assessment.
4.5	Isolate the suite of feasible strategies and inform policy makers to develop adaptation measures with respect to the impacts of climate change and WSD on water security.	• Feasible strategies discussed with stakeholders (A, PC) • A set of policy documents prepared (A, PC)	Dec 2013	Holding extensive discussions with stakeholders where modelling outputs of hydrologic and economic performance were presented for the full range of scenario-response combinations was completed as part of the consultation process with stakeholders.

OBJECTIVE 5. *TO FACILITATE CROSS-LEARNING OF METHODOLOGIES AND ADAPTATION STRATEGIES TO CLIMATE CHANGE BETWEEN INDIA AND AUSTRALIA.*

no.	activity	outputs/ milestones	due date of output/ milestone	Progress to date
5.1	Select appropriate irrigation areas in the Murrumbidgee catchment for comparison of climate change impacts and adaptation policies	• Australian study area selected for comparative analysis (A)	Aug 2011 (Dec 2012)	The focus of this analysis has been changed to the Murray-Darling Basin. A preliminary literature review of climate adaptation in the basin has now commenced.
5.2	Analysis of climate change responses in selected areas of the Murrumbidgee catchment	• Downscaled climate data available (A) • Running climate output through hydrologic models (A) • A tested methodology available for detailed assessment (A)	Sept 2012 (Jan 2013) Oct 2012 (Feb 2013) Dec 2012 (Apr 2013)	See variation to future activities (Sections 6 & 8)
5.3	Comparative analysis of approaches to climate adaptation policies and potential outcomes in Australia and India.	• A report on generalities of policies and methodology (A, PC) • A joint workshop between Australian researchers and Indian researchers (A, PC)	Jan 2013 (May 2013) Feb 2013 (Jun 2013)	See variation to future activities (Sections 6 & 8)
5.5	Dissemination of methodologies for	• Organising annual workshops (A, PC)	Dec 2010	The project team meets once every six months to review

	selection and evaluation of adaptation approaches to climate change impacts in Australia and India.	•		progress and communicate findings to and receive feedback from stakeholders.
		• Project final workshop organised (A, PC)	Dec 2011,	A final workshop was organised in collaboration with ACIAR Project LWR/2010/0051 on 3-4 February 2015. (see appendix 11.E for workshop report) The workshop consisted of a set of papers presented from both projects with a focus on finding optimal pathways for translating project results into policy evidence. The workshop involved a number of high level water resource management officials which offered significant input to the workshop and ways to implement project results.
		• Policy briefs prepared and communicated (A, PC)	Dec 2012 Dec 2013	A project workshop with the stakeholders was organised in February 2012 and policy messages arising from this project have provided to the Climate Change Forum project led by WALAMTARI. An additional stakeholders meeting was held on the occasion of the final project review on 3-4 February 2014.
		• Presentation in international conferences (A, PC)	Nov 2013 Dec 2013	A number of papers has been presented in International Conference (See Communication and Dissemination section in Annual Report June 2013).
		• Project final report submitted (A, PC)	June 2014 (March 2015)	Project final report submitted.

PC = partner country, A = Australia

PC = partner country, A = Australia

7 Key results and discussion

7.1 Stakeholder engagement

Stakeholder consultation was an intensive process that involved regular interactions with the identified key stakeholders at three important tiers. A comprehensive methodology was used to develop the adaptation framework. Different stakeholders proposed different adaptation responses for various scenarios. The initial round was done on the basis of 'what-if scenario' which produced around 50 responses from various tiers.

A second round of consultations were carried out for the same set of stakeholders (at state and district levels) and villages to identify and weight the criteria that should be used to analyse the adaption options that were suggested by various stakeholders during the earlier Round. The main objective of this exercise was to select and prioritize the most important options at all tiers. The various forms used in these surveys are shown in Appendix 11.B.

The stakeholders at tier 2 and 3 were asked to identify criteria that were important from their viewpoint, and were also asked their opinion on the criteria that would be important from the farmers' perspectives. Subsequent consultations were conducted in the field to discuss criteria with farmers as well. The exercise yielded interesting comparisons between what the government officials perceive to be important to farmers and what actually is important to them. The criteria adopted discussed include the following;

- Scale of benefit
- Time for implementation
- Technical complexity of the project
- Social acceptability
- Visibility
- Political acceptability
- Focus on small and marginal farmers
- Whether the project had co-benefits

The key responses elucidated from the three main tiers are presented in Figure 7.

Additionally, each stakeholder was walked through a pairwise exercise for weighting the criteria against each other. This helped TERI to establish the weights to be assigned for each criterion. Subsequently, stakeholders were asked to score each option with respect to each criterion, and then a final score for each option was computed by multiplying the weightage with the score given.

These prioritized responses from all the important stakeholders of various tiers came after rounds of consultation and using various tools like pair-wise analysis and ranking criteria. At the village level, participatory approaches like Focused Group Discussions (FGD) were adopted to elucidate the adaptation responses. The adaptation responses were received under various categories and while some overlap occurred amongst the various tiers.

Figure 7. Key Responses from stakeholder tiers

To further refine the number of adaptation options, each short listed option was further discussed using the following criteria with a view to reduce the number of options and ensure that they were mutually exclusive and encompassing of most of the suggested options:

- Is it an adaptation strategy that enhances water security?
- Is it possible to subject it to water security and economic modelling?

Based on the above criteria and further discussions, a final list of four adaptation options was made from a long list of options at each tier. The finalized four adaptation options are listed in Table 1.

Table 1. Adaptation strategies adopted

Sl. No.	Adaptation Option
1	Changing cropping patterns
2	Increasing watershed development
3	Improve irrigation efficiency
4	Increase volume of groundwater extraction

In the final selection of adaptation strategies, Options 2 and 4 were combined into a single strategy as the two alternatives must be implemented together to allow for an increased volume of groundwater extraction.

7.2 Climate analysis and modelling

Spatio-temporal variations in the climate features of the Krishna Basin

Knowledge about the spatio-temporal variations in climate parameters is essential for analysing climate change adaptation responses within a river basin. Such information also forms the basis for the validation of climate projections generated by the climate models. The spatio-temporal variations of the climate features were analysed using daily gridded rainfall (1951-2009) and temperature data (1969-2005), and daily records on other climate parameters such as relative humidity, wind speed, sunshine hours at a few stations during the period 1969-2009 (with variable data length) in the Krishna river basin. The key variables analysed are rainfall characteristics such as annual cycle of rainfall, seasonal rainfall, onset and withdrawal dates of rainy season, number of rainy days/heavy rain days and excess/deficit years of rainy season are examined using observed data. This analysis also examined spatial patterns of trends in seasonal rainfall/temperatures.

It was found that annual rainfall of the Krishna basin is 78.3 cm, out of which 71% contributed by The Southwest Monsoon season (June to September). The Northeast Monsoon contributes 18% to the annual total.

The spatial patterns of seasonal rainfall indicate that the central part of the basin receives rainfall of the order of 40 cm owing to the rain shadow region of the Western Ghats, while the western part of the Basin located in the hilly region of the Western Ghats receives rainfall amounting to more than 200 cm during the season (Figure 8). The eastern part of the basin also receives heavy rainfall amounts due to the passage of monsoon disturbances originating in the Bay of Bengal and moving in southeast to northwest direction. The coefficient of variation (CV) is low in the parts of heavy rainfall zone because of low variability while regions of low rainfall have high CVs. The rainy season of the southern part of the Krishna Basin is of 142 days extending to the month of October. No substantial change in the southwest monsoon rainfall, its onset and duration is observed during the last 50-60 years, while an area in the eastern part of the basin shows rise in the seasonal rainfall.

In Figure 10, it can be observed that the average annual extreme daily rainfall accumulation is less than 70 mm in the central parts but it exceeds 150 mm/day in western hilly parts of the basin. Spatial pattern of linear trends for 100 year shows significant rise in the central and eastern part of the basin. Similarly, from the analysis it was found that heavy rain days are increasing significantly in the Krishna Basin which is seen from the CDF of daily rainfall series of the basin (as shown in Figure 10).

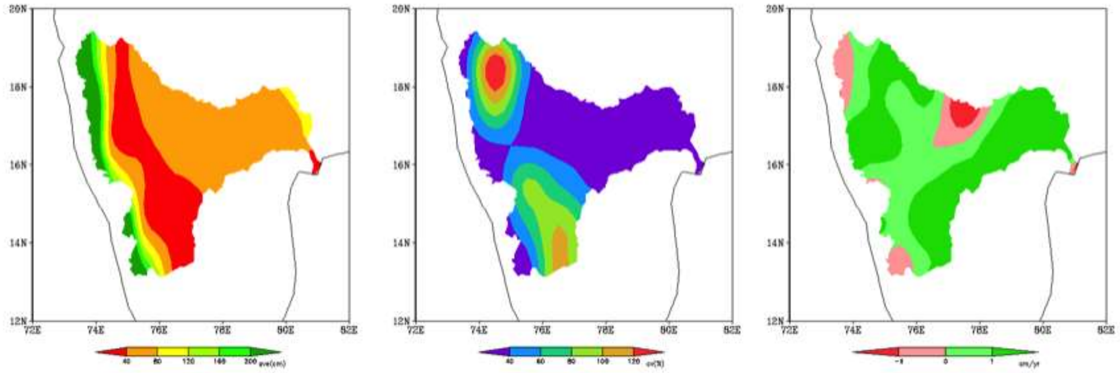


Figure 8. Spatial patterns of mean monsoon rainfall, coefficient of variation (%) and linear trend in the seasonal rainfall of Krishna Basin during 1951-2009.

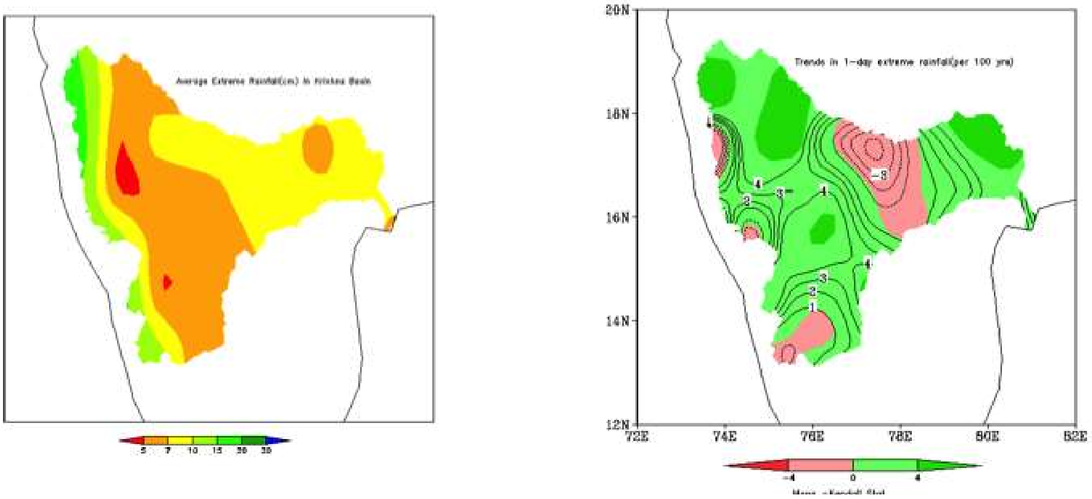


Figure 9. Spatial patterns of 1-day extreme rainfall and temporal changes

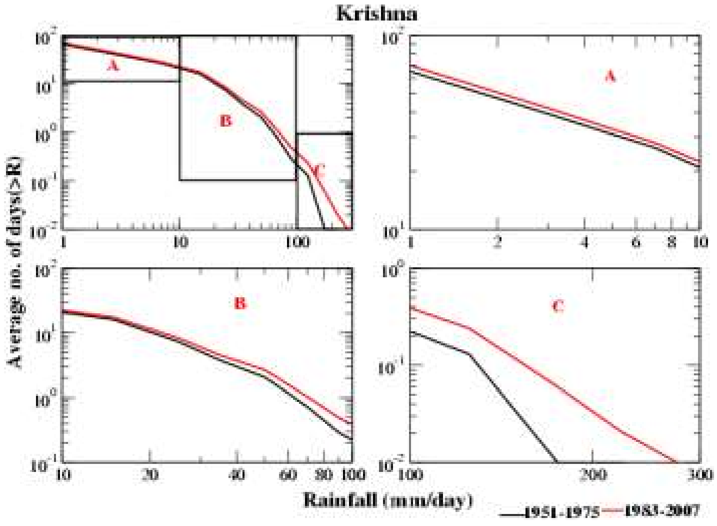


Figure 10. Cumulative distribution functions (CDFs) of daily rainfall in monsoon season in the basin

Daily gridded temperature datasets (mean, maximum and minimum) with 1-deg x 1-deg (lat/lon) resolution are analysed to examine the temporal variations in these parameters during the period 1969-2005 (Figure 11). Temperature data shows that maximum temperatures exceed 45^0 C in the eastern part of the basin while western part of the basin remains below 40^0C. Low values of minimum temperature ($<10^0$C) are recorded frequently in the northern parts of the basin. In the eastern part of the basin around 50 days are observed when temperature exceeds 37^0C while only 10 days have temperatures over 37 ^{0}C in the western part of the basin.

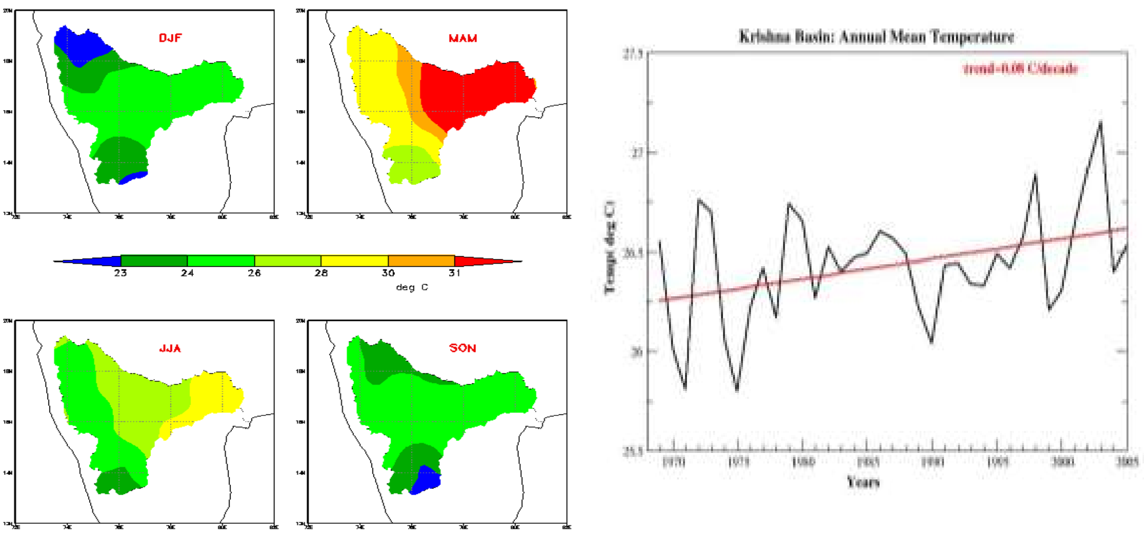


Figure 11.Spatial patterns of seasonal mean temperatures and trend of mean annual temperature in the Krishna basin.

Seasonal mean temperatures are increasing and the rise is statistically significant at a few places. However, annual temperature shows significant increase (0.08^{0}C /decade) in the Krishna basin as shown in the Figure 11. Hot days (>37^{0}C) are increasing (but not significantly) in the central parts of the basin.

Daily relative humidity (RH) was analysed for 30 stations during the period 1969-2009. Analysis indicates that RH exceeds 80% along the west coast in the month of June, while in July-August the entire basin (except central part) experiences humidity >80%. Humidity starts decreasing again in September. The minimum relative humidity is observed in the month of March (around 30%) for all stations except for Agumbe where it is 60 %, while humidity reaches its maximum in July-August (80%). The Mahabaleshawar and Agumbe stations, which are located in hilly stations in the Western Ghats, show 100% relative humidity in these 2 months. Most of the stations in upper Krishna Basin show increase in relative humidity during post-monsoon months.

Projected climate change over the Krishna River basin under global warming scenarios

The PRECIS simulations corresponding to the IPCC-SRES A1B emission scenario were carried out at 50 km x 50 km horizontal resolution over the South Asian domain for a continuous period between 1961 and 2098. Three continuous simulations are used to assess the range of uncertainty in model simulations as well as the impact of climate change on the Krishna River Basin for the three future time slices representing the near time horizon (2011-2040), medium (2041-2070) and long term (2071-2098).

The observed spatial distribution of rainfall and surface air temperature over the Krishna basin are reasonably well simulated by the model. However all the three PRECIS simulations present a cold bias of 1-2 ^{o}C over the western region of the basin and 1-2^o C warm bias over central and eastern parts of the basin.

The simulations for A1B scenarios over Krishna basin do not indicate any significant change in the frequency of deficit rainfall years in relation to the model baseline. However, the deficient years may be more intense towards the 2080s compared to the baseline. The changes in the frequency of excess rainfall years indicates high uncertainty among the three model simulations.

Simulation of seasonal precipitation and annual temperature

The gridded 1° x 1° daily rainfall data set prepared by the India Meteorological Department (Rajeevan *et al.*, 2006) for the period 1961-1990 was used to validate the model baseline simulations. QUMP simulations are already validated for the Indian sub-continent (Kumar *et al.*, 2011) and they simulate Indian summer monsoon climate reasonably well. The observed spatial distribution of rainfall over Krishna basin shows maximum rainfall over western parts of the basin and a gradual decrease towards the east with minimum rainfall over the south eastern parts of the basin. Rainfall again shows a slight increase over the eastern boundary. These features are well reproduced by the two QUMP simulations, Q0 and Q14, however both show a wetter bias on south eastern region. Q1 is able to capture the pattern reasonably well although it produces a dry bias over the entire basin.

The CRU (Climate Research Unit, UK) gridded monthly temperature data was used for the validation of the model-simulated temperature. The annual average temperature over Krishna basin is in the range 26-27° C. All the three QUMP simulations show a cold bias of 1-2°C over the western region of the basin and the warm bias of 1-2°C over the central and eastern parts of the basin.

Projected changes in seasonal precipitation and annual temperatures

The simulation of all three ensemble members predict a 2-6% increase in seasonal rainfall over the Krishna basin towards 2020s with respect to model baseline simulations (1961-1990). However towards the middle of the next century (i.e. 2050s) rainfall is projected to increase in the Q0 and Q14 members while Q1 predicts a decrease in rainfall. This decrease in rainfall in Q1 simulations may be inherited from the parent global run. Towards the end of the century (2080s), rainfall is projected to increase by 2-11 % as compared to 1970s in all the three ensembles. The analysis suggests that rainfall variability could be greater in the north-western part of the basin towards the end of present century.

Unlike precipitation, the mean annual temperature shows consistent warming in all three time slices. A projected warming of around 2.5° C is expected towards the end of the present century, i.e. 2080s. This warming is consistent in all the three QUMP simulation

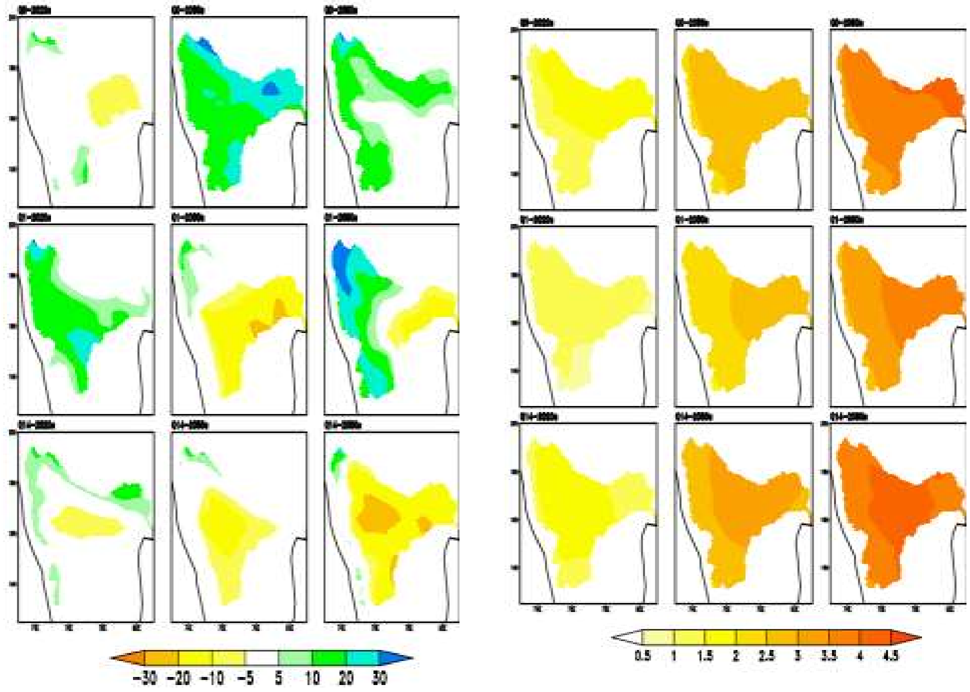
Predicted changes in the mean monsoon onset date

The southernmost grid in the Krishna basin (75.355°E, 13.45°N) where the summer monsoon sets in was selected using the normal onset date chart by IMD. The criteria used to define onset over selected grid is that if daily rainfall at this grid is greater than 2.5 mm for consecutive three days, of which the first day is identified as the onset date. The mean onset date varies from 24th May (Q0) to 16th Jun (Q14) in the model baseline simulations. However, there is little difference in variability of onset dates in the three ensemble members. Significant changes are not observed towards the end of 21st century both in either the mean onset date or its variability.

Predicted changes in excess/deficient monsoons

For the purpose of this analysis, a year is defined as deficient (excess) year if the seasonal rainfall over basin if rainfall is less than [mean - std. dev.] or greater than [mean std. + dev]. The excess and deficient years over the Krishna Basin were identified for the three time slices using this criteria. Q0 and Q1 indicate that there will be a decline in the frequency of excess years towards the 2080s whereas Q14 shows a likely increase of 8% increase in frequency of excess years.

The simulations for A1B scenarios over the Krishna Basin do not indicate any significant change in the frequency of deficient years in the future compared to the model baseline, as shown in Figure 12. However, the deficient years when they occur are likely to be more severe towards the 2080s in relation to the baseline. Variants Q1 and Q14 show that the composite rainfall during deficient years may be less in 2080s compared to model baseline simulations.



(a) (b)

Figure 12. (a) Changes (%) in summer monsoon precipitation over Krishna Basin using three PRECIS simulations Q0 (upper), Q1 (middle) and Q14 (lower), for 2020s (1st col), 2050s (2nd col) and 2080s (3rd col). (b) Same as (a) but for changes in mean annual surface air temperature over Krishna Basin using three PRECIS simulations

Summary of highlights:

- The annual rainfall of the Krishna basin is 78.3 cm, of which 71% is contributed in the Southwest Monsoon season (June to September). The Northeast Monsoon contributes 18% to the annual total.
- The rainy season of the southern part of the Krishna Basin is 142 days long extending up to October. No substantial change in the southwest monsoon rainfall, its onset and duration is observed during last 50-60 years, although some areas in the eastern part of the basin shows a rise in the seasonal rainfall
- The summer monsoon rainfall over the Krishna Basin may increase marginally towards the end of present century
- A change in annual average temperature of around 2.5 °C is predicted towards the end of the present century.
- Future projections do not indicate any significant changes in the mean onset date or its variability over Krishna basin.
- The simulations over Krishna basin does not indicate any significant change in the frequency of deficit rainfall years in future. The changes in the frequency of excess rainfall years project high uncertainty among the three model simulations.

7.3 GIS and land use

Human-induced changes in land use and land cover can influence terrestrial water cycle by altering surface geophysical properties and water fluxes. In the past several decades, large-scale irrigation development in India has contributed to important changes in freshwater redistribution over time and space. For example, a large number of irrigation developments were completed in the three states over the Krishna River Basin (KRB) – Andhra Pradesh (8), Karnataka (21), and Maharashtra (17) – in the period of 1982-2001 (*Government of Maharashtra*, 2005; *Government of Andhra Pradesh*, 2006). In this project, a spatially distributed monthly evapotranspiration (ET) estimated from satellite observations in the Krishna River Basin, India, was used to quantify the long-term trend of evapotranspiration (ET) for the 1983-2005 time period. The analysis compared the spatial distribution of the trend is estimated over the basin and basin-average trends for Kharif and Rabi seasons.

The spatial distribution of the annual ET trend in 1983-2005 is shown in Figure 13. On average, ET has increased at the rate of 3.48 mm/year/year in the period 1983-2005 over the whole basin. However, a close observation of the spatial map also exhibits some regions that have experienced a decrease in ET during the same period. The regions of steep ET increase are in general overlapping the irrigated agricultural regions where the major irrigation developments were completed during this period. The irrigation commands in Maharashtra and Karnataka feature the largest ET increase regions. On the other hand, the majority of the rainfed agricultural land in southern Krishna basin and the dryland agricultural land in the central KRB experienced a slight decrease in Et. The decrease in Et over the north-eastern wing of KRB, represented predominantly by irrigated agricultural lands, indicates that irrigation over the region reached the recent level prior to our analysis period. This region features the highest ET on average for the analysis period.

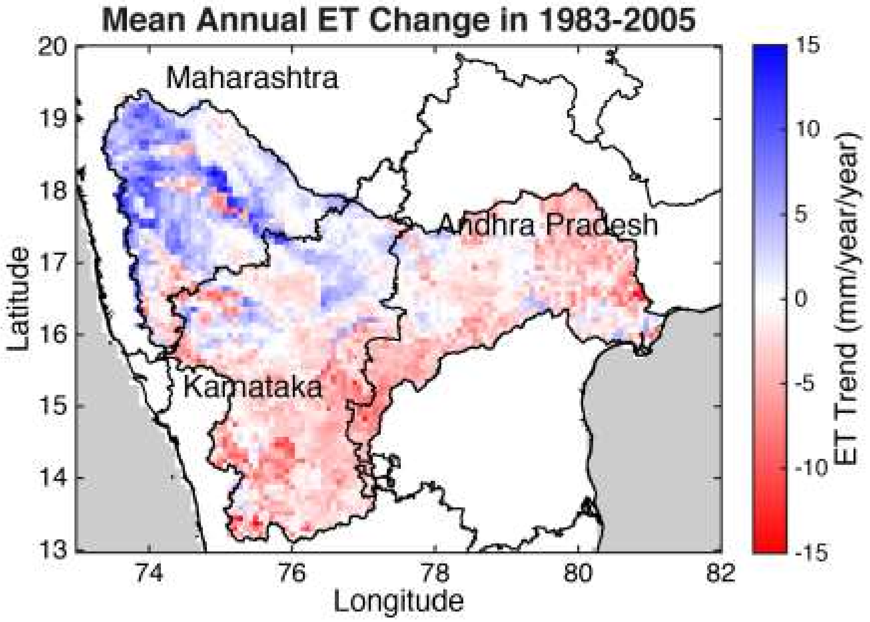


Figure 13. Average annual ET trend map in 1983-2005 over the Krishna River Basin.

Basin-average ET trends at monthly and yearly time scales are shown in Figure 14. On average, annual ET over the KRB increased by 13.4% between 1983 and 2005 (Figure 12b). The rate of ET increase was steeper in 1983-1994 when the majority of the irrigation development in the three states over KRB (31 out of 46) was completed, then declined noticeably in the 1995-2005 period. The inter-annual fluctuation of ET is highly correlated with the temporal pattern of annual rainfall, although the rainfall pattern does not show any significant trend during the analysis period. *Teluguntla et al.* (2013) reports that the Et trend is more closely associated with the increase in surface biomass for the period, which is quantified by NDVI derived by AVHRR, and that the ET increase rate is higher over the irrigation commands areas they analysed.

A steeper increase of ET during the low ET season (typically March-May) compared to the high ET season (September-November) is shown in Figure 14a. Separate estimation of ET increase rates for Kharif and Rabi seasons, 9.0% and 20.3%, respectively, in 1983-2005, confirms the higher increase in the low ET season. This result supports the interpretation that the increase in annual ET was driven by irrigation development given that agricultural irrigation is more consistently applied on Rabi crops.

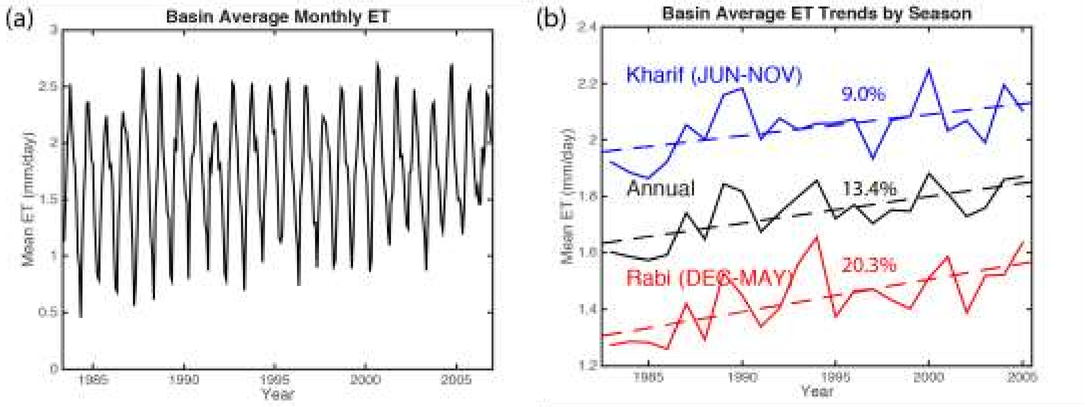


Figure 14. (a) Time series of monthly average ET (mm/day) from July 1983 to December 2006 over KRB; (b) Time series of annual (black), Kharif (blue), and Rabi (red) mean ET and their linear trends in 1983-2005.

While both Kharif and Rabi ET estimates closely follow the inter-annual fluctuations of annual rainfall patterns, more recent Rabi ET shows decoupling from the annual rainfall anomalies evident in the Kharif ET. For example, Rabi ET shows anomalous increase in the years of 1994, 1997, 2001, and 2005. This may show the impact of agricultural irrigation on the inter-annual variability of ET at regional scale. Considering that most land surface models are run by natural input forcing and thus are not capable of reproducing the effect of irrigation, results of this work demonstrate the important utility of satellite remote observations.

7.4 Surface water assessment

The hydrologic model SWAT was set up for the Musi catchment to analyse the impacts of climate change and WSD on the hydrology of the catchment. The SWAT model is a process-based continuous and distributed hydrological model that was used to assess the impacts of land use and hydrological structures on stream flows. The SWAT model uses land use distribution data, soil and climate to capture human induced land and water management practices in the catchment. Daily data from 12 rain gauges were collected and used from the Indian Directorate of Economics and Statistics to calibrate and validate the model. Daily meteorological data were sourced from the IMD, Pune including maximum and minimum temperature, relative humidity, solar radiation and wind speed. Daily streamflow data from two gauging stations, Osman Sagar and Himayat Sagar were used to calibrate and validate the model.

The SWAT model was run for three generated QUMP simulation variants (Q0, Q1, Q14) of the IPCC A1B scenarios corresponding to the baseline (1961-1990), early-century (2011-2040), mid-century (2041-2070) and end-century (2071-2098) extracted by Indian Institute of Tropical Meteorology. The downscaled climate forcing data was used to carry out using all three variants and an ensemble of climate projection data. The reservoir option available in the SWAT model has been used to assess the impact of watershed development structures.

SWAT Model Calibration and Validation

The surface hydrological model was calibrated using the observed inflow data of the two gauging stations in the catchment (Himayat Sagar and Osman Sagar). The calibration procedure involved adjusting the SWAT parameters manually such that the resulting streamflows at the downstream produce matched the observed inflows at HS and OS reservoir between the period 1979 and 1989 (Garg et al. 2011a; Nune et al. 2013). Model was validated with the observed data for the period 1990-1995. This period was selected because it preceded the start of WSD program in India. Sensitive analysis was carried out to identify and assess the sensitive model parameters. Based on the sensitivity analyses following parameters were identified as sensitive in predicting the streamflows which includes: curve number (CN2), the water holding capacity of the soil, plant uptake compensation factor (Epco), groundwater delay time (Gw_Delay), and surface runoff lag coefficient (Surlag).

The model parameters were adjusted manually by trial and error perturbations based on certain statistical indicators and the field experimental data collected from the study area (Soil parameters like field capacity, wilting point etc.) The statistical criteria used to evaluate the hydrological goodness of fit were Nash-Sutcliffe coefficient and coefficient of determination. The result of the model calibration for the HS gauging station is presented in Figure 15. We can observe that the model captures the trends of monthly observed streamflows reasonably well throughout the simulation period. It is observed that the model performs well for the calibration period (1979-1989, E=0.76, R^2=0.81) and validation period (1990-1995, E=0.71, R^2=0.75) for the monthly streamflow comparison (2). The comparison of annual flows resulted in an R^2 of 0.96 and 0.91 during the calibration and validation phases.

In Osman Sagar, the Nash Sutcliffe efficiency and coefficient of correlation for monthly flows during calibration period was 0.78 and 0.75 respectively and 0.68 and 0.65 for the validation period, respectively. The comparison of annual flows yielded a coefficient of correlation of 0.82 and 0.94 during the calibration and validation period, respectively.

Table 2. Nash-Sutcliffe coefficient for calibration and validation (monthly flows)

		Sagar	Sagar
Calibration	1980-1989	0.76	0.78
Validation	1990-1994	0.71	0.65

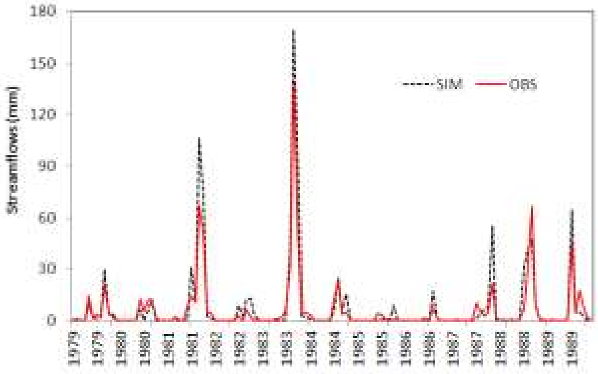


Figure 15. **Monthly observed and simulated flows for the calibration period at HS**

Climate Change Impact on Water Resources

Using the SWAT model, streamflows were projected into the future using the based on the projected rainfall and meteorological data for the Q_0, Q_1 and Q_{14} QUMP climate scenarios generated using the PRECIS model (George et al. 2013). For the Q_0 scenario, streamflows show a decreasing trend in the near future and an increasing trend towards the end of the century (Figure 16) for both gauging stations (Osman Sagar and Himayat Sagar). When we compare the average inflow estimated for the entire period 2011-98 in relation to historical flows, the comparison shows an increase of 95% and 103% at Osman Sagar and Himayat Sagar, respectively. The streamflow reduction during the period 2011-2040 is estimated at 38% and 36%, respectively, for Osman Sagar and Himayat Sagar gauging stations (Figure 17). However, in both stations, we observe a large increase in flows from the middle of the next century onwards for the period 2041-70 and 2071-98. The percentage increase in streamflows is estimated at 102 and 123% from the historical average for the period 2041-70 and 2071-98, respectively at Osman Sagar. For Himayat Sagar, the increase in streamflows is estimated at 126% and 125% from the historical average for the period 2041-70 and 2071-98, respectively. This is mainly because of the predicted increase in rainfall by more than 200 mm in comparison to the historical average. The comparison of monthly average streamflows for various time slices conclude that there is a shift in the peak flow period from September at present to August in the next few decades. This has significant implications for agriculture in the catchment as more water will be required to meet crop water requirement in those months of reduced precipitation.

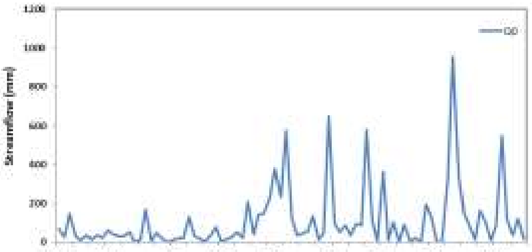


Figure 16. Projected annual streamflow in for Q_0 scenario

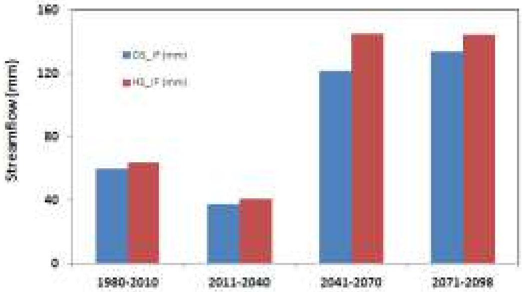


Figure 17. Projected annual average streamflow at different time periods-Q_0 scenario

Potential evapotranspiration (PET) shows an increasing trend throughout the three time slices analysed under the Q_0 scenario. The average annual PET was estimated to be 1715 mm for the historical time series. Average annual PET is expected to increase by 2% and 5% for the period 2011-2050 and 2050-2098 in comparison to the baseline average values. These results indicate that water resources availability will decline in the next few decades while demand will rise, thus requiring adaptation strategies to cope with this change.

For the Q_1 scenario, annual streamflow shows a net decline for the entire period 2011-2098 for both gauging stations (Osman Sagar and Himayat Sagar). A comparison of the average inflow estimated for the future (2011-98) with the historical period shows a decrease of 43% and 63% at Osman Sagar and Himayat Sagar, respectively. There is a significant flow reduction over the next few decades after 2011 although the trend reverses towards the end of the century. Streamflows show a reduction during the period 2011-2040 estimated at 68% and 61% for Osman Sagar and Himayat Sagar, respectively, in comparison to historical averages. The decline in mean streamflows is estimated at 65% and 80% from the average historical records for the period 2041-70 at Osman Sagar and Himayat Sagar, respectively; and 10% and 48% for the period 2071-2098 for the same stations, respectively. Average PET shows an increasing trend and is estimated to increase by 12% and 15% in comparison to current averages in both Osman Sagar and Himayat Sagar.

For the Q_{14} scenario, future average flows are expected to increase by 46% and 13% at Osman Sagar and Himayat Sagar, respectively in comparison with the historical flows. Streamflows show an increasing trend over the next few decades after 2011 and then decline towards the end of the century. The streamflow increase during the period 2011-2040 is estimated at 60% and 18% respectively for Osman Sagar and Himayat Sagar in relation to the historical average. Average PET increases by 2% and 4% for the period 2011-2050 and 2051-2098 in comparison to the base period, respectively.

The impact of hydrological structures on streamflows using the Q_0 climate scenario was simulated by the calibrated model with reservoirs (2005 level of development) and without reservoirs at sub-basin outlets for the period from 1995 to 2098. It can be observed that streamflows decline due to the impact of hydrological structures in the catchment. The average annual reduction in streamflows was observed as 13% in HS (varies from 10 to 19%) and 22% (varies from 10 to 38%) in OS (Table 3).

Table 3. Impact of hydrologic structures on streamflows

	% Streamflow reduction Himayat Sagar	% Streamflow reduction Osman Sagar
1995-2010	-10.25	-9.27
2011-2040	-19.94	-38.43
2041-2070	-9.13	-20.22
2071-2098	-13.64	-23.02

The disaggregated analysis during the wet (Annual rainfall>850mm), normal (Annual rainfall between 600-850 mm) and dry years (Annual rainfall <600 mm) shows that a reduction in streamflows of 1-7 %, 4-32 % and 14-80 %, respectively. It is evident from the analysis that hydrological structures have a reversed effect on streamflows at a catchment scale and this effect is greater than proportional to the rainfall variation due to the large rainfall-runoff elasticity. The analysis also shows that the impact will be most severe during the period from 2041-2070. The large impact during the period 2071-2098 is mainly due to the frequent occurrence of dry years.

Summary of surface hydrology impacts

The following conclusions can be drawn from the modelling analysis:

- Under the Q_0 scenario, the comparison of the future streamflows with the historical flows (baseline) shows a significant net increase of 95% and 103% at Osman Sagar and Himayat Sagar, respectively over the period 2011-2098. However, the analysis of flows at different time slices shows that streamflows decline in the near future (2011-40) and then increase towards the end of the century.
- Under the Q_1 scenario, annual streamflows show a systematic decline over the period 2011-98. A net decrease of 43% and 63% is predicted to take place at Osman Sagar and Himayat Sagar, respectively.
- The Q_{14} scenario shows an increase in streamflows over the next few decades followed by a decline towards the end of the century. On average, streamflows are predicted to increase by 46% and 13% in the future in comparison with the historical period at Osman Sagar and Himayat Sagar, respectively
- More importantly, all three scenarios show an increase in flow variability over the entire time series.

- Potential evapotranspiration (PET) is predicted to increase throughout the time slices analysed for all the three climate scenarios. PET was found to be the highest for the Q1 scenario. This would indicate that irrigation water demand will increase in future.
- An assessment of the impact of hydrological structures on streamflows shows that streamflows have been declining due to the growth and impact of these structures in the catchment. The flow decline due to hydrological structures was significant during drought years.

7.5 Groundwater Hydrology

Hard rock aquifer systems are vitally important for the millions of smallholder farmers in India who derive their livelihoods from these water resources. Groundwater models that describe groundwater flow process and quantify sustainable yields are of value for predicting the past, present and future groundwater dynamics in response to climate change threats, watershed development and the ever-increasing demands on the resource. The 11,257 km^2 Musi River Basin in Telangana, India, where about 67% of the area is classified as over-exploited, was used as a case study. A numerical groundwater flow model was constructed using pertinent hydrogeological, agronomic and climate data (1989 to 2010). The water balance results indicate that over the observed time frame a net storage loss of 140 MCM per year resulted in falling water levels of 0.18 m/yr on average or around a 4 m fall in total. The calibrated groundwater flow model was used to quantify the plausible impacts of climate change, watershed development and increased water demands on future groundwater availability and groundwater levels for the subsequent 86 years (2011 to 2096) under three RCM climate scenarios (Q_0, Q_1 and Q_{14}), down scaled from a GCM.

The present study focuses on the Musi river sub-basin, a major sub-basin of the Krishna river covering an area of 11,257 km^2 in Telangana state, India (Figure 18). Here all of the hydrologic process that impact on the groundwater flow system in typical hard rock

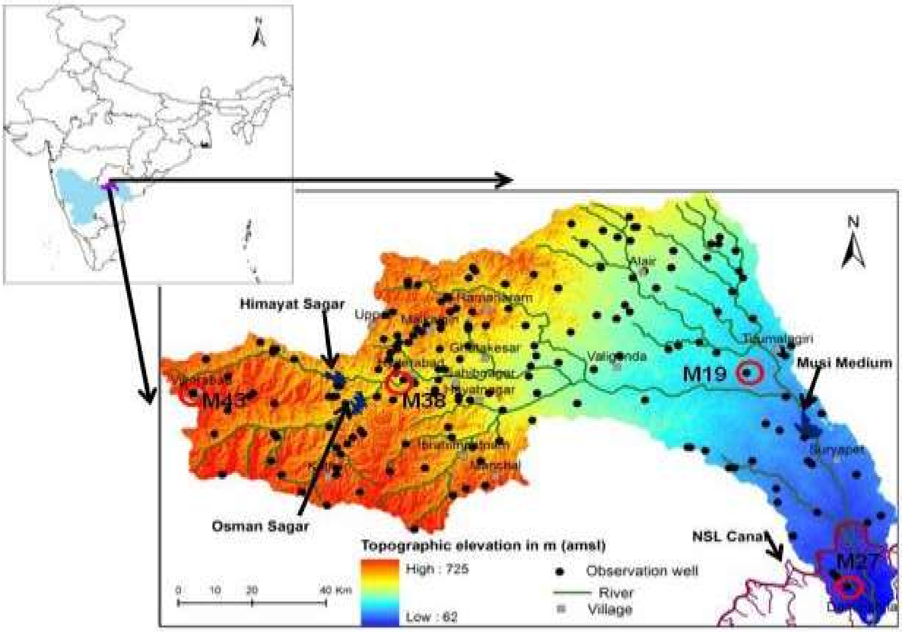


Figure 18. Location of the Musi river basin and observation wells used in the study

aquifers are addressed with the help of integrated hydrologic modelling tools. Specifically, the impact of climatic change, watershed development and changing demand associated pressures on future groundwater availability and groundwater levels dynamics under three climate change scenarios (Q_0, Q_1 and Q_{14}) from 2011 to 2096 are quantified.

Groundwater Model Calibration and Testing

The model calibration is achieved using groundwater levels from 150 monitoring wells distributed throughout the catchment through manual adjustments by changing recharge, discharge and conductivity values to match observed and computed groundwater heads during the calibration period from 1989 to 2004. The Root Mean Square (RMS) and Normalized RMS (NRMS) values are considered for model calibration. Initially the model calibration was achieved in steady state for 1989 then in transient mode from 1989 to 2004. The calibrated model has been validated with observed groundwater heads from 2005 to 2010. The zonation and parameter distribution in the catchment is attempted based on geology and fracture density of each sub-watershed. The groundwater balance was estimated using the zone budget package in MODFLOW. Upon calibration and validation, three climatic scenarios (Q0, Q1 and Q14) were modelled for the periods of 2011-2040, 2041-70 and 2071-2096.

Observed groundwater dynamics

Groundwater levels are very shallow (< 3.0 m) upstream of the dyke ridges and deep (> 15.0 m) downstream of the dyke. The quantity of groundwater recharge and the range of water level fluctuations are primarily controlled by fracture density in the Musi. The long term (22 years average) annual average groundwater recharge is 1346 Mm^3 while annual groundwater withdrawals are 1267 Mm^3. The net groundwater base flows are 216 Mm^3 and river leakage to the aquifer is 74 Mm^3. The net average annual storage loss over the 22 years is 140 Mm^3 has created water level depletion of 0.18 m/yr over the observed time frame. The level of groundwater development, expressed as the percentage of total discharge relative to recharge, in the low rainfall/dry years is >130% and it is 73% in the average rainfall years.

Projected rainfall trends

The analysis of average annual rainfall in comparison with historical data indicates that climate change is going to produce more rainfall by about 14 - 15% between 2011 to 2040 and 2070 to 2098, and 11% between the intervening 2040-2070 in the Q_{14} scenario. The Q_0 scenario shows a decline of about 5%in the first three decades (2011-2040) followed by a subsequent 11-14% increase. However, the Q_1 scenario shows a gradual decrease of rainfall of about 25-34% from 2011 – 2096. The annual average rainfall for these different scenarios are shown in Figure 19.

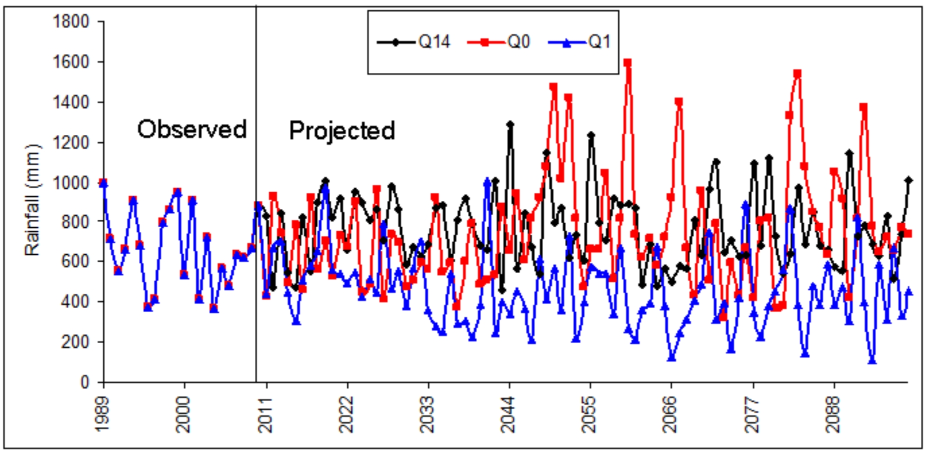


Figure 19. Observed and projected rainfall for three different climate scenarios in the Musi

Climate impacts on groundwater levels

In the Musi the observed groundwater levels indicate that there is a progressive decline in groundwater levels of 21 cm/yr from 1989 to 2004 and 16 cm/yr between 2005 and 2010. The comparison of groundwater levels with rainfall indicates that climate is the major driver for the groundwater hydrology of the catchment. These results also reveal that there is a large temporal variation in recharge creating temporal groundwater depletions in the catchment. The analysis of projected groundwater levels are attempted based on comparison between the reference observed time period (related to 2010) to the projected time period in the four selected observation wells in the study area. In the present study area, the projected groundwater levels are simulated under three climate scenario with 6 × 3 matrices (Table 4). The observed and projected groundwater levels for four selected observation wells from upstream to downstream are shown in Figure 20. The climatic scenarios predict a clear decrease in groundwater levels of 4 m by the end of 2045 and 2 m from 2069 to 2081 for all scenarios throughout the basin. On the other hand groundwater levels are predicted to increase 2 m between 2045-50 and 2057-61. The groundwater levels can be stabilized at 2010 levels by gradual reduction in groundwater demand by 20% from 2011 to 2050.

The B2 scenario shows that the groundwater levels are predicted to fall continuously revealing that in the urbanised Hyderabad area, the shallow groundwater levels are completely going to be depleted by 2080 (assuming a 20 m aquifer thickness). The annual projected groundwater levels indicate the significant policy implications for the basin to cope with the anticipated climate change.

Table 4. Supply and demand side scenarios (6×3)

CCS	Controlled pumping (A)	Increased pumping (B)	Decreased pumping (C)	A +WSD (D)	B+WSD (E)	C+WSD (F)
Q0	A1	B1	C1	D1	E1	F1
Q1	A2	B2	C2	D2	E2	F2
Q14	A3	B3	C3	D3	E3	F3

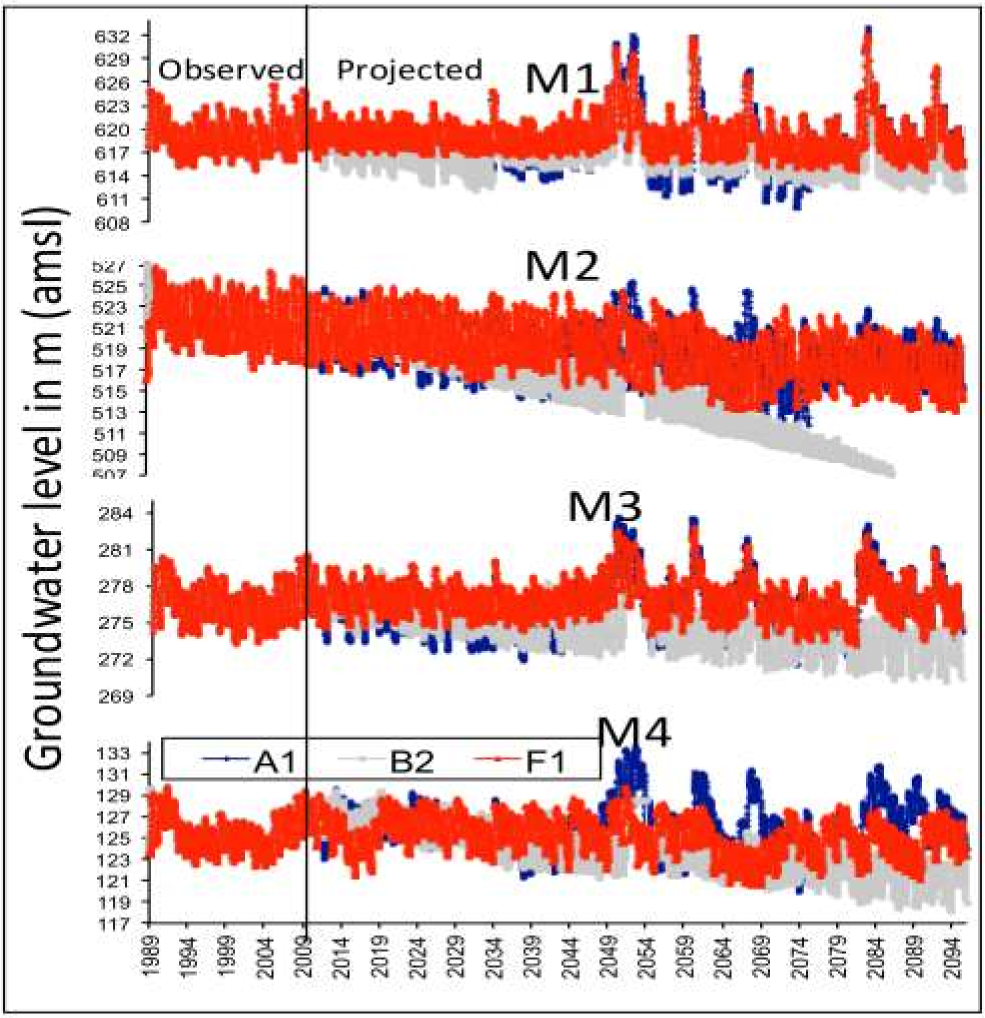


Figure 20. Observed and projected groundwater levels in the Musi basin

Summary of groundwater impacts

The analysis of groundwater availability under future climate change and with different demand related pressures reveals that that the future impact of climate change on groundwater resources will be significant and vary over time. Groundwater levels are predicted to fall or increase depending upon the prevailing climatic conditions. Based on the suite of scenarios tested, it may be anticipated that groundwater levels would fall by around 2 to 4 m by 2050 and regain by around 1 to 2 m by 2098 relative to the reference year of 2010. The effects of climate change are likely to be most dramatic in the more urbanized areas including Hyderabad in particular.

7.6 Water security

The allocation model REALM was calibrated and validated before it was used to simulate the performance of adaptation responses. Detailed calibration and validation procedures and results are presented in George et al. (2011). Following calibration, the stakeholder derived adaptation options of changing the cropping pattern, increasing watershed development, and improving irrigation efficiency were simulated. The increased groundwater extraction option was subsumed with the watershed development adaptation option as it is assumed that increased groundwater extraction can only occur if additional groundwater recharge takes place through increased watershed development. A subset of climate ensembles were chosen to carry out detailed water security modelling with a view to limiting the number of climate-strategy combinations to those that more likely to yield observable differences with the baseline strategy (Q_0, Q_1 and Q_{14}) The following discussion presents the results of the water security analysis for the alternative climate-adaptation options.

BAU Strategy

The business-as-usual (BAU) baseline scenario is based on combining the expected future demand from each water demand activity with projected river stream flows and groundwater recharge into the future, based on the projected rainfall and meteorological data for the QUMP Q_0 climate scenario. This scenario (as its name suggests) is used as a point of comparison for all other simulations of the model.

The REALM model generates several outputs for each demand node including unmet demand (shortfall) and supplied volume supplied for each month of the simulated time series. These are then aggregated to calculate the annual values. The annual values were then used to carry out the frequency analysis and reliability of supply for each climate scenario-response combination. The frequency analysis was carried out in three time slices (2011-2040, 2041-2070, and 2071-2098). Figure 21 exhibits a typical representation of water security in which volumes of water available are provided for a range of probability levels (probability of exceedance). Appendix 11.D presents the water security and associated shortfalls frequencies for the entire set of scenario-adaptation combinations

Under the BAU response, water security of various demand centres in the Musi catchment (Urban, Industry, Musi Medium, Anicut, Zone 1, Zone 2, Zone 3, and Zone 4) is shown to improve in the last two periods in comparison to the period 2011-2040. The volume supplied was the lowest for the period 2011-2040 in comparison to 2041-2070 and 2071-2098. The results suggest that shortfall occurs in every demand centre but were higher in those centres with the largest demand. The system can only provide irrigation to 68% of average annual demand at 90% reliability, in the Musi medium irrigation area. The reliability of supply to the NGJS-LC and NGJS-RC area has declined for the period 2041-2070 in comparison to 2011-2040 mainly because of the increasing demand expected from Hyderabad City. An increasing amount of water is being allocated to Hyderabad city from the Nagarjuna Sagar project to meet the increasing urban and industrial demand as the city's water demand takes priority over agriculture.

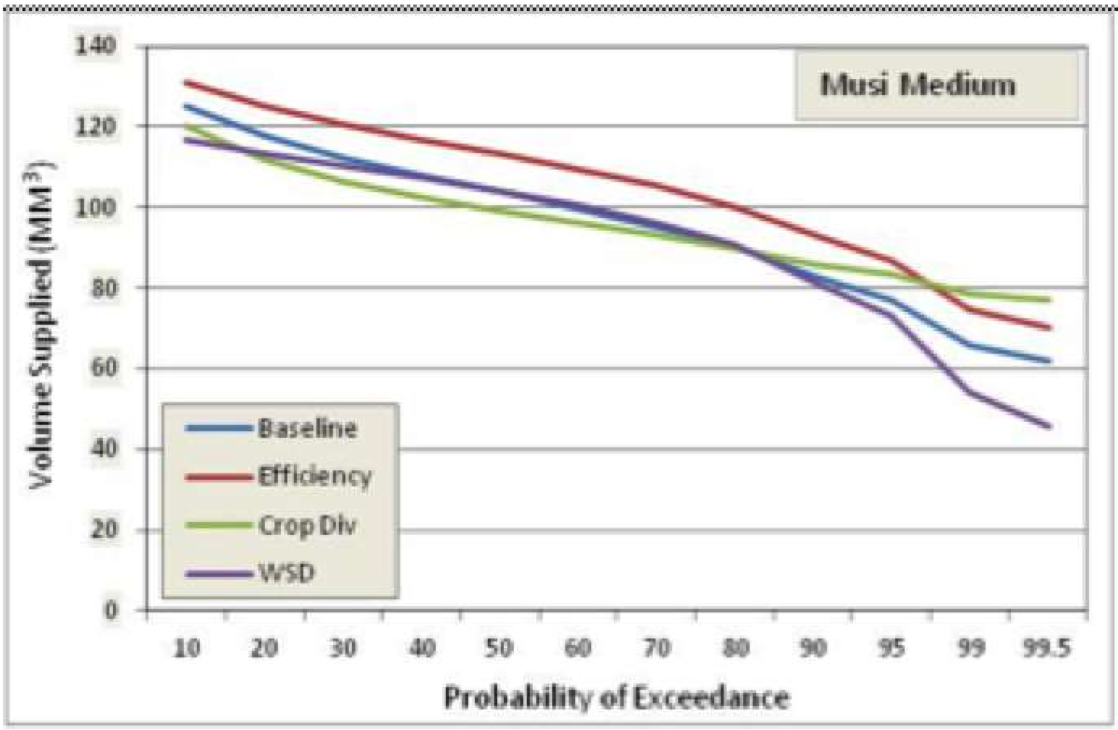


Figure 21. Typical water security diagram for BAU strategy (Musi Medium irrigation area)

The demand in the Musi wastewater area was almost completely met as more wastewater is generated as a results of increased supply to Hyderabad city which in turn it generates additional wastewater effluent. The demand from those zones dominated by groundwater irrigation (Zone 1, 2, 3 and 4) is never met as the model imposes a cap on groundwater extraction in line with the sustainable yield of the aquifer. Under current practice, this threshold is exceeded resulting in a steady decline in groundwater levels.

Adaptation response 1: Improved Irrigation Efficiency

Under this strategy, it is assumed that there is a 10% improvement in efficiency leading to 2040 and then an additional 5% improvement until 2096 for all the surface water irrigated areas and urban supplies. This improvement in efficiency is assumed through the adoption of both, structural and non-structural improvements, which involve significant investment in infrastructure. The investment includes the cost of rehabilitating the canal system, establishing better metering and implementing drip and sprinkler system. This option is modelled by changing the level of losses in the carriers.

Under this scenario, the volume supplied to the various demand centres is greater than the BAU scenario. The volume supplied to agriculture in the Musi region is estimated to be 1,374 Mm^3, 252 Mm^3 and 742 Mm^3 more than the BAU for the periods 2011-2040, 2041-2070 and 2071-2096, respectively (Table 5). The level of security improves with increased efficiency as shown by the supply curve (Table 6) for all the three periods analysed. For the period 2011-2040, the volume that can be supplied under 80 percent reliability is estimated to be 110 Mm^3, 541 Mm^3, 100 Mm^3, 1500 Mm^3 and 2310 Mm^3 for Industry, Hyderabad Urban, Musi Medium, NGJS-LC and NGJS-RC, respectively. The level of security has increased for all the nodes in the Musi catchment for the latter periods in comparison to 2011-2040 mainly because of increased inflows predicted in the future.

Under this scenario, it is expected that for the initial period 2011-2040, a 1 in 25 year shortfall of 88 Mm^3 can be expected to occur in Hyderabad, compared to a 100 Mm^3 shortfall (1 in 25 year) for the BAU scenario (Appendix 11.D -Figure D.4). In addition, the shortfalls in all the agricultural demand nodes in the Musi, NGJS-LC and NGJS-RC are reduced in relation to the BAU. Results were similar for all the time slices analysed.

Table 5. Changes in volume supplied (Mm^3) compared to the BAU

Scenarios	Change in volume supplied (Mm^3) 2011-2040					Change in volume supplied (Mm^3) 2041-2070					Change in volume supplied (Mm^3) 2071-2096				
	Musi Agr.	Domestic	Industrial	NGJS-RC	NGJS-LC	Musi Agr.	Domestic	Industrial	NGJS-RC	NGJS-LC	Musi Agr.	Domestic	Industrial	NGJS-RC	NGJS-LC
Improving efficiency	1374	66	0	7854	9579	252	138	15	5106	8679	742	65	45	3625	7217
Diversifying the cropping pattern	147	-6	9	20790	3753	-3336	63	-33	11157	888	-2862	-25	42.5	-1025	-1152
3. The impacts of strWSSWSDne WSD	2373	-96	-15	-4872	-8004	723	-267	-120	-6441	-7287	4712	-167.5	-20	-5710	-6812

Table 6. Comparison of volume supplied (Mm^3) to various demand centres for the period 2011-2040 at three probability levels.

	Adaptation Responses											
Nodes	**Business as Usual**			**Crop diversification**			**Improving efficiency**			**Watershed Development**		
	70%	**80%**	**90%**	**70%**	**80%**	**90%**	**70%**	**80%**	**90%**	**70%**	**80%**	**90%**
Urban	586	538	469	586	537	468	590	541	473	581	532	464
Industrial	120	111	97	120	111	98	120	110	98	119	109	97
Musi Medium	95	90	83	93	90	86	105	100	93	93	90	81
Anicut	61	57	50	65	61	56	69	64	58	72	66	58
Groundwater Zone 1	446	420	380	428	410	387	447	425	395	434	395	343
Groundwater Zone 2	173	150	117	178	160	133	180	157	124	202	179	146
Groundwater Zone 3	112	104	93	112	104	94	110	101	91	113	103	92
Groundwater Zone 4	198	182	156	190	175	150	195	179	153	194	178	153
NGJS-LC	1538	1061	410	1745	1360	847	2008	1499	756	1270	764	63
NGJS-RC	2346	1967	1440	3395	3096	2627	2724	2310	1689	2130	1728	1170

Adaptation strategy 2: Crop Diversification

Crop diversification is a strategy that envisages shifting the crop mix to less water intensive crops by changing crops and the cropping system. In the Musi sub-basin rice has the highest irrigation water demand followed by chillies, gram, jowar and vegetables on the other hand, have the lowest crop water demands. To model crop diversification, the cropping pattern was altered by replacing the area planted to rice in summer (Kharif) by 10% and by 5% in the winter (Rabi) seasons to dry crops in all agricultural zones in Musi, NGJS-LC and NGJS-RC for the period 2011-2040. Dry crops replaced an additional 10% in summer and 5% in winter of the rice area for the period 2041-2070 and 2071-2098. This area is equally distributed among other crops like gram, jowar, pulses and cotton. It is assumed that all other variables remain the same as in the BAU baseline scenario.

Shortfalls occur in all demand centres in this scenario although they are smaller for this scenario than for BAU (Figure D.4 in Appendix 11.D). The volume supplied to the agriculture sector in the Musi sub-basin is estimated at 147 Mm^3 more than BAU scenario for the period 2011-2040 and 3,336 Mm^3 and 2,862 Mm^3 less than the BAU for the periods 2041-2070 and 2071-2096, respectively. The main reason for this reduction during the later periods is the lower crop water demand from the alternative crops compared to rice. Therefore, the overall water demand of the region has reduced.

The increase in the supply to NGJS-LC and NGJS-RC in comparison to BAU in the early periods is mainly due to an increase in supply to those areas due to reduced demand from the Krishna Delta. For a return period of 1 in 25 years, the shortfall in NGJS-RC is estimated at 93 Mm^3, 1172 Mm^3 and 610 Mm^3 less than the baseline scenario for the periods 2011-2040, 2041-2070 and 2071-2096, respectively. It was found that in the Musi medium, groundwater and Anicut region showed reduced shortfall in all time periods analysed. The volume that can be supplied under 80 percent reliability is estimated to be 111 Mm^3, 537 Mm^3, 90 Mm^3, 1360 Mm^3 and 3096 Mm^3 for Industry, Hyderabad Urban, Musi Medium, NGJS-LC and NGJS-RC respectively for the period 2011-2040.

Scenario 3: Increased Watershed Development

Since 1987, in drought prone areas of India, the Government of India has implemented various small-scale water resource developments including the Drought Prone Area Programme (DPAP) and the Integrated Wasteland Development Programme (IWDP). From 1994-95, these programmes have intensified after the launch of detailed new guidelines on organizational aspects, finance training and stakeholder participation. In many arid and semi-arid regions of India, the aim with these programmes is to improve socio- economic conditions through increased agricultural production in rainfed areas, and to control land degradation by conserving rainwater for use during dry periods. The commonly constructed watershed development structures include percolation tanks, mini-percolation tanks, check dams, sunken pits, and farm pits. The WSD programme is one of the poverty eradication programs of the Government of India with budgetary allocations exceeding $100 million per year.

At a whole-of-catchment level, WSD has been found to reduce downstream surface flows as a direct result of greater capture of runoff and enhanced recharge to groundwater. In an attempt to quantify the impacts of WSD changes, the SWAT model was run with increased WSD scenarios to generate streamflow that are used as input to the REALM allocation model. The WSD scenarios used to run hydrologic model is given in Table 7.

Table 7. The adopted WSD options

Period	Volume (m^3/ha)
Current	14
2011-2041	28
2041-2070	42
2071-2096	49

The water available for agriculture diversions in Musi sub-basin was found to increase sharply by 2,373 Mm^3, 723 Mm^3 and 4712 Mm^3 above the baseline for the periods 2011-40, 2041-70, 2071-96 (Table 5) because of the increase in the GW availability due to increased recharge and return flows from Hyderabad. The impact of WSD was lower during the period 2041-2070 due to the high rainfall predicted by the climate models during this period. As a result, water security increases significantly in the groundwater irrigated areas in the last period (2071-2096) due to increased WSD. It is also found, that shortfalls increase in all surface water irrigated areas in comparison to baseline (BAU) (Figure D.4 - Appendix 11.D). The supply to domestic sector also declines by 96 Mm^3, 267 Mm^3 and 167 Mm^3, respectively for the time periods 2011-2040, 2041-2070 and 2071-2096. At the same time, the decline in supply to the industrial sector was 15 Mm^3, 120 Mm^3 and 20 Mm^3 for the same periods. Agriculture in the Musi medium, NGJS-LC and NGJS-RC is expected to suffer a supply shortfall of approximately 10 Mm^3, 415 Mm^3 and 318 Mm^3 respectively in 1 out of 25 years for the period 2011-2041. The shortfall has declined in the groundwater irrigated areas mainly because of increased recharge from WSD structures.

7.7 Economic assessment

In India, while the stresses on water resource systems have increased (due in part to the challenges of increased demand for scarce water supplies and the potential long run threats of climate change affecting supplies), the way irrigation systems have developed has also changed. Since the 1980s there has been a decline in the number of large scale irrigation projects being built and an increase in projects that are designed to improve the localised efficiency of water use, known collectively as WSD. These challenges (i.e. the future growth in demand, the threats from climate change and increasing WSD to the detriment of large scale irrigation systems) are all impacting in a dynamic way on the one water course (a catchment) affecting the reliability of water supply across the catchment. What is reported in this component of the study are the results of what happens to the quantities and values of water reliably supplied at the 80% level (80 years in 100) across the catchment as the climate changes or if a WSD or some other response is enacted in the catchment.

Climate change

In Figure 22 the physical and economic impacts on water reliably supplied at 80% (in MCM) of the high, average and low rainfall scenarios, over three distinct periods (1: 2011 to 2040, 2:2041 to 2070 and 3:2071 to 2096) are shown. As expected the quantities decline as the rainfall scenarios decline, from roughly 500 to 1000 MCM from the high to the low rainfall scenarios (Figure 22a). Regardless of the scenario, there is more water reliably supplied during the first period, with the least supplied in the second period (2041-2070). During the third period quantities supplied recover somewhat.

When individual zones are assessed the impacts on the NGJS-RC (Figure 22b), the NGJS-LC and to a lesser extent the impacts on Zone 1 are great. The rest is relatively unaffected by changes in climate (less than 200 MCM in the whole system). However, this conclusion needs to be tempered by the fact that while the impacts of the smaller regions on the whole is not much, the variation relative to each total can be quite significant.

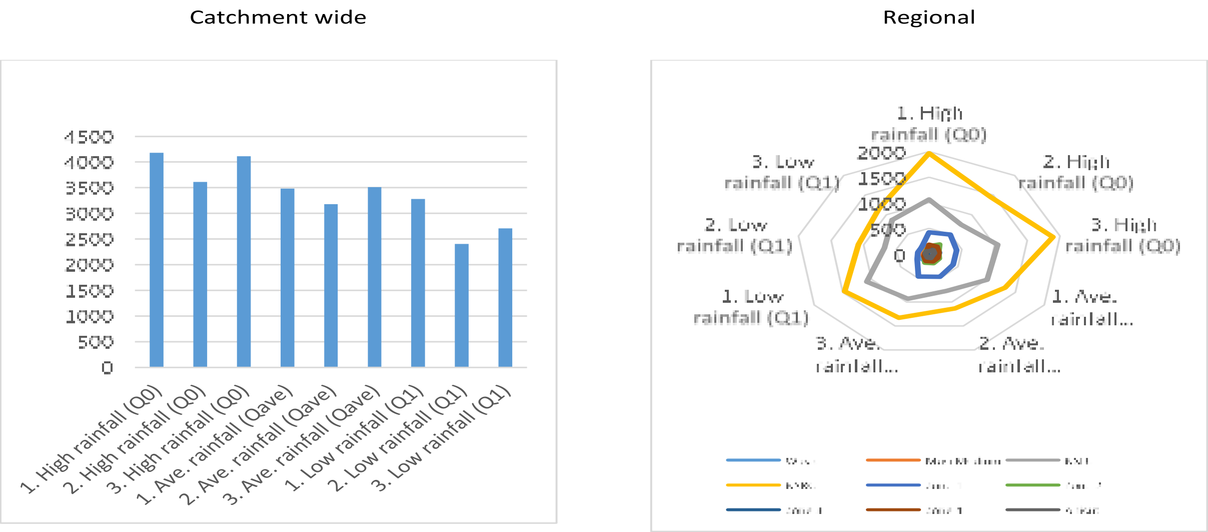
From an economic perspective looking at the catchment as a whole (Figure 22c), it is apparent that the same pattern of the first period (from 2011 to 2040) returning a higher value that the second (from 2041 to 2070) and recovering during the third (from 2071 to 2096), regardless of what climate scenario (high, average or low rainfall) is chosen. If a high rainfall scenario is chosen values could improve by between Rs.4/m^3 in the latter third of the 21st century and Rs.12/m^3 during the first third of the century. Under any scenario, other than a high rainfall one, the system starts to make some significant losses. If a low rainfall scenario eventuates, then considerable losses will be made, in the order of Rs.20/m^3 in the latter periods of the 21st century.

The values do decline as the scenarios become dryer. However, there is a divergence in regional impacts (Figure 22d). The highest average values were found in Zone 1 (which is close to Hyderabad). There the water is relatively more valuable because it is used to produce fruits, vegetables and other high valued crops. In the rice producing regions of the NGJS-LC and NGJS-RC, the average values are relatively low and negative for some. Still the losses from climate impacts can be quite high during a dry period, especially in the NGJS-LC, in the order of approximately Rs.70/m^3.

Adaptation responses

The physical and economic impacts of either increasing water efficiency, WSD or crop diversification are shown in Figure 23. Encouraging producers to move away from producing rice and increase the amount of dry crops increases the quantities of water reliably supplied (Figure 23a). Efficiency improvements would appear (from a quantity perspective) would appear to be the next best response. Both these responses result in more water being available. WSD results in less water being made available.

The physical impacts in different regions of different responses (Figure 23b) most water is used in the NGJS-LC and NGJS-RC command regions. The impacts of different responses hardly change anything in all other regions. From a purely physical perspective, the best response in the NGJS-RC is derived from crop diversification. Watershed developments in the dryland zones have a negligible impact, but are somewhat greater in the irrigation command regions.



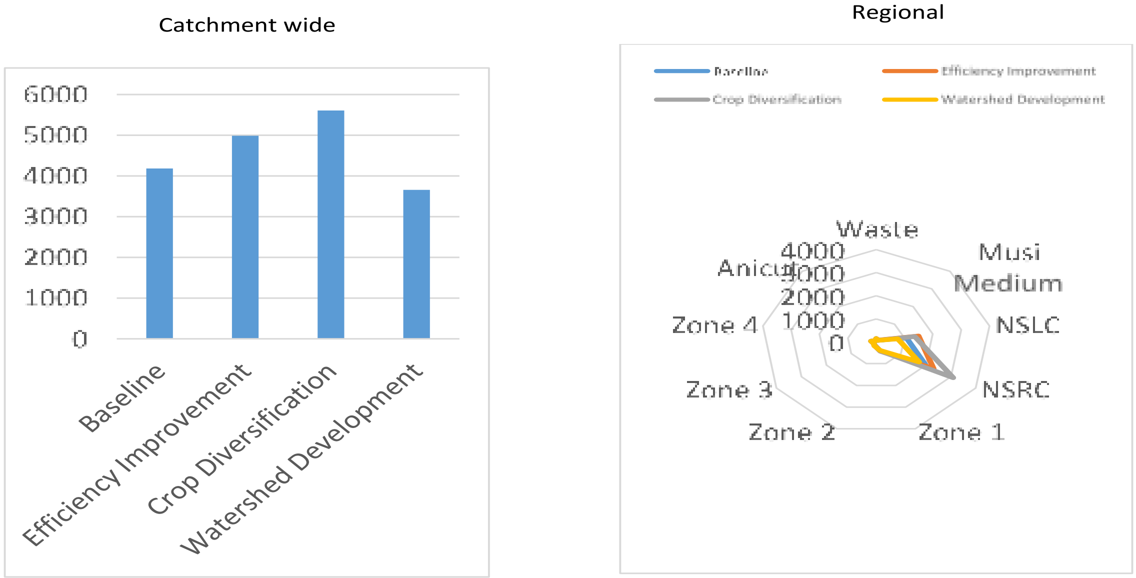
a: The overall physical impacts (MCM)

b: The regional physical impacts (MCM)

c: The overall economic impacts (Rs./m3)

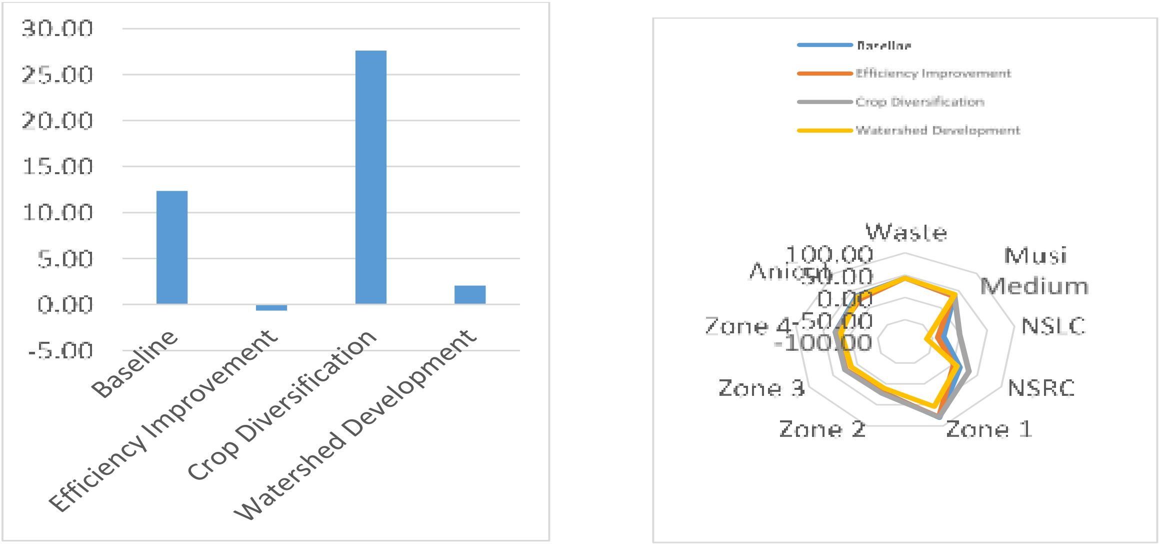
d: The economic impacts on the regions (Rs/M3)

Figure 22: The Impacts of Climate Change



a: The physical impact of responses on the catchment (MCM)

b: The regional physical impacts (MCM)



c: The economic impacts (catchment wide) (Rs/m3)

d: The regional economic benefits (Rs/m3)

Figure 23: The Impacts of Responses

The average values of each response (Figure 23c) implementing a crop diversification policy have the greatest returns (in the order of approximately Rs.27/m^3 saved). This occurs not only because it is inexpensive to implement, but also because the dryland crop chosen to base this analysis on was maize; which has a much higher return than rice. WSD and efficiency improvements result in values of water being much lower than currently exist. These other actions are expensive to implement, especially efficiency improvements (which comes at a cost of approximately Rs.1/m^3), would drive the system as a whole into a deficit situation.

As with the earlier results, a final analysis can be conducted on the impacts responses have on the regional values of water (Figure 23d). It would (again) appear that the variability in the average values is greatest in Zone 1 (where the values are high) and in the NGJS-RC and NGJS-LC (where the quantities are great). The other regions do not change greatly. It should be noted that the low and significant negative values shown above that arise from WSD and efficiency improvements are most pronounced in the NGJS-LC. In a similar, but opposite manner, Zone 1 benefits quite significantly from these two responses, but not as much as it does from crop diversity.

8 Impacts

8.1 Scientific impacts – now and in 5 years

A number of studies (most notably Stern, 2007 and Garnaut, 2008) have pointed out that the impact of climate change and the resultant costs of adaptation can be quite high. They both pointed out that the effectiveness of adaptation strategies is greater if the efficiency of resource utilization is higher. They argue that more definitive estimates of the returns and cost-effectiveness of mitigation and adaptation responses was required. This study was designed to address the scientific concerns surrounding adaptation responses to expected climate change in a sub catchment of the Krishna Basin.

Like many other analysts Garnaut (2008) argues that "If mitigation strategies are not implemented quickly, and in the current economic climate this is most likely, then the world will need to learn how to adapt to some degree of global warming". In other words climate change was expected to have heterogeneous and spatially diverse impacts. It would appear that the quantities of water in the Musi catchment in general first decline and then after 2040 increase as a result of climate change. What is not known is whether the outcome will be dryer or wetter in the future.

This work has important implications to the broad scientific community, including climate, earth, ecological and agricultural sciences. There are areas where our project has made significant scientific advances that impact this domain of science because of the approaches taken in the project These include the:

- Integrated assessment of future performance of adaptation strategies to climate change using a novel hydro-economic approach has been recognised as a significant improvement on the classical approach limited to a physical assessment of water availability. This is evidenced by the number publications of this approached in reputed peer reviewed journals and presentations in various scientific conferences. (Refer to Reference sections for details of publications)
- Effort to integrate the remotely sensed hydrologic and biophysical variables (e.g., spatially distributed actual evapotranspiration, time series of vegetation maps and land use classification) with a modelling framework is an innovative example of combining hydrologic models with ever improving monitoring technology to reduce the prediction uncertainties.
- Watershed development, which has been in practice in India for several decades at a cost of over $6.0 B, yet this project has for the first time specified and tested a methodology that quantifies the hydrologic and economic impacts of this practice.

Over the next five years, we anticipate that there will be some significant impacts arising from this project. These will occur because of the generic nature of the methodological approach taken in this project, the number of papers already published in the international literature and a planned publication of a monograph synthesising the entire adaptation framework. It is envisaged that new research will be based and build on this approach and include additional publications arising from the work carried out in this project are now under preparation. These include studies on the:

- Costs and Benefits of Irrigation System Reliability - Brian Davidson, Petra Hellegers & H Malano
- Economic impacts of measures designed to maintain and improve system wide reliability that arise from redistributing water in the Musi catchment - Brian Davidson, Biju George, Hector Malano and Petra Hellegers.
- Water security and groundwater management in the age of Climate Change: Science and policy interface – H Malano, B Davidson & B Maheshwari.

8.2 Capacity impacts – now and in 5 years

The highly interdisciplinary and integrated nature of this project provided an opportunity to expose the participating scientists to other disciplines and the key interactions needed to undertake the task of climate change adaptation in water resource management. Much of the emphasis on training was placed on ensuring that the participating scientists were in a position to implement the framework on other catchments with diverse hydrologic, social and economic characteristics.

Degree Training

There have been 3 PhD students funded by the John Allright Scholarship program who are approaching the completion of their PhDs:

- Pardhasaradhi Teluguntla: Evapotranspiration modelling using SEBAL technique.
- Rajesh Nune: Assessing anthropogenic and climatic impacts on hydrology.
- Venkata Radha: Soil Moisture Modelling using RS MS (University of Melbourne)

- Master student: An Endeavour Fellowship sponsored student at the University of University, Sai Deepa, working under the supervision of the project scientists (Dr George & Dr Pavelic) developed a conjunctive water management tool for surface and groundwater which has received wide publicity (see http://www.hyderabadfirst.in/?p=429). The tool is currently used by WALAMTARI for assessing the feasibility of conjunctive surface-groundwater use in AP.

Project training

- Three IITM staffs (Dr. Ashwini Kulkarni, Dr. Savitha Patwardhan and Dr.Nayana Deshpande) were trained in hydrologic modelling, in particular the SWAT model. This forms part of the training and deployment of the hydrologic models to IITM by the conclusion of this project.

Several Indian staff were trained to use Remote Sensing equipment:

- CROPSCAN to collect 12-band reflectance measurements
- Infrared Thermometer to collect surface skin temperature
- Temperature probes for soil temperature
- Theta probe soil moisture sensor for soil moisture content

- Portable weather station for meteorological measurements

Related training

The Melbourne team has made use of the project knowledge base in imparting training to a group of Indian Water Managers as part of the AusAID funded project titled “Establishing A State-Level Systemic And Adaptive Water Governance Authority Of Excellence In India”. Project outputs were used to convey to participants an understanding of the critical hydrologic and economic processes involved in climate change adaptation that must be considered in the formulation of water resource adaptation policy. This process has translated into a greater understanding of climate change issues by these officials who are currently deploying this knowledge on the development of State sponsored climate change policies in their respective States. This project involved a workshop/training in Melbourne and workshops/training in Bhubaneshar (Odissa) and Jaipur (Rahasthan)

Round table with Federal Indian MPs: The project team was invited to take part of a round-table organised by the Australia-India Institute at the University of Melbourne to explain aspects of climate change adaptation and inform a group of Indian federal MPs. The ensuing discussion on adaptation policies was extensive, particularly on the role of the project in informing policy formation. The members of the group were:

- Madhu Yaskhi, Andhra Pradesh
- Kalikesh Narayan Singh Deo, Orissa
- Neeral Shakhar, Uttar Pradesh
- Shivkumar Usadi, Karnataka
- Dr Sanjay Jaiswal, Bihar
- Harsimrat Kaur Badal, Punjab

Likely impacts in 5 years

The main potential capacity building impacts arising from this project are the enhanced capacity of the project participants to undertake integrated projects involving multiple dimensions and disciplines. The participating staff have demonstrated a sound understanding of the methodology undertaken in this project and are able to transfer these skills to other colleagues and scientists.

The project staff has also developed a sound understanding of the issues associated with the science-policy interface in climate change adaptation. As such, they are in a prime position to influence the current and future debate underway in India as the new recently elected government makes climate change a high priority policy issue.

8.3 Community impacts – now and in 5 years

8.3.1 Economic impacts

In this study, it can be concluded that the Andhra Pradesh government has pursued a policy strategy (WSD) that conflicted with, and has diminished the outputs from a previous policy endeavour focus on large scale irrigation development. Using the principles enunciated in this project, one where a whole-of-catchment approach is employed to assess dynamic water resource decisions has reduced the counter intuitive impacts of WSD. While it cannot reclaim the sunk costs associated with these prior poor decisions, this research may well inform the policy and stop such errors in the future.

In addition, far from reacting to climate change with a large supply side effort (like WSD or improving the efficiency with which water is distributed), a far better approach is to manage demand by changing the cropping pattern. Such assessment can only be done using an integrated approach as that developed and used in this project.

Finally, an important economic lesson learnt in this project relates to the costs associated with maintaining and improving reliability. Water security was shown to come at a cost; that of the foregone value of water that could have otherwise been deployed, but isn't, in order to maintain high reliability. The level of reliability that is most beneficial to society in the Musi catchment was found to be approximately 35%. It was found that maintaining the costs of reliability beyond the 80% level would result in increasing exponential losses to the system.

Likely impacts in five years

In 5 years, the likely economic impacts of this project are principally related to the costs of implementing future sound policies. Economically, if the Government of Andhra Pradesh (now Telangana) has little to do to realise the benefits of implementing these sound policy ideas. It needs to resist the temptation to invest in water resource management measures like WSD and irrigation efficiency without a thorough assessment as that enabled by this framework. Employing such an adaptive approach, it will allow policy makers to incorporate new learnings and continue improving the water security and economic performance of the systems.

8.3.2 Social impacts

Climate change is expected to have a significant impact on water security. This is also expected to be exacerbated by increased variability in inflows arising from WSD in the Krishna basin. The allocation of water to various users requires knowledge of hydrology, economics and the social and institutional governance mechanisms to support the necessary adaptive changes. The focus in this project was on science based development of water management adaptation strategies to ensure future water security. Not much was known about the policy pathway needed to adapt water resource management to climate change before this project.

Understanding the key priorities of policy makers and relevant stakeholders and integrating these priorities into the scenario framework was a key element of this project. A four-tier approach that matches the spatial scales addressed in this project is proposed to involve stakeholders in this project. This includes Ministry of Water Resources at the Centre, Water Resources Departments in each State, District Collectors and other relevant departments in the district and Panchayati Raj Institutions in the local level. This project ensured that the climate adaptation scenarios selected for evaluation were based on wide consultation and participation of the key stakeholders likely to be affected by water security. The selected stakeholders will play a role in informing the best pathway for implementing climate change adaptation policies into the future.

The project involved an extensive consultative process with all the relevant stakeholders, including farmers and the local community. The results obtained from scientific assessments, such as the projected climate change impacts on the water availability in the Musi basin, were conveyed to the local communities and farmers in a simplified vernacular language. This helped in building their understanding of the environment and related social and financial aspects associated with climate change. This helped them to better understand and comprehend the situation they face. Based on their understanding, they provided inputs for developing adaptation responses, which they opined to be useful for mitigating the impacts of climate change.

Likely impacts in five years

The responses received from the communities and farmers were shared with officials at the various district and state levels. The information shared in terms of project outcomes raised awareness of the local communities, as well as amongst decision makers and stakeholders working in various government and allied departments of the study area. This integrative consultation is now understood by all stakeholders and can be applied by the project partners in other projects given the successful outcome obtained in this project.

8.3.3 Environmental impacts

There are strong environmental implications arising from climate change and the adaptation strategies that will be implemented to ameliorate its impacts. The provision of environmental flows in Indian rivers has largely been neglected in the past in favour development of water resources for agriculture. This problem is now further compounded by rapidly increasing demand for water from the urban and industrial sectors. The adaptation framework developed in this project allows for the inclusion of environmental flows in the future planning of water resources management. The application of the generic modelling framework used in this project can also be used to inform managers and planners of water resources on the hydrologic and economic implications of making water allocations to supply environmental demand.

Likely impacts in five years

The Indian project partners, IWMI, IITM and TERI are all intimately involved in water resources research and policy in India and regionally. As such, we envisage that there will be multiple opportunities to translate the outputs from this research into further applications of the research framework as concern with the health of rivers and aquifers in India increases and are incorporated into future water planning. These, however, are likely to extend beyond the five-year time horizon.

8.4 Communication and dissemination activities

This project was based on the extensive stakeholder consultation process. During this process, issues related to agricultural water security assessed through scientific and technical methods were regularly disseminated to the stakeholders to apprise them and receive their feedback. During the course of the project, stakeholder consultation workshops were held to disseminate strategic findings and take their valuable feedback.

The project concluded with an international workshop held at New Delhi on February 3-4, 2015. The main objective of the workshop was to disseminate the findings of the project. To achieve this aim, the workshop focused on:

- Disseminating the latest research findings and methodologies for developing sustainable water resource management strategies to cope with climate change impacts on water and food security;

- Promoting an informed debate between scientists, policy makers and various stakeholders on management and adaptation approaches to climate change impacts on water security;
- Facilitating a dialogue among the diverse and competing stakeholders (government agencies, NGOs and research organisations) to assess the competition, conflicts and possible ways forward;
- Establishing a bridge between science and policy to develop evidence based climate adaptation and water management policies to ensure improved water and food security.

The announcement brochure of this workshop and workshop recommendations are included in Appendix 11.E.

Along with one-on-one and group interactions during the final workshop, extended abstracts of various work packages concluded in the project were also disseminated in printed form.

This project also resulted in the publication of a number of articles and presentations to learned societies. The list of publications emanating from this project is shown in Section 10.2.

Members of the research team made a number of presentations related to the project at various domestic and international events including:

- Anshuman, presented at a Workshop on Meta-Guidelines for Water and Climate Change, October 2012, University of Tokyo, Tokyo, Japan
- The project team organised a workshop on “Understanding Water-Energy-GHG nexus for future water and food security” in collaboration with Indian Society of Water management and Australia-India Institute in September, 2012. One of the workshop theme was water management and food security and a number of topics related to climate change was discussed in this workshop. About 100 participants attended this workshop.
- B George presented a paper at a workshop on “Understanding Water-Energy-GHG nexus for future water and food security” organized by the Indian Society of Water Management and Australia-India Institute in September, 2012
- B Davidson also presented at the workshop on “Understanding Water-Energy-GHG nexus for future water and food security” September, 2012
- H Malano presented a paper to the European Geophysical Union Regional Conference, Turin, November 2012.
- H. Malano presented a paper to the Politecnico di Torino, December 2012
- H Malano presented a paper to the University Technology Valencia, November 2012.
- Anshuman, presented a paper at the World Aqua Congress; November 2011. New Delhi
- H Malano presented a paper to the Department of Remote Sensing, Anna University, Chennai, February 2013.
- B George presented a paper to the National Academy of Agricultural Research Management, Hyderabad, February 2013.
- Vivekanand Honnungar presented a paper to the Climate Water Forum, 2nd Regional Workshop. Sharing Research and Strategic Knowledge on "Climate Change and Water for Policy". March 14, 2013, Hyderabad.
- H. Malano in 2015 Presented a paper titled ‘Spanning the Science-Policy Chasm for Sustainable Water Management’ at the UNESCO International Workshop on Sustainability Science, 3-4 March, 2015. Kuala Lumpur, Malaysia.

- H. Malano presented a paper to the International workshop on Water Security and Groundwater Management for Agriculture in the Age of Climate Change. 3-4 February, 2015, New Delhi. (see appendix 11.E)

Stakeholder interactions

- CGWB, Andhra Pradesh State Council of Science and Technology; Department of Agriculture; Irrigation and CAD Department; Department of Rural Development, Hyderabad, July 2011.
- Water Resources Department; Department of Mines and Geology; Central Ground Water Board; Krishna Bhagya Jal Nigam Limited, Bangalore, July 2011.
- District Water Management Authority (DWMA)- Rangareddy, Nalgonda and Mahbubnagar districts; WALAMTARI; Agromet Cell, ANGRAU, Hyderabad, Rangareddy, Nalgonda and Mahbubnagar. February 2012.
- Department of Agriculture; Irrigation and CAD Department; Department of Rural Development; Agromet Cell-ANGRAU; District Water Management Authority (DWMA)-Rangareddy; State Groundwater Department; Agriculture Research Institute. Hyderabad, July 2012.
- Village heads, farmers, households (a total of 97 respondents) from ten villages in three study districts. Hyderabad, Feb 2012.
- Department of Agriculture; Irrigation and CAD Department; WALAMTARI; Department of Rural Development. Hyderabad, March 2013.
-

Project website: http://www.ie.unimelb.edu.au/aciar/index.html

9 Conclusions and recommendations

9.1 Conclusions

This project was characterised by its interdisciplinary and integrated nature designed to address the main dimensions of the problem of adaptation of water resources management to climate change. This was a complex and yet successful project due to the excellent collaboration experience between the project scientists and, more importantly, between scientists and the large number of stakeholders involved. From the very inception of the project, a strong and continued partnership was established between scientists, stakeholders and all tiers of government. This partnership ensured that the selection of climate adaptation strategies emerged from a wide consultation process with those forming part of this partnership. In line with the structure of the project, we present the conclusions of the project according to the project main disciplinary areas involved.

Stakeholder consultation

This consultation process was used to engage stakeholders from the beginning of the project to elicit the adaptation strategies that will guide the hydrologic and economic analysis. Because of its continuity throughout the project, this process helped build strong relationships amongst participants and understand the existing policy and programs in the region in the context of agricultural water security. Similar consultations were also held at the larger spatial scale of Krishna Basin involving all important institutes in the basin states: Karnataka, Maharashtra and Andhra Pradesh. The consultation process, which involved several rounds with the various stakeholders, resulted in a set of adaptation options that required further narrowing down to ensure that the selected options were sufficiently well defined and there was no potential overlap between them. The final four selected adaptation options included:

1. Changing cropping patterns;
2. Increasing watershed development; and
3. Improving irrigation efficiency.

Climate change

Knowledge about the spatio-temporal variations in climate parameters is essential for analysing climate change adaptation responses within a catchment. Such information also forms the basis for the validation of climate projections generated from the climate models.

This analysis concluded that the annual average temperature and the number of heavy rainfall events are increasing trend over the Krishna Basin in a statistically significant manner. Annual temperature shows a significant increase (0.08^{0}C /decade) in the Krishna basin and hot days (>37^{0}C) are increasing in the central parts of the basin.

Of critical importance in this project, is the prediction of future climate trends and the impacts it may have on the surface and groundwater resources in the Musi catchment. These predictions were made using the PRECIS simulations corresponding to the IPCC-SRES A1B emission scenario. The modelling projections indicates that while deficit rainfall years will not change significantly, deficient are predicted to be more intense towards 2080s compared to the baseline. Rainfall is projected to increase by 2-11 % relative to 1970s in all the three ensembles (Q_0, Q_1 & Q_{14}) by the end of the century. The mean annual temperature shows consistent warming in all the time slices with a projected change of around 2.5°C towards the end of the present century.

Hydrologic Impacts

The impact of climate change in the study area involves the quantification of historical land use changes and crop water use by remote sensing analysis and the predicted impacts of future climate on the behaviour of the surface and groundwater hydrology in the Musi catchment. The key insights from this analysis shown that long-term (monthly) evapotranspiration increased in the period 1983-2006 as a result of irrigation development projects in the basin.

The climate change impacts on the surface hydrology of the catchment show that under the Q_0 climate scenario, the future streamflows show a significant net increase of 95% and 103% at Osman Sagar and Himayat Sagar, respectively over the period 2011-2098. Under the Q_1 climate scenario, annual streamflows show a systematic decline over the period 2011-98. A net decrease of 43% and 63% is predicted to take place at Osman Sagar and Himayat Sagar, respectively. The Q_{14} scenario shows an increase in streamflows over the next few decades followed by a decline towards the end of the century. On average, streamflows are predicted to increase by 46% and 13% in the future in comparison with the historical period at Osman Sagar and Himayat Sagar, respectively. More importantly, all three scenarios show an increase in flow variability over the entire time series.

The groundwater study was aimed at determining the potential impacts of future climate change modelling on the behaviour of the groundwater aquifer. This analysis shows that the groundwater levels are predicted to fall or increase depending upon the prevailing climatic conditions. However, at the same time the scenarios indicated that groundwater levels would fall by 4.0 m by 2050 and regain by 2.0 m by 2098 from the reference year (2010). Climate change is likely to have dramatic impact on groundwater resources in the more urbanized watersheds such as Hyderabad.

Water security

At the centre of this study is the evaluation of water security and economic performance of the scenario-adaptation strategy combinations identified through the stakeholder consultation process. This task entailed integrating the water resources available (surface and groundwater), the potential demand associated with each climate scenario-adaptation strategy combination, the infrastructure present in the catchment and the institutional arrangements governing the resource allocation priorities and preferences. This task was accomplished with the use the REALM model. The water security analysis shows that under the BAU strategy, shortfalls occur in every demand centre in the sub-basin assuming current unrestricted supply from NJSP. The reliability of supply to the NGJS-LC and NGJS-RC area declines for the period 2041-2070 due to increased pumping from NJSP to Hyderabad. Using an Improved Efficiency strategy, water security of all demand centres improves for all the time slices. While reducing the shortfalls in relation to BAU, these will still occur under the Crop Diversification strategy. Adopting the WSD strategy will improve water security in the groundwater irrigated areas at the same time that shortfalls will increase in all surface water irrigated areas in relation to the BAU. This is mainly because of increased recharge from WSD structures which lead to reduced surface flows.

Economic assessment

From the economic component of this study two startling conclusions can be drawn. First, the level of reliability (the degree of water security desired by policy makers) has a significant impact on what society gains from the irrigation system. A higher degrees of water reliability (i.e. greater water security) comes at a cost that is not always apparent to those who manage irrigation systems. Treating the Musi system in aggregate, it was found that running the system at reliability levels greater than 85% would result in exponentially rising losses to society. If those who operate the system desire to maximise the gains from the system, then running it at 35% would be ideal. In addition, it was found that the reliability levels differed across the catchment, and improving reliability in one region or node would make would make it worse in another. Second, it was found that changes in the climate would have an impact on the total value of agriculture produced in the Musi. Depending on the climate scenario assessed, the impacts vary greatly from Rs.4/m^3 in the latter third of the 21st century and Rs.12/m^3 during the first third of the century, if a high rainfall scenario eventuates. However, under any other scenario the system starts to make some significant losses. If a low rainfall scenario eventuates, then considerable losses will be made, in the order of Rs.20/m^3 in the latter periods of the 21st century. In addition, there is a divergence in regional impacts as well with some losses from climate impacts as high as Rs.70/m^3 in the NGJS-LC. Thirdly, the average values of each response also varied greatly. Implementing a crop diversification policy would appear to have the greatest returns (in the order of approximately Rs.27/m^3 saved). WSD and efficiency improvements result in values of water being much lower than currently experienced. These other actions are expensive to implement, especially efficiency improvements (which comes at a cost of approximately Rs.1/m^3) and would drive the system as a whole into a deficit situation. It would (again) appear that the variability in the regions is also great. Some regions are not greatly affected, yet they are most pronounced in the NGJS-LC. In a similar, but opposite manner, Zone 1 benefits quite significantly from these responses, but not as much as it does from crop diversity.

9.2 Recommendations

The main recommendation arising from this research is that potential policy intervention should be evaluated for both its water security and its economic outcomes at a catchment scale.

To this end, policy makers should be aware that:

1. There is more than one possible policy intervention to adapt to climate change and trade-offs exist between different forms of policy intervention; one will affect another;
2. Improving water security in one region affects all other regions, yet some regions are more affected than others, and impacts across the system must be assess hydrologically and economically.
3. What is optimal and ideal from a physical perspective in water security does not necessarily provide the best economic outcome;
4. Increasing reliability comes at a cost that is more than just that associated with the policy intervention itself, it also involves the hidden costs of maintaining a selected level of reliability (a measure of the systems water security);
5. The costs of increasing reliability increase exponentially, so much so that beyond a certain level these costs to society outweigh its benefits;

6. In response to climate change, it is ideal to focus on ‘no-regret’ flexible adaptive approaches (like changing cropping patterns) over the less flexible WSD and the highly inflexible improvements to irrigation efficiency;
7. Climate change is going to have an impact on the Basin’s river flows in the next 30 years and beyond, thereafter the impacts are more uncertain and must continually be reassessed.
8. Climate change can have a detrimental economic impact, especially if a dry scenario eventuates, but even if it does not then extreme events become a problem if the future is wetter;
9. Designing climate change strategies needs to be made in the context of the catchment in which it is made and yet, must not be made in isolation of its impacts on individual parts of the catchment or strategies employed at a higher spatial scale such as whole-of-basin.;
10. There is merit in making decisions based on the best available evidence grounded on the climatic-hydrological-economic system which are embedded in a social and political context;
11. Any hydrological impact must be assessed in terms of the interaction between and within the ground and surface water systems as a means of assessing resource availability to satisfy multiple demands and assess water security; and,
12. In designing strategies that can be implemented, the political structure and stakeholder interests need to be aligned and this is best achieved through a process of multi-level consultation and negotiation.

10. References

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11 Appendixes

11.A Scenario Planning

Scenario Planning Ontology

Scenario Planning is a planning technique originally developed in the 1970's by Royal Dutch Shell to make flexible long-term plans (Schoemaker, 1995). While this planning approach has found wide applications in business and military strategies, the literature records a paucity of applications to water resource management (Stewart & Scott, 2010)

Van Notten (2006) defines "scenarios" as "*consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action*". Scenario development entails constructing an explicit story about how the future may unfold, which in the context of this project is represented by alternative climate futures. Scenario planning must involve the selection of significantly different views of the future and they must represent a set of mutually exclusive and exhaustive *States of Nature*. The narratives of alternative plausible futures describe the scenarios. In this project, these are represented by simulation of futures climates under various possible world development economic trajectories adapted and downscaled to focus on the specific geographical area of the project, the Musi catchment in Andhra Pradesh.

These model representations of the future climate are typically selected on how well they represent the past climate. However, when they are used to model the future climate, they diverge over a wider range of predictions ranging from high to low temperature and high to low precipitation changes. For the purpose of this study, five main alternative future climates generated by the Indian Institute of Tropical Meteorology (IITM) were selected. These are ensemble members of the A1B scenario of world development (IPCC, 2001).

Insights gained from scenario planning equip organisations and government to recognise and respond to significant emerging threats and opportunities. In the context of this project, this process involves the development and evaluation *of adaptation responses* to make the system more resilient by choosing strategies that provide better water security and economic performance.

As with any area of knowledge sharing, it is important to develop an ontology that defines the *'specification of a conceptualisation'* that exist as a set of concept definitions for a community of agents CGruber, 1993). It is the way they can communicate about these domains. In this particular case, the research community involved in scenario planning and water resource planning and management.

From Scenario to Responses

Scenarios have two purposes: (a) The design of strategic responses and (b) evaluation of the proposed strategies. Arguably, scenarios may eventuate to a different degree over time, or not at all. Our framework needs to accommodate a variable degree of eventuality for each scenario and provide a vehicle for continuous adaptation as the problem evolves in future (Lindgren & Bandhold, 2009)

The climate change adaptation problem requires that we evaluate different responses over time to climate change and other changes in the *State of Nature.* This is why we have included an additional "time" dimension to the options analysis, one that incorporates changing responses over time. To address the time dimension, the climate modelling horizon 2011-2098 was divided into three time slices - 2011-2040; 2041-2070; 2071-2096.

Each scenario-response combination also needs to be ascribed a level of probability of occurrence. Probability values are derived from actual climate-hydrologic analysis using hydrologic flow duration analysis.

Water management adaptation strategies in this project have been defined through an interactive and structured process involving project researchers and stakeholders. Stakeholders have been involved through a comprehensive plan that involves formal and informal Interactions that have taken place throughout the entire project cycle.

Evaluation of Adaptation Responses

The notion of *option* conjures up fairly clear-cut ideas in the minds of most decision makers. In the context of this project, scenario planning involves identifying plausible future climate scenarios and concomitant *adaptation responses (options)* selected through a multi-level comprehensive stakeholder consultation. As in any decision making process, the ‘value’ of each option must be determined through the application of a rationalistic and objective process that eliminates all possible subjectivity. This project has taken a dual hydrologic-economic approach to the evaluation of performance from each climate-adaptation option. At the centre of this methodology are two key criteria of performance assessment, namely: hydrologic assessment of water security and economic assessment of adaptation cost-effectiveness . The project relies on a combined hydrologic-economic modelling framework to carry out the evaluation task.

11.B Stakeholder survey forms

Questionnaire (Farmers, Locals)

Date____/_____/2012

Basic Information about Interviewee

Name________________________________Location______________________________________

Age__________Gender_______________Occupation______________________________________

Whether landowner or tenant/labourer__________________________

Annual income______________________________________

Whether holds any official/administrative post in village___________________________

TECHNICAL QUESTIONS:

1. What is the major water source for you?
   -
   -
2. What is this water used for?
   a. Domestic/household uses
   b. Irrigation
   c. Other _________________________________
   -
3. What is your perception about the water quality?
   -
   -
   -
4. What technology do you use for irrigating your field?
   -
   -
5. Are there any traditional water conservation/management practices that are practiced in your region? If not, why?

SECTORAL QUESTIONS:

6. How much quantity of water is used for household/domestic purposes?

   -
   -
7. What is the size of your farm? Do you own it?

8. What are the major crops grown by you, season wise?
   -
   -
9. How much water is used for agricultural purposes, crop wise?
   -
   -
10. How much of this is met by your primary source of water?

11. Is sufficient water available to you throughout all seasons?
    -
    -
12. If not, then how do you cope with it?

13. Are you using any secondary source of water (any traditional water body?)
    -
    -
14. How dependent are you on rains for irrigating your field?
    -
    -
15. Have you ever witnessed droughts in your region? When? What was the duration? What is the frequency?

16. What strategy did you adopt during the drought?
    -
    -
17. Have you ever witnessed floods in your region? When? What was the duration? What is the frequency?

18. What strategy did you adopt during the flooding?
    -
    -
19. What are your future strategies against such extreme events?

FINANCIAL QUESTIONS:

20. How much do you pay for water? Did you pay a connection fee? Is there a volumetric charge?

21. Do you pay (financially or otherwise) for any government scheme to provide you water? If yes, how much and when?
    -

22. What are your other costs (of doing agriculture)?

23. Has the government provided any financial incentives to you to grow certain crops, for example water efficient ones?
    -

24. Is there any existing financial institution from which you can get loans/subsidies/financial assistance?

25. Do you have crop insurance? Why/why not?
    -
    -
26. Will climate change affect your cost of doing agriculture?

INSTITUTIONAL QUESTIONS:

27. Who is the owner of the water source that supplies you water? Is it public/private/shared?

28. Are there any restrictions on water extraction- institutional, financial, social?
    -
29. Who is responsible for water management according to you?
    -
    -

-

30. Who should be responsible?

31. Is the current institutional set up able to handle changing situations that will arise due to climate change? i.e., Is Climate change planning a part of the process currently?
    -
    -
    -

REGULATORY QUESTIONS:

32. Are there any schemes/policies/programmes for water provision?

33. When were these schemes launched?
    -
    -
34. Which agency/body has provided the scheme?
    -
    -
35. What are the features of this scheme?

36. Who is regulating the scheme?
    -
    -
37. Coverage of scheme?

38. Benefits of scheme?
    -
    -
39. Problems in scheme?
    -
    -
    -
40. Are you satisfied/dissatisfied with scheme? Why?

41. Are there any programmes for you under drought/flood conditions?

CONCLUDING QUESTIONS:

42. What do you think currently are the problems in water management in order of the complications (in context of climate change)

a)_____________________

b)_____________________

c)_____________________

-

43. What you think is the most important need of your community in terms of better water management

a)_____________________

b)_____________________

Impacts of climate change and watershed development on whole-of-basin agricultural water security in the Krishna Basin, India

Criteria Weighing and Options Scoring (Tier 2)

Date____/_____/2012

Basic Information

Department____

Interviewee______________________________________Designation____________________________

-

- **PART I: Criteria identification**
-

1. On what basis should the project prioritize and evaluate the various adaptation options that are generated by stakeholders? In your opinion, what criteria should we use? For example, time for implementation, number of people helped etc.
   -
   -
   -
   -
   -
   -

2. Please say yes or no depending on whether you think the following criteria are relevant to compare adaptation options:
   -
     - Number of people benefited/scale of impact (preference for projects that help more number of people, more area?) ____________
     - Time for implementation (preference for shorter duration projects?)_______
     - Cost of implementation (preference for projects that are more economical?)____
     - Cost effectiveness (preference for projects that increase the benefit/cost ratio?)________
     - Technical know-how required (preference for projects that require less technical know-how?)________

- Social acceptability (preference for projects that are socially easily acceptable?)______
- Institutional barriers (preference for projects that have low institutional barriers, i.e., will fit within existing institutional arrangements?)__________
- Co benefits (preference for projects that have large co-benefits)______________
- Others:____
  ____
  ____
  ____

-
-

3. Please say yes or no depending on whether you think the following criteria are relevant to compare adaptation options from the farmers' perspectives:
   - Number of people helped/scale of impact (preference for projects that help more number of people, more area?) ____________
   - Time for implementation (preference for shorter duration projects?)_______
   - Cost of implementation (preference for projects that are more economical?)____
   - Cost effectiveness (preference for projects that increase the benefit/cost ratio?)________
   - Technical know-how required (preference for projects that require less technical know-how?)________
   - Social acceptability (preference for projects that are socially easily acceptable?)______
   - Institutional barriers (preference for projects that have low institutional barriers, ie. will fit within existing institutional arrangements?)__________

- Co benefits (preference for projects that have large co-benefits)_______________
- Others:____
____
____
____

4. Please state which criterion is more important in the pairwise analysis below.

	# of people benefitted/scale of impact	Time to implement the option	Cost of implementation	Technical know-how required	Social Acceptability	Institutional Barriers	Co-benefits
# of people benefitted/scale of impact							
Time to implement the option							
Cost of implementation							
Technical know-how required							
Social Acceptability							
Institutional Barriers							
Co-benefits							

5. Please rank each option as per your preference.

Adaptation Options	**Rank**
Creating more water storage structures	
Change in cropping pattern	
Convergence of institutions	
Restriction on the digging of bore wells	
Temporal water apportionment	
Regulatory body to check water withdrawal limits	
Financial resources to be used for restoring/renovating already in-place structures	
Livelihoods apart from agriculture	

Impacts of climate change and watershed development on whole-of-basin agricultural water security in the Krishna Basin, India

Criteria Weighing and Options Scoring (Tier 3)

Date____/_____/2012

Basic Information

Department____

Interviewee______________________________________Designation____________________________

PART I: Criteria identification

6. On what basis should the project prioritize and evaluate the various adaptation options that are generated by stakeholders? In your opinion, what criteria should we use? For example, time for implementation, number of people helped etc.
   -
   -
   -
   -
   -
   -

7. Please say yes or no depending on whether you think the following criteria are relevant to compare adaptation options:
   -
     - Number of people benefited/scale of impact (preference for projects that help more number of people, more area?) ____________
     - Time for implementation (preference for shorter duration projects?)_______
     - Cost of implementation (preference for projects that are more economical?)____
     - Cost effectiveness (preference for projects that increase the benefit/cost ratio?)________

- Technical know-how required (preference for projects that require less technical know-how?)________
- Social acceptability (preference for projects that are socially easily acceptable?)______
- Institutional barriers (preference for projects that have low institutional barriers, i.e., will fit within existing institutional arrangements?)__________
- Co benefits (preference for projects that have large co-benefits)______________
- Others:____

  ____

  ____

  ____

8. Please say yes or no depending on whether you think the following criteria are relevant to compare adaptation options from the farmers' perspectives:
    - Number of people helped/scale of impact (preference for projects that help more number of people, more area?) ____________
    - Time for implementation (preference for shorter duration projects?)_______
    - Cost of implementation (preference for projects that are more economical?)____
    - Cost effectiveness (preference for projects that increase the benefit/cost ratio?)________
    - Technical know-how required (preference for projects that require less technical know-how?)________

- Social acceptability (preference for projects that are socially easily acceptable?)______
- Institutional barriers (preference for projects that have low institutional barriers, ie. will fit within existing institutional arrangements?)__________
- Co benefits (preference for projects that have large co-benefits)______________
- Others:____
____
____
____

9. Please state which criterion is more important in the pairwise analysis below.

	# of people benefitted/scale of impact	Time to implement the option	Cost of implementation	Technical know-how required	Social Acceptability	Institutional Barriers	Co-benefits
# of people benefitted/scale of impact							
Time to implement the option							
Cost of implementation							
Technical know-how required							
Social Acceptability							
Institutional Barriers							
Co-benefits							

10. Please rank each option as per your preference.

Options	**Rank**
Improved accuracy in weather forecasting	
Dissemination of new technologies to farmers	
Change cropping patterns based on water availability	
Strict water allocations within the basin	
Dissemination of information through IT at village level	
Improve efficiency of water management within the basin	
Need increased participation from farmers in government schemes	

11.C The economics of water security and reliability

In this project the overall objective is to understand the effects watershed development and climate change may have on the degree of water security on the Krishna Basin of India. At the heart of this study is the concept of 'water security'; it is the measure upon which changes in watershed development and those wrought by climate change need to be judged. Water security, in this study, is measured by the degree of reliability achieved in a managed irrigation system. That system includes all a catchment's water resources (ground and surface), that are manipulated and put to some intended use. It does not include the free unregulated flows of a river, wild storms, inaccessible and untapped aquifers or any water that is not consciously collected with some intention of using it, even if that use involves an unintended loss in the system (like a leaking canal).

Economics has a role to play in this assessment because it is the study of how people make choices. The definition of a managed irrigation system (provided above) implies that choices need to be made regarding how it should be managed. The policy responses to climate change and the acts of implementing a watershed development are conscious choices by policy makers that affect the management of catchments water resources. These choices need to be understood and the impacts assessed if any improvement to the management of an irrigation scheme is to be improved.

To gain some handle on what is meant by 'improved' requires some scale upon which different choices can be assessed. In this study the focus is on improving water security. Water security is about providing users with some certainty about the amount of water they will receive in any given year. This concept is known in hydrology and irrigation studies as the 'reliability' of the system. The reliability is measured as the number of years in 100 that a certain quantity of water can be provided to a selected point in an irrigation system. The more reliable a system is (in other words the more secure the water supply is) the more years in 100 that a certain quantity of water can be supplied.

It should be noted that those who operate a system have the means to run it at different levels of reliability. However, by choosing to run a system at a high level of reliability, means that they can only guarantee to supply a small quantity of water. Running the system less reliably (less years in 100) results in a greater supply of the regulated water in the years in which it is guaranteed. Thus, the set of choices facing policy makers is much wider than implementing policies such as water shed developments or those directed at mitigating or adapting to climate change; they also include choices about the degree to which the system should be regulated.

The aim in this component of the report is to explore the economic elements associated with water security. The concept of reliability in irrigation has been used for a range of purposes way beyond what it was intended for. It was and essentially remains a measure of how well a system performs to meet its user's expectations. That in essence means in how many years (in 100) water could be provided to a user if the irrigation system is run in a certain way. The problem in using this measure arises in determining what the user's expectations exactly are. If they extend beyond the simple belief of the provision of water to the income derived from the water itself, then the simple measure of reliability and the implication that more reliable water also means more reliable income becomes tenuous. Yet it is this simple relationship that is used to justify greater expenditures on irrigation infrastructure.

What is reliability?

The reliability of an irrigation system is a measure of the effectiveness of the actions involved in managing water resources. Within the context of integrated water resource management, the concept has been extended from its purely physical connotations and uses (to measure the ratings of physical assets), to also assess the impacts and expectations regulating water has on the incomes of those who use it, the societies who live off it and even the environment within which it exists.

Malano, Chien and Turrell (1999) suggest that reliability is a measure of the confidence in the irrigation scheme to deliver water as specified by the level of service. Similarly, Renault and Vehmeyer (1999, p75) define the reliability of irrigation service "... as the degree to which the irrigation system, and its water deliveries, conform to the prior expectations of its users. The perception of the user is central to the process of defining expectations and to the process of making strategic and tactical choices for the cropping pattern, the quantity of inputs, etc."

To understand reliability in an irrigation system more fully, it is necessary to come to terms with what is being attempted in water resource management and the way in which variability is thought of in the process. After all, irrigation is an attempt to reduce the vagaries and variability of what could be termed the "natural flow of water" so that it conforms to the desires by users to what could be termed the 'regulated flow". Both the regulated and natural flows have a degree of variability, where the natural flow is usually more variable than the flow that has been regulated.

So the amplitude of the natural flow has a greater frequency than the regulated flow. A simple measure of reliability is how well the variability of the regulated flow is maintained to that originally specified before the intervention was undertaken. In other words, given the definitions of Malano et al. (1999) and Renault and Vehmeyer (1999), reliability is not about the differences between the variability of natural and regulated flows, but is about maintaining the pattern of the regulated flow.

However, the ability to do this is related to the variability of the natural flow. To reliably maintain the regulated flow of the river, natural high flows must be used to supplement natural low flows. In other words, flows are reduced by ‘extracting and storing’ water during natural high flows, which are in turn ‘released’ during natural low flows. The extraction and storage occurs when the regulated flow is below the natural flow and the release occurs when the opposite is true. Water resource management is about balancing these two functions. Reliability can be defined as the ability to manage this balance of extraction and release with the interventions employed, on a continuing basis. As a consequence reliability is measured in terms of the number of times that that balance is successfully achieved, divided by the total number of times it is attempted.

From this simple analysis a false impression of the ease to which the tasks of water resource management are undertaken as the amplitudes and frequencies of both the natural and regulated flows do not occur in a regular manner. So the amount extracted and stored is not approximately equal to the amount used in any cycle, and the cycles are not of the same duration. Looking at water resource management as if the cycles are of the same duration and size would reduce the task to a stock inventory problem, where an attempt is made to keep the stock (in this case water) within some definable limits to meet ongoing demand for it. However, the frequency and amplitude of the natural flow of a river are not normally so regular and extended periods of drought and peaks of floods exist. During the periods when then there is no extraction or use of the water, there is no control on the water resource. It is this impact that a reliability measure is trying to assess: over the whole period how many times do water resource managers adequately store and release the water according to its users. The system is said to be unreliable during those periods when water resource managers have no control over the resource, which occurs when the natural flow is active in the system.

So, is this the concept that hydrologists and those who manage water resources view reliability? As it transpires, the answer to this question is no. The concept of measuring the difference between the natural and regulated flow is not only a meaningless theoretical construct, but is also impossible to do with any degree of accuracy. Once a river has been regulated, then the flow is affected and the natural flow no longer exists. Thus, all that exists upon which hydrologists can talk of flows is the regulated flow.

Hydrologists calculate what is known as a flow duration curve from the (regulated) river flows (see Figure C.1) to characterise reliability. These regulated flows reordered from highest to lowest and the probability of exceedance in the series calculated. Thus, (in Figure C.1) there is a 10% chance that the highest flow on record or greater occurring (something that happened only in year 4), which is the same chance associated with the lowest flow (in Year 8). However, there are four years (1, 3, 4 and 5) in which a more moderate flow can occur.

Irrigation system operators are interested in ‘reliably’ supplying a certain quantity of water to a point in a catchment, so many years in 100. Thus, if asked to provide a system with 90% reliability they would allocate only the lowest flow (in year 8 in Figure C.1) to irrigators. Asked to provide a system that is only 40% reliable would result in a medium allocation (that which would be provided 4 years in 10). If asked to provide only 10% reliability, then the quantity allocated is high (Figure C.1). Thus, a regulated system can be run at any level of reliability required. Policy makers need to resolve the level of reliability they wish and hydrologists and system operators can then comply. Then the quantities to be allocated to irrigators, the enshrining of the property rights and allocations to irrigators can be determined. The level of reliability chosen determines the quantity allocated and/or enshrined in their entitlement. If policy makers implement new infrastructure or management interventions in the catchment, the flow rates of the river will change, altering the reliability curves and ultimately the quantities of water allocated to irrigators.

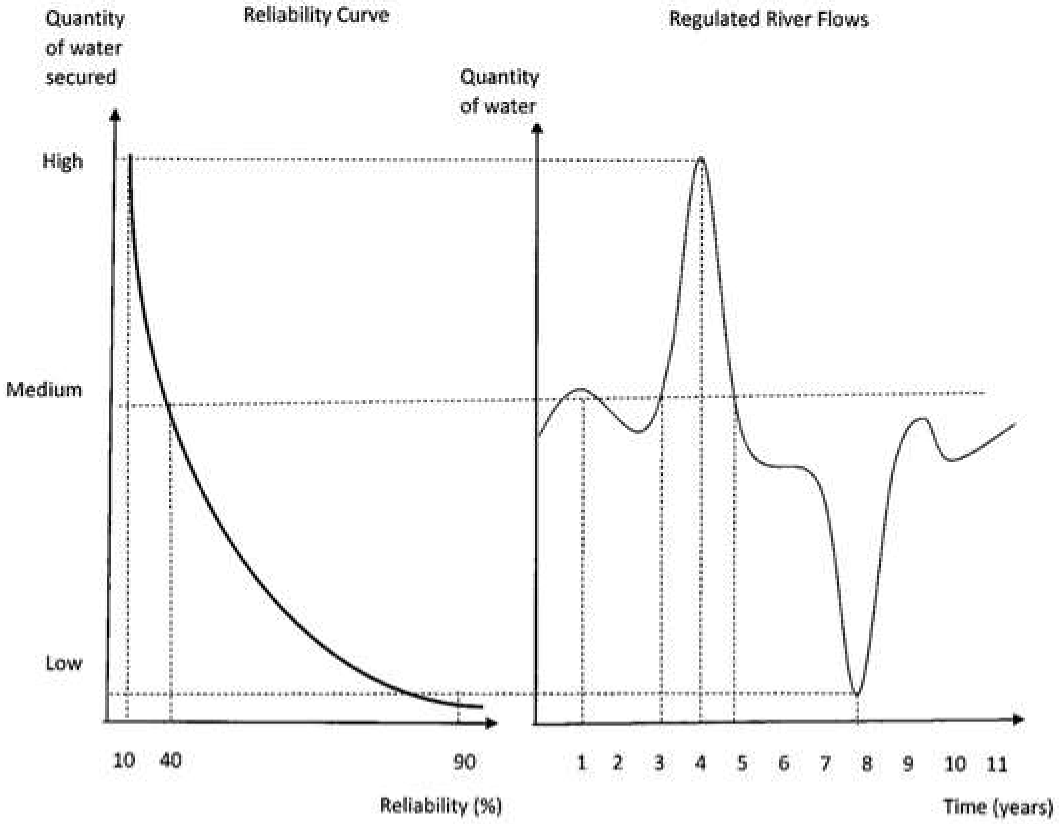

Figure C.1. Determining Reliability from the regulated flows of a river

Some implications that arise from reliability

While reliability is a probabilistic measure, it also is used to measure the changes in variability that result from an intervention. Thus, measures of reliability have become associated with the notion of being a measure of uncertainty. Once uncertainty is quantified, that uncertainty then becomes a risk, which in turn can be used to measure the reduced degree of vulnerability people face from an intervention.

Cai (2005) makes this point most clearly, by stating that reliability relates to how often a system remains at a satisfactory level with an assumed level of confidence. Variability reveals the corresponding variation in the system status due to one or more uncertain factors. Vulnerability is a measure of the severity of a systems failure. Mathematically Cai suggests that reliability is equivalent to the number of times a system succeeds divided by the total number of times it is operated. Variability is measured by the standard deviation of how that system operates and vulnerability is the maximum variability.

Because of this connection (between reliability, variability and vulnerability) it is easy to associate the measures of reliability with a risk factor. Users of the system make decisions based on those reliability ratings. Perhaps this is done as they are the only measures of risk available. Regardless of the reason why, investment decisions are made on these risks and as most economists would agree, risk has a direct relationship to the returns from that investment. There are implications from making these connections, some of which are known, but many which are unexpected.

This way of thinking about the role of water resource management being about cutting off and smoothing the amplitude of natural flows would appear to have a number of contradictions to it, beyond purely those of reliability and risk. For instance, it would appear that the greater the amplitude of the natural flow, the greater the will be the impact of a water resource management intervention. Why? Well the more the peaks are cut off, the more the hollows can be filled and the more of the resource can be used. So, does this imply that water resource management should be practiced in places where the amplitude is greatest? Surely not, as where the amplitude is greatest is also where the water availability is most plentiful. Australia provides a good example of this contradiction, where in the north of the country water is most plentiful, yet the irrigation schemes are the most underutilised (especially in the Ord and Burdikin rivers).

The common measures of reliability only work on the number of times water is delivered successfully is measured. This has nothing to do with the severity of a failure, which is measured by quantity not delivered. So reliability cannot be used unless some notion of the vulnerability is recognised as well. What this means is that from a physical perspective, any measure of reliability is only partially useful in describing the performance of a system. The extent to which it can be relied on is dependent on the extent and duration of the failure of the system, which is not measured or mentioned. The probability of an event occurring is only useful if it is accompanied by an estimate of the possible consequences. As a consequence some, such as Eijgenraam (2009), suggest optimal safety rules in operating systems between constant boundaries to minimise losses and to balance different risks.

The measure of reliability is not an independent variable that can be used to rate water resource interventions, but rather can be used as a control variable (see the discussion associated with Figure C.1 and how reliability is calculated). Water resource managers can use it to measure the degree of control from any number of different strategies. For instance, it could be the case that if a conservative strategy is pursued, say of supplying water to downstream users 99 years in 100, less water is released in any one year to users in order to maintain the rating. This strategy deprives users of the benefits of more water in select years, as some is used to ensure the reliability of supply. Consequently, the implication that a higher rating of reliability implies greater benefits to users cannot be asserted

Summary

The concept of reliability rests on the well held belief that it is ideal to make users of a system or resource 'more reliable'. That this is a good thing that one should aim for, can be questioned. Situations were identified where greater variability and thus less reliability are ideal, and cases were presented where farmers tended to act in a contrary manner. It should be noted that while reliability is directly related to variability, it cannot be implied that less variability means more reliability, especially of what users are principally interested in, which is the return from water use.

It could be the case that running a scheme more reliably results in society benefiting less from a water resource management reliability alone is not a measure that should be used to promote and justify the establishment of an intervention. The economic consequences of the intervention need to also be assessed. In addition, it should not be used to relate the risk associated with or mitigated by an intervention measure, or for that matter extended to encapsulate notions of economic return. Other measures of water resource management exist, such as the percentage of regulated flows taken, etc. However, none of these really encapsulate the impact water resource management decisions have on risk and returns. To understand this good definitions of what is meant by risk (the probability of not succeeding in a venture), returns (price by quantity at the very least, net with costs extracted) are required.

11.D Water security diagrams

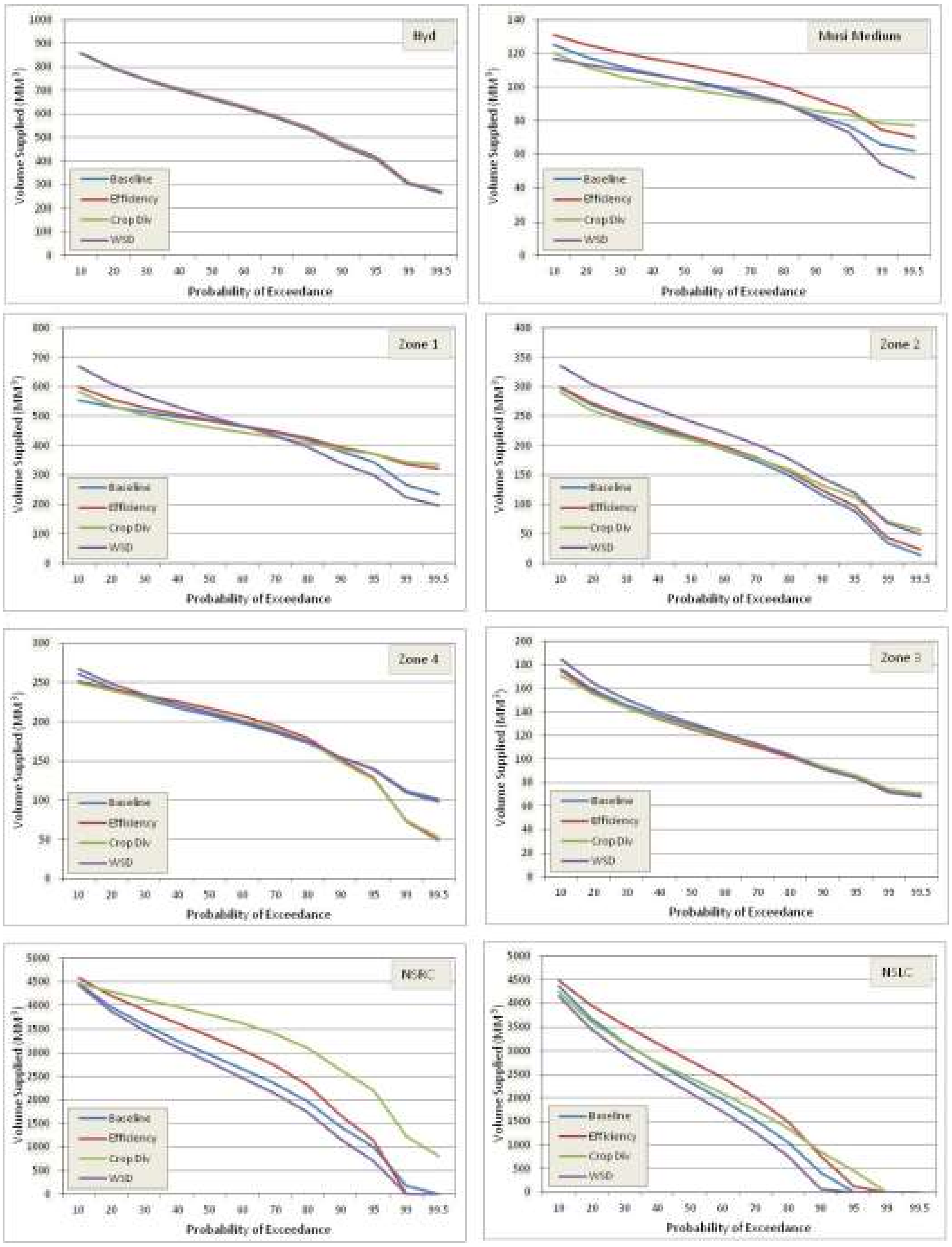

Figure D.1: Comparison of volume supplied to demand centres under climate scenario Q_0 for the period 2011-40

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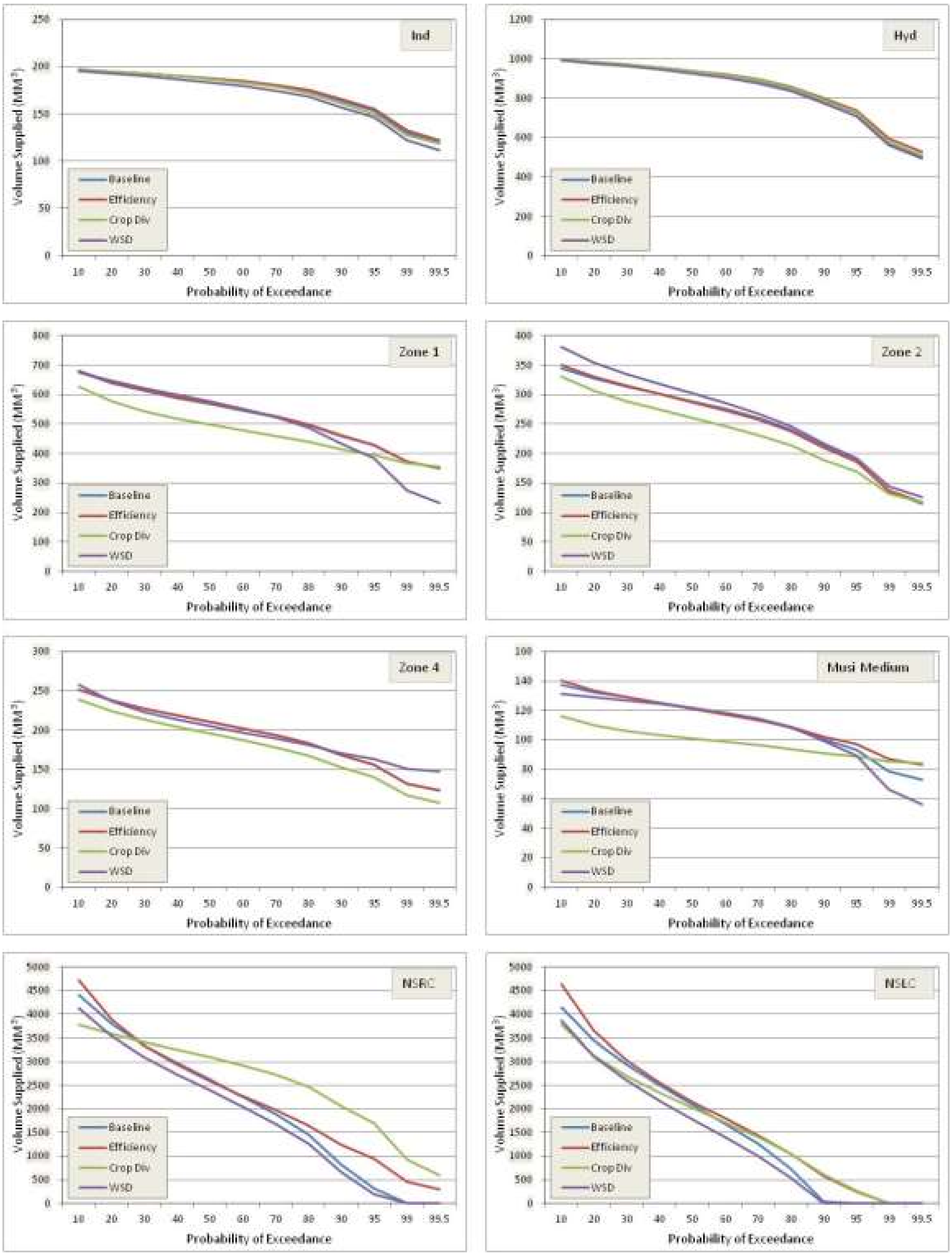

Figure D.2: Comparison of volume supplied to various demand centres under climate scenario Q_0 for the period 2041-207

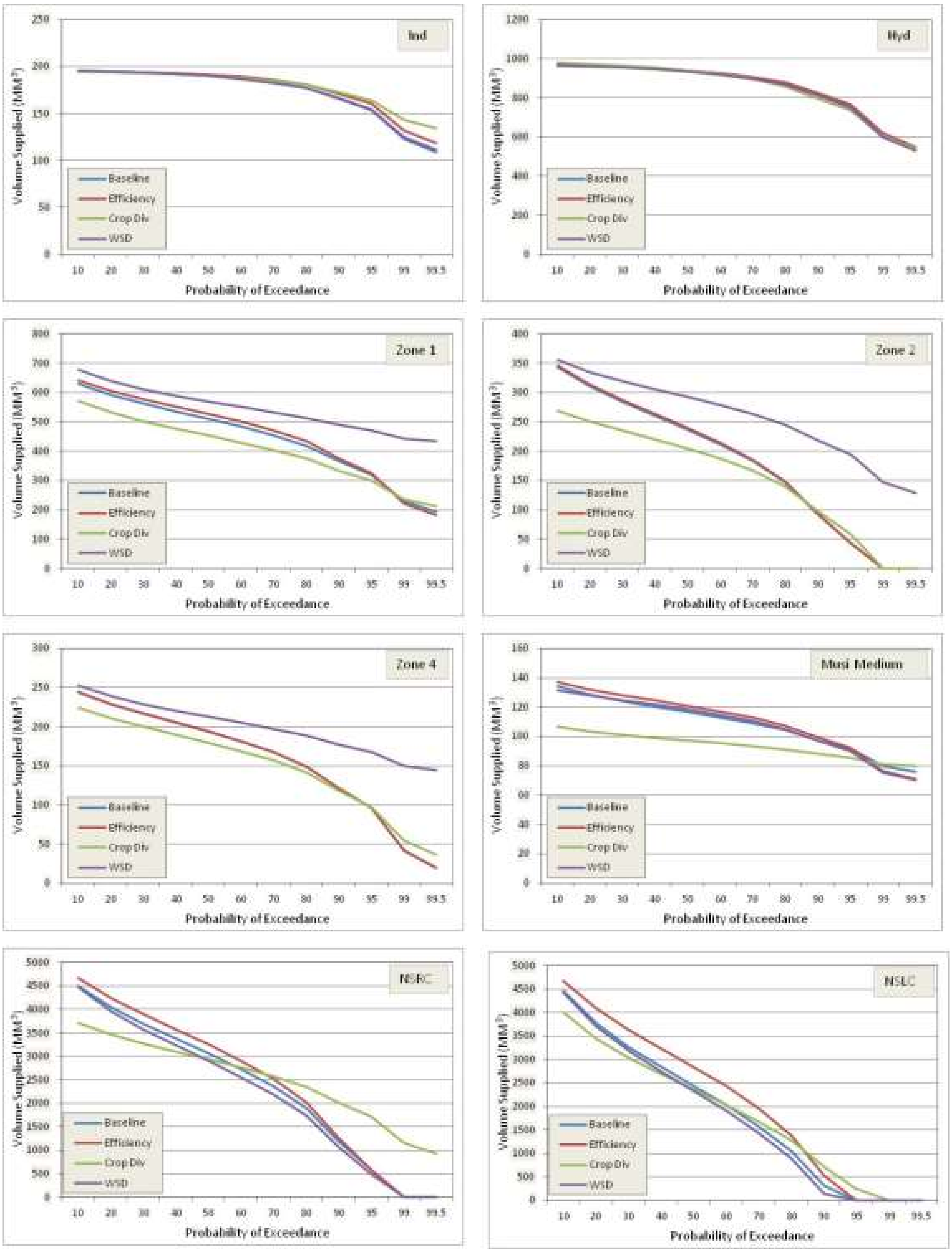

Figure D.3: Comparison of volume supplied to various demand centres under climate scenario Q_0 for the period 2071-2096.

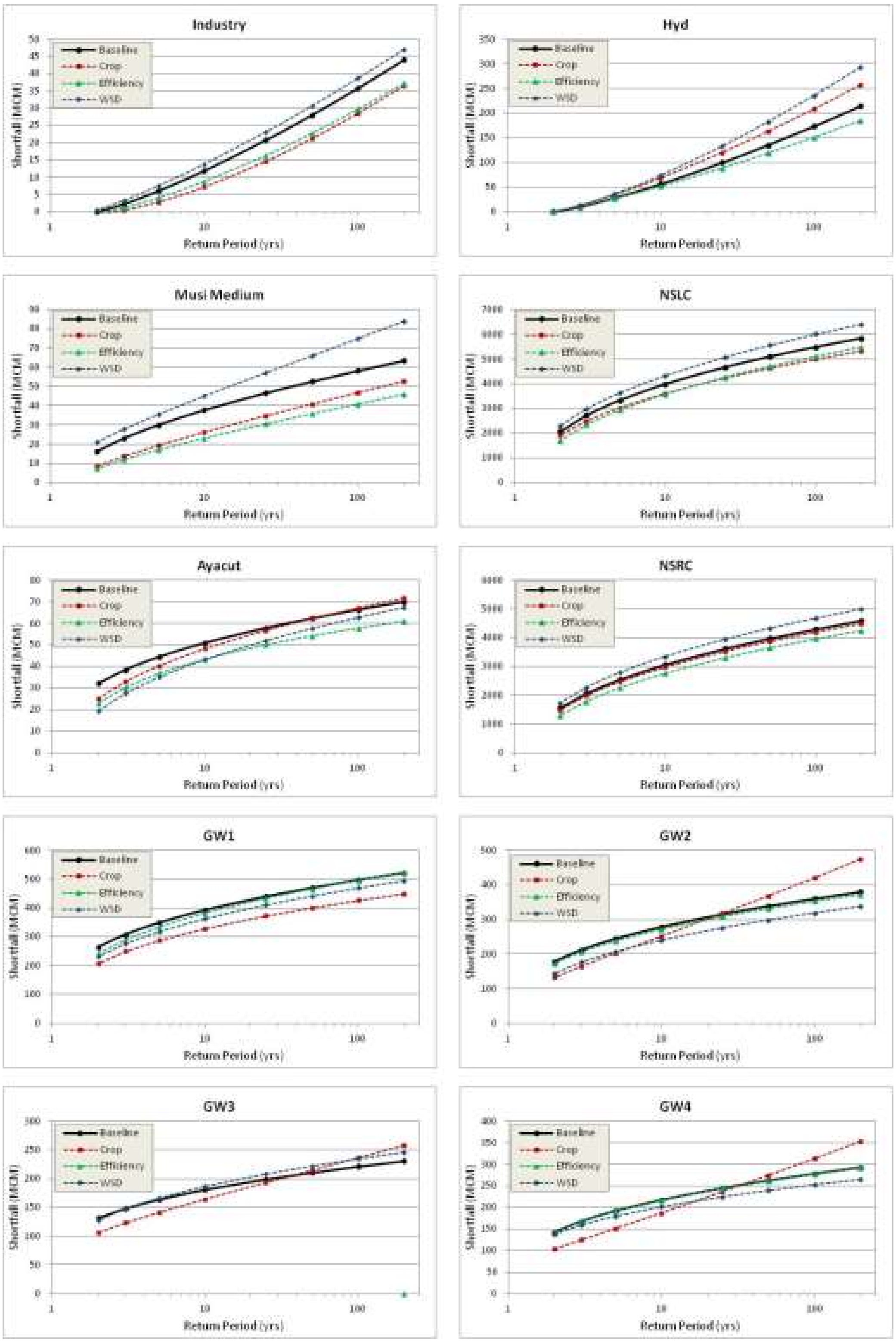

Figure D.4: Shortfalls recurrence interval for various demand centres under climate scenario Q_0 (2011-2040)

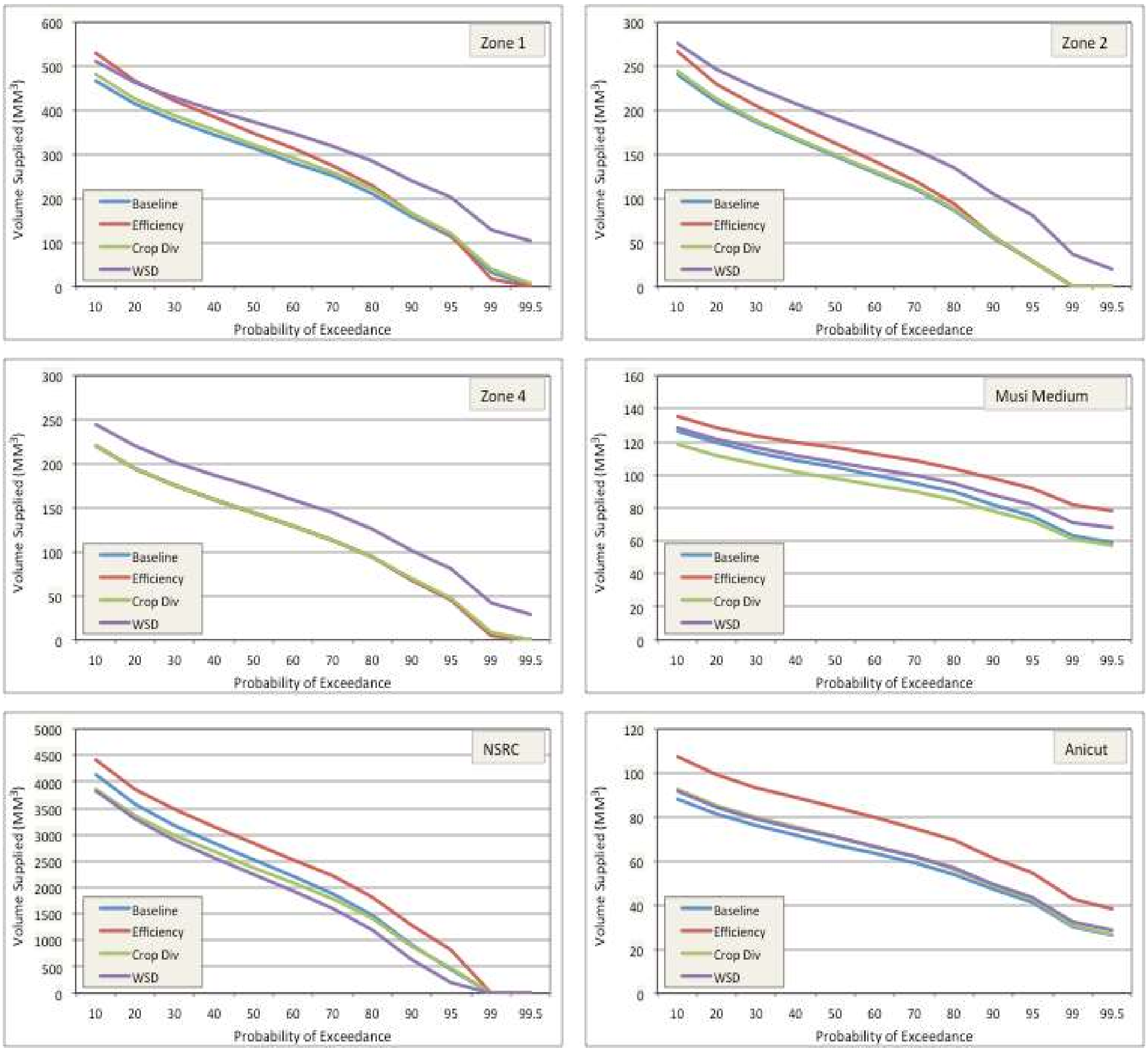

Figure D.5: Comparison of volume supplied to various demand centres under climate scenario Q_1 for the period 2011-2040.

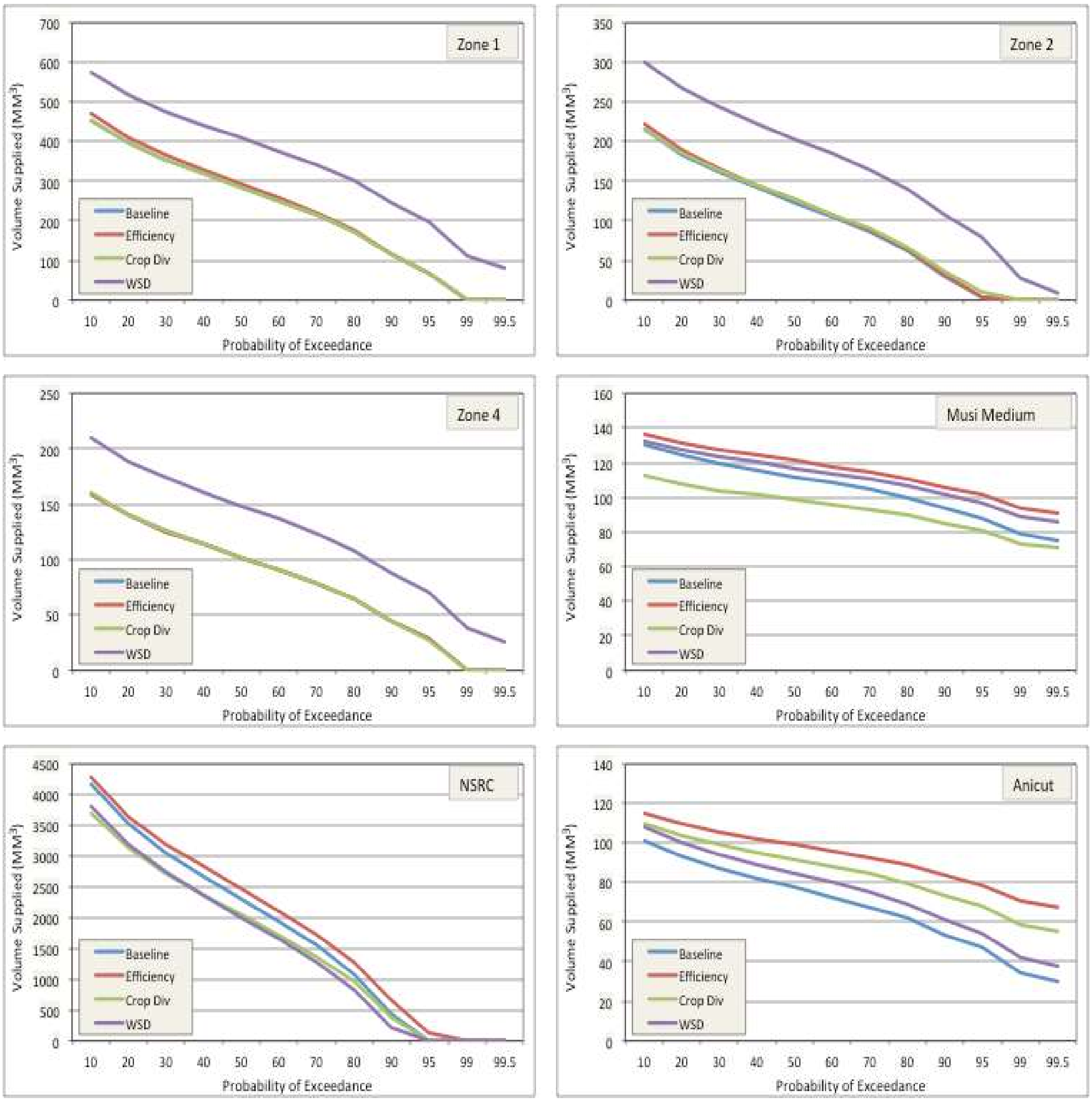

Figure D.6: Comparison of volume supplied to various demand centres under climate scenario Q_1 for the period 2041-2070.

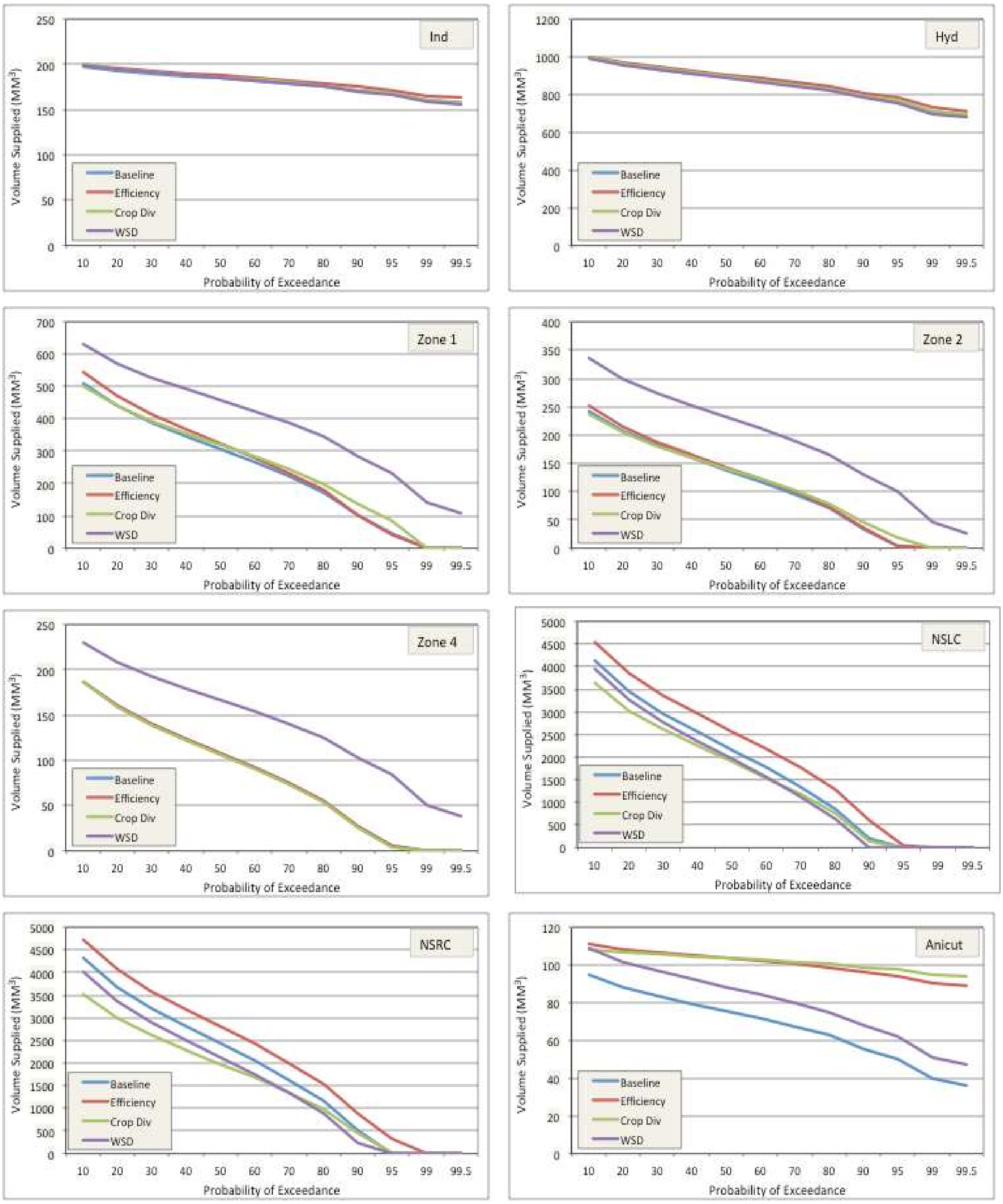

Figure D.7: Comparison of volume supplied to various demand centres under climate scenario Q_1 for the period 2071-2096.

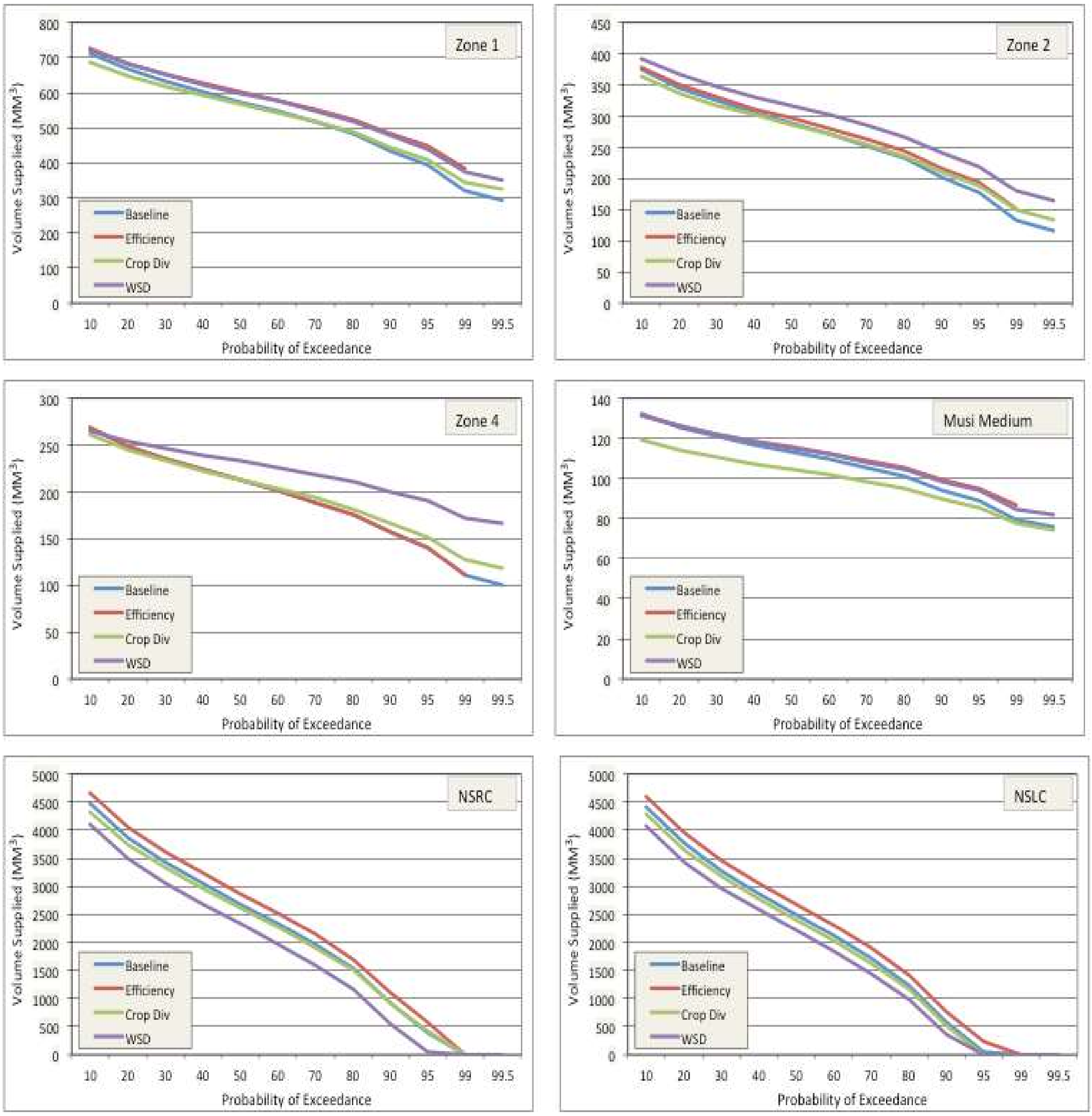

Figure D.8: Comparison of volume supplied to various demand centres under climate scenario Q_{14} for the period 2011-2040.

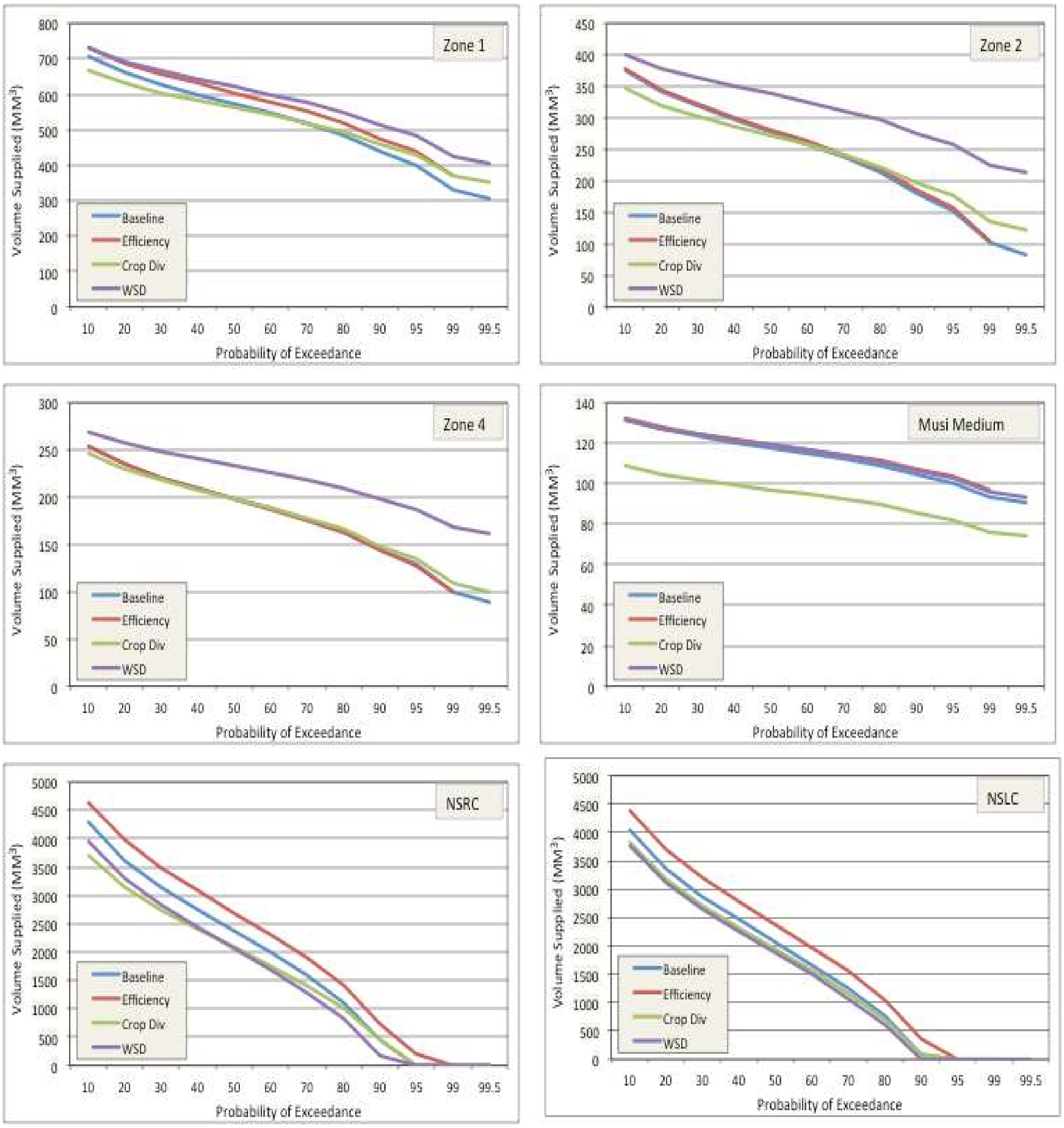

Figure D.9: Comparison of volume supplied to various demand centres under climate scenario Q_{14} for the period 2040-2071.

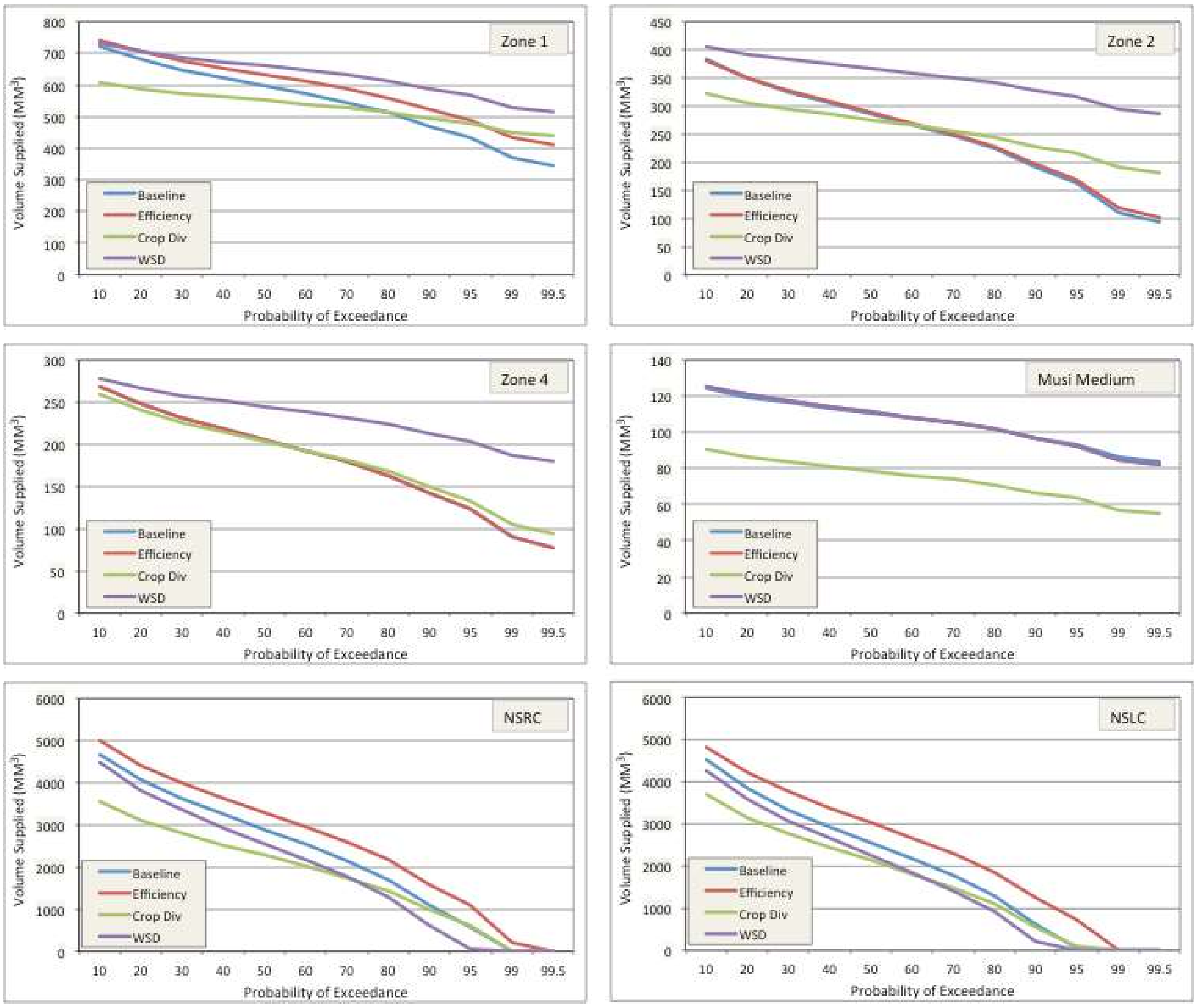

Figure D.10: Comparison of volume supplied to various demand centres under climate scenario Q_{14} for the period 2071-2096.

11.E. International workshop brochure

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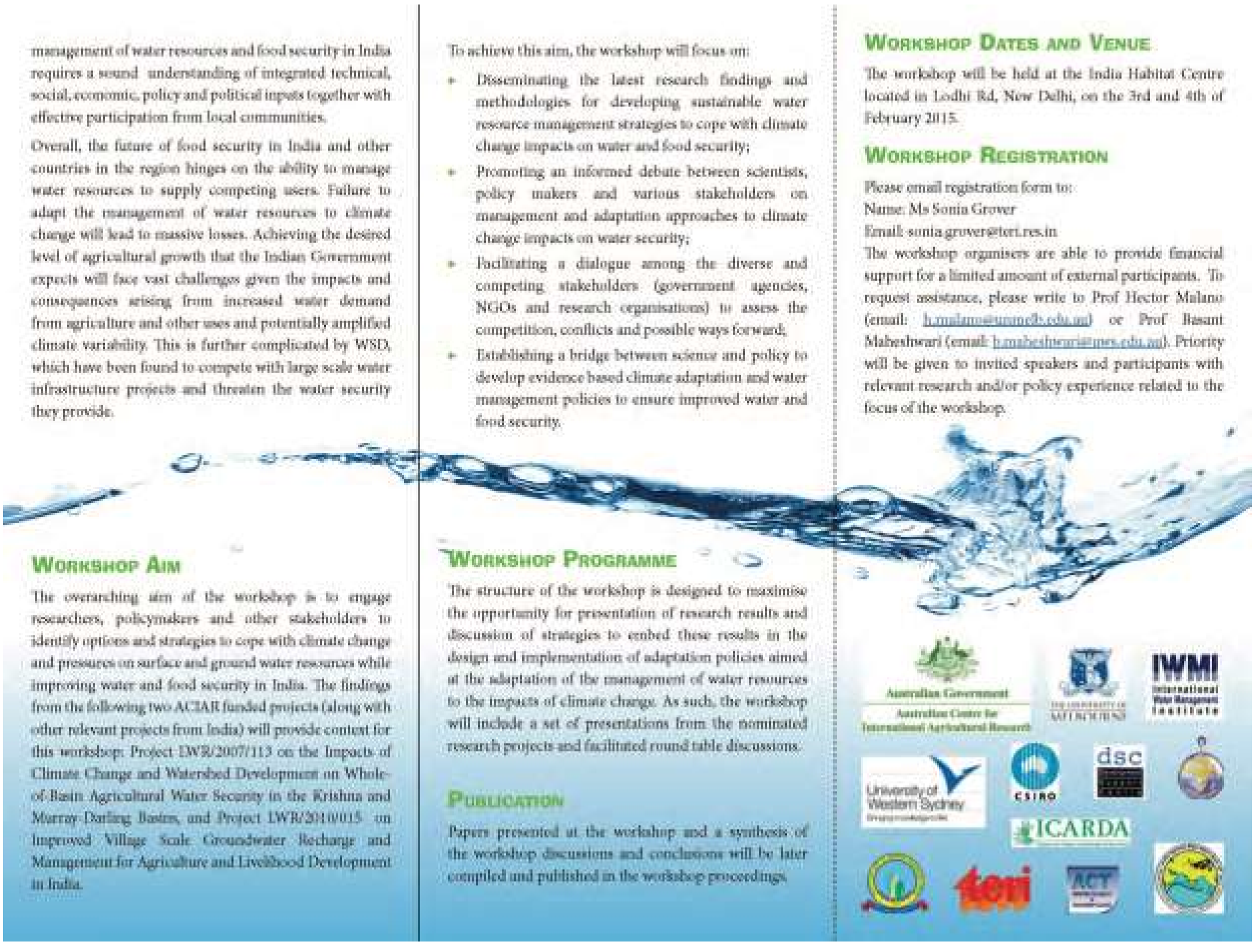

management of water resources and food security in India requires a sound understanding of integrated technical, social, economic, policy and political inputs together with effective participation from local communities.

Overall, the future of food security in India and other countries in the region hinges on the ability to manage water resources to supply competing users. Failure to adapt the management of water resources to climate change will lead to massive losses. Achieving the desired level of agricultural growth that the Indian Government expects will face vast challenges given the impacts and consequences arising from increased water demand from agriculture and other uses and potentially amplified climate variability. This is further complicated by WSD, which have been found to compete with large scale water infrastructure projects and threaten the water security they provide.

Workshop Aim

The overarching aim of the workshop is to engage researchers, policymakers and other stakeholders to identify options and strategies to cope with climate change and pressures on surface and ground water resources while improving water and food security in India. The findings from the following two ACIAR funded projects (along with other relevant projects from India) will provide context for this workshop: Project LWR/2007/113 on the Impacts of Climate Change and Watershed Development on Whole-of-Basin Agricultural Water Security in the Krishna and Murray-Darling Basins, and Project LWR/2010/015 on Improved Village Scale Groundwater Recharge and Management for Agriculture and Livelihood Development in India.

To achieve this aim, the workshop will focus on:

- Disseminating the latest research findings and methodologies for developing sustainable water resource management strategies to cope with climate change impacts on water and food security;
- Promoting an informed debate between scientists, policy makers and various stakeholders on management and adaptation approaches to climate change impacts on water security;
- Facilitating a dialogue among the diverse and competing stakeholders (government agencies, NGOs and research organisations) to assess the competition, conflicts and possible ways forward;
- Establishing a bridge between science and policy to develop evidence based climate adaptation and water management policies to ensure improved water and food security.

Workshop Programme

The structure of the workshop is designed to maximise the opportunity for presentation of research results and discussion of strategies to embed these results in the design and implementation of adaptation policies aimed at the adaptation of the management of water resources to the impacts of climate change. As such, the workshop will include a set of presentations from the nominated research projects and facilitated round table discussions.

Publication

Papers presented at the workshop and a synthesis of the workshop discussions and conclusions will be later compiled and published in the workshop proceedings.

Workshop Dates and Venue

The workshop will be held at the India Habitat Centre located in Lodhi Rd, New Delhi, on the 3rd and 4th of February 2015.

Workshop Registration

Please email registration form to:
Name: Ms Sonia Grover
Email: sonia.grover@teri.res.in
The workshop organisers are able to provide financial support for a limited amount of external participants. To request assistance, please write to Prof Hector Malano (email: h.malano@unimelb.edu.au) or Prof Basant Maheshwari (email: b.maheshwari@uws.edu.au). Priority will be given to invited speakers and participants with relevant research and/or policy experience related to the focus of the workshop.

Summary of Final Workshop Recommendations

Workshop Outputs

The workshop discussions were held over sessions following each of the paper sessions. In them, each group was asked to combine their discussions and to draw out the ***four or five key issues*** or points that had arisen for them that they believed would provide a way forward *to develop evidence based climate adaptation and groundwater management policies to ensure improved groundwater and food security*.

The final two workshop sessions were then first a plenary to share and discuss the key group outputs, followed by a panel discussion on the value of the research and the way forward for policy makers and scientists. To facilitate the plenary discussion, a small group of the workshop organisers quickly summarised the group outputs and presented them at the start of the plenary. These are given in addendum (1) below. Addendum (2) contains the actual typed version of each group output as they recorded them. Following the plenary, the following six points were developed to represent the combined workshop discussion outputs:

Workshop Key Outputs

- Groundwater needs to be managed locally. It is essential to engage with farmers to understand their needs and their perceptions of well-being and that they are empowered to manage their water resources with a view to adapting to climate change.
- There is a need to inform farmers so they can monitor their groundwater systems, assess how they are changing and understand the effects of irrigation on future supplies.
- There is a need to inform farmers about options for selecting crops and for enhancing irrigation efficiency to get improved livelihoods in the context of climate change and well-being with a sustainable level of groundwater use.
- There is a need to encourage farmers to develop participatory cooperative water resource management, and to use data about the current status of their groundwater availability to convince them of the amount of sustainable extraction, and then help them to achieve this level of extraction.
- There is a need to develop and implement plans for watershed management to enhance groundwater recharge as a strategy for climate change adaptation, improve groundwater quality and maintain recharge structures.
- There is a need for State and National government to support climate change adaptation measures and local groundwater management through the development of consistent policies associated with land and water ownership and governance, energy, food production, education, health, social stability, and economic development. Provision of information and financial resources to implement the above activities at the local level and to ensure coordination of local management at groundwater basin and surface water catchment levels, is necessary.

Addendum 1: Summary Outputs of initial combined table points as presented to the plenary session

-

1. **Monitoring and implementation**

-

   a. WSD can have –ve & +ve impacts and has diversity of options but keep objectives and focus clear
   -
   b. Clarity and agreement of important indicators lead to alignment of objectives especially where impacts on other systems or places leads to strategies for **water security**
   -
   c. Water quality integral part of water security. Need to improve knowledge base leading to actions
   -
   d. Groundwater demand management through crop diversification so that the use of GW matches with recharge
   -
   e. Adaptation strategies should be tested first on pilot scale before implementing in project area
   -
   f. WSD can have –ve & +ve impacts and has diversity of options but keep objectives and focus clear
   -
   g. Development should be implemented to increase wellbeing of people

-
-

2. **Civil Society engagement**

-

   a. Engage local people through different methods to enhance awareness leading to informed decisions and actions
   -
   b. Local communities should be involved in each stage of planning and decision making
   -
   c. **Increasing effectiveness of community feedback** (evaluation and testing, benchmarking performance and upscaling). This applies to groundwater management and climate change adaptation.
   -
   d. Engaging and understanding needs and what will improve their livelihood and GW sustainability
   -
   e. Determine incentives for participatory GW management and cooperative use
   -

3. **Systems integration**

-
    a. Clarity and agreement of important indicators lead to alignment of objectives especially where impacts on other systems or places leads to strategies for water security under climate change
    -
    b. Accurate climate change impacts should be made **available on** a **regional scale**
    -
    c. Developing comprehensive evaluation framework to assess a variety of spatially relevant adaptation options (modelling, spatial distribution performance evaluation, extreme climate events)
    -
    d. Make available good quality data and appropriate models for IWRM
-
-

4. **Policy and institutions**

-
    a. Clarification and increased understanding around nexus between property rights, land ownership, water allocation and infrastructure access
    -
    b. Policy needs to be sensitive for range of issues like water budget audits, socio-economic aspects and available technologies.
    -
    c. GW is a village level resource and should be managed at village level and by village level people
    -
    d. Policy should be planned to enhance water use efficiency. This is one of the climate change adaptation responses.
    -
    e. Design of relevant incentives around GW and energy (tariff) use efficiency
    -
    f. Groundwater demand management through crop diversification so that the use of GW matches with recharge. Crop diversification is one of the selected climate change adaptation options.
    -
    g. Adaptation strategies should be tested first on pilot scale before implementing in project area

Addendum 2: Recorded Outputs from each discussion table

Table 1 discussion

1. Engage local people through different methods: enhance awareness, informed decisions and actions
2. WSD can have +ve and -ve impacts and it has diversity of options but keep objectives and focus clear
3. Clarity and agreement of indicators are important, alignment of objectives especially where impacts, other systems or places, strategy for water security
4. Water quality is an integral part of water security. Need to improve knowledge base and action

Table 2 discussion

1. Availability and accessibility of good quality climate, models, geophysical, hydrological data is critical.
2. Integrated water resource management – SW, GW, RRF
3. Empowering local groups with knowledge and real time information on status of GW & SW to manage utilization in a cooperative manner
4. Transfer flood water to over-exploited aquifers in view of persistent decline in GW levels
5. Adaptation strategies should be tested first on pilot scale before implementing in full project area
6. Crop diversification, socio-economic aspects should be considered
7. Improved technology for precision irrigation capacity building in SW, GW monitoring and management.

Table 3 discussion

1. Engaging and understanding farmer's needs, what will improve their livelihood
2. GW Demand Management through crop diversification so that the use of GW matches the recharge.
3. Indirect improvement but with the choices of farmers.
4. Determining incentives to participatory ground water management (At Village) cooperative-extraction.
    - *Sustainable levels of water extraction – Empowerment
        - Real time data
        - Knowledge absent
        - GW level and quality
        - Village level panchayat water level
        - Groundwater literacy
5. GW is a village level resource and it has to be managed locally on village level
6.

Five key points emerged from all the presentations

1. More crop/dollar per drop of water
2. Holistic approach
3. Strong & effective communication between community, science and research
4. Decentralize approach for ground water management

Table 4 & 5 combined discussion

1. Accurate climate change impacts should be made available on a regional scale.
2. Policy needs to be sensitive for range of issues like water budget audit, socio-economic aspects and available technology.
3. Local communities should be involved in each stage of planning and decision making.
4. Policy should be planned to enhance water use efficiency and irrigation efficiency.
5. All above issues/aspects should be implemented to increase the well-being of people.

   -

- **Table 6 discussion**
  1. Getting clarification + increased understanding around nexus of property rights, land ownership, water allocation and infrastructure access.
  2. Design of relevant incentives around groundwater energy use efficiency
  3. Developing comprehensive evaluation framework to a variety of spatially relevant adaptation options/ modelling spatial distribution, performance evaluation, extreme climate events.
  4. Increasing effectiveness of community feedback (evaluation + testing, benchmarking performance and up-scaling