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Final report

Small research and development activity

project	**SRA for handover and training of surface-groundwater and econometric models to end users in Pakistan**
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1 Acknowledgments

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2 Executive summary

Project Overview

The aims of proposed SRA activities are to handover project outcomes and also provide training for the Pakistani stakeholders for capacity building for the management of canal and groundwater resources resulting from ACIAR Project (LWR/2005/144) workshop held in Lahore, Pakistan during Dec 2014. The major project outcomes are: (i) remote sensing techniques used to estimate spatial and temporal distribution of rainfall and ET; (ii) surface water and groundwater interaction model for the Rechna Doab to address problems of sustainable groundwater and surface water use; (iii) econometric model to explore options for more equitable and economically efficient distribution of water resources.

Remote sensing techniques for estimation of potential and actual evapotranspiration offer new approaches for improved spatial and temporal estimation or evapotranspiration. The use of improved spatial and temporal assessment of rainfall and evapotranspiration has greatly assisted in providing accurate inputs for the groundwater model.

A regional groundwater and solute transport model for Rechna Doab in Punjab Pakistan was developed for PID. The model is a significant enhancement over previous models carried out in Pakistan which were based on seasonal time steps covering Kharif and Rabi seasons. The Rechna Doab model was developed at monthly time steps which offer PID an opportunity to better understand the temporal and spatial surface water and groundwater dynamics. Moreover, the regional model also provides opportunity to create sub-models at a finer spatial scale for detailed studies of canal and groundwater interaction. Examples of these are the LCC East and Rakh Branch sub-models.

A socio-economic study was also undertaken for LCC East (Lower Chenab Canal Command). The results of the water user scenario analyses, resulting from econometric as well as hydrological modelling approaches, will assist PIDA and Farmer Organisations for implementing more equitable, economically efficient and improved water quality options in the study areas.

A major concern for Punjab Irrigation Department (PID) is the lack of capacity within the department to monitor, model and manage groundwater resources to achieve sustainability of the resource over the long run. There is a significant concern of groundwater levels being depleted in the major irrigation areas where cropping intensities have increased from the design levels of 67% to over 150% and a concomitant increase in tubewells and groundwater withdrawals. The increase in tubewells to over 1 million tubewells in Punjab alone is cause for concern as depletion of groundwater also increases the risk of salinisation of fresh groundwater resources which many smallholder farmers depend on for their livelihoods. Thus one of the most important goals was to provide training to PID staff to improve knowledge of how the Rechna Doab model was developed, construction of the conceptual model, usefulness of monitoring data for model calibration and verification, water balance analysis and scenario analysis. The training also covered introduction to MODFLOW and MT3D and various example models to help trainees understand how models can be applied to evaluate demands on the groundwater resources.

A unique addition to the modelling training program was to provide training in remote sensing and the use of GIS for estimating spatial distribution of crop water use for various canal commands in Rechna Doab. The trainees were introduced to NDVI and crop spatial mapping analysis techniques to identify various crops grown in Rabi and Kharif. Additionally training was provided in the use of a Google API tool for estimating crop water use for various locations within the study area.

In groundwater irrigated agricultural areas of Punjab Province, Pakistan, salinity intrusion due to over extraction of groundwater and deepening watertable adversely impacts crop yield and agricultural production. Such salinity effects are significant at distributaries towards tail end of canal systems. The purpose of this SRA, i.e. training program, has been to disseminate the hydrological and econometric modelling results of a completed ACIAR project in Punjab, Pakistan (LWR/2005/144) on how to redistribute conjunctive use of surface and groundwater to minimize the salinity effects on crop yields and redistribute the water sources in an equitable manner along the distributaries in the Lower-Chenab Cannel (LLC) irrigation system.

The SRA for groundwater modelling, remote sensing and socioeconomics included training sessions and field visits conducted at two occasions in Pakistan in August 2015 and April 2016. One of the objectives of the SRA was to enhance capacity of PID, PIDA, and postgraduate students at UAF, and UAAR in groundwater modelling, remote sensing and econometric modelling.

The SRA activities also included additional focussed scenario runs and providing review for policy support materials. The scenarios undertaken included: increased pumping and drought impacts of various durations. Additionally a simplified TMR (Telescopic Mesh Refinement) model of the Rakh Branch was extracted from the regional Rechna Doab model as a training exercise and for future detailed studies.

The framework for the groundwater status report is provided as a starting point for consideration. The report can be tailored to meet the needs of a particular region, the aim being to propose a framework for a Groundwater Status Report that would be provided to management annually to enhance planning and decision making within the Department.

Draft papers for the Rechna Doab model and additional scenario modelling, and remote sensing applications and analysis is under preparation and abstracts are included in the appendix. A draft paper on the impacts of irrigation water user allocations on water quality and crop productivity has been completed and is attached.

Two reports were prepared by PID on awareness raising and capacity building of FO's and farmers on groundwater management issues for Kamalia Distributary and Khikhi Distributary have been completed and form separate reports.

Key Recommendations

The project, following two training sessions, field visit to Pabberwala distributary near Faisalabad, consultation and engagement with stakeholders, and feedback from trainees provides the following recommendations:

1. There is a strong case for continuing capacity development for building in-country skills in groundwater monitoring, modelling, management and groundwater policy particularly in the Universities and Irrigation Departments. At the present time the Irrigation Department in Punjab has mostly engineers with tremendous experience in surface water. However, experience in hydrogeology, groundwater management and modelling is lacking. Developing in-country skills will require a much broader approach than isolated training programs. In order to ensure significant knowledge uptake in groundwater modelling and management, it is recommended that PID appoint dedicated staff within irrigation departments to work on groundwater monitoring, modelling and management. This issue is not unique to Punjab but is similar in other irrigation Departments in Sindh, Balochistan and KPK.
2. Participants indicated developing a real world groundwater model would be very useful. The training provided a step by step approach to developing a simplified groundwater model with increasing complexity. However, PID lacks the necessary groundwater software and needs to have dedicated staff working on model development (at present only one copy of the groundwater modelling software is available but it needs updating to be able to run on their computers).

3. Establishment of a dedicated groundwater unit within PID has been discussed with the Secretary Irrigation Department, who has intimated that there is a pressing need for skilled groundwater professionals within Punjab irrigation Department.
4. The Rechna Doab flow and transport model developed under ACIAR Project (LWR/2005/144) provides a good basis for staff to utilise the model for planning and scenario modelling. Rather than using the model as a black box PID staff were provided training on how the model could be enhanced, and how extending the model calibration period would be beneficial as additional monitoring data becomes available post 2012.
5. Additional scenario modelling was undertaken to examine the impact of increased groundwater pumping under drought conditions. The results of these scenarios are detailed in the report and showed that increased pumping by 30 percent would result in declining water levels and increased salinity impacts particularly in the lower parts of the doab. The drought scenarios showed that the groundwater system could cope with two droughts of 3 years duration with increased pumping by 30%, however, this assumes that the pumping would return to a sustainable level post the drought years. An additional scenario simulating a long duration drought over 10 years, similar to the millennium drought experienced in Australia, and 30% increased pumping during the drought would result in negative groundwater storage, declining water levels and greater salinity impacts. Moreover, farmers at the tail end are likely to experience greater water stress as they will be affected by both lower surface water deliveries and increased risk of salinity as tail enders will make up the shortfall by pumping greater volumes of groundwater which is likely to be of higher salinity.
6. Remote sensing and GIS technologies were used to estimate spatial and temporal crop water requirements to provide input data for ground water modelling. Additionally training was provided in the use of a web enabled Crop Water Needs calculator and a Spatial ET0 calculator for PID, PIDA staff and UAF students. We recommend that these tools should to be tested in the field for further improvement and implementation. We recommend that PID make use of these tools for estimating irrigation water requirements and to contribute suggestions for improving and enhancing these tools to suit their requirements. Moreover, these tools can be made available to farmers after rigorous field testing to estimate crop water use for their particular farm.
7. The socioeconomic training sessions and exercises utilised a set of sample data (which was a sub-set of actual data used in the project), using Excel for data entry, setting up water use scenarios in Excel spreadsheet, using SPSS for running regression analysis, estimating gross margins in Excel spreadsheet, and also specifying Discrete Choice models for the farmers adaptation behaviour and interpreting results. Following the results from the sample data, the trainees were asked to provide interpretation of the results and their implications in relation to groundwater management and policy options were discussed. All the relevant materials (such as power point presentations, sample data in Excel spreadsheet and model results in SPSS files) were given to the participants to understand the modelling approaches for any real life (case study) situation. Following the example of water use scenario, effect of water redistribution on minimizing salinity, improving crop yield and farm income (gross margin) were discussed. The exercise undertaken offers rethinking of groundwater use and irrigation practices.
8. The socioeconomic analysis undertaken to estimate the technical, allocative and economic efficiency with respect to the crops produced in the study area showed that technical efficiency was higher in salinity hit Khikhi distributary area (0.88). This shows that farmers were using resources more efficiently in the Khikhi distributary as compared to the other two distributaries i.e. Tarkhani (0.69) and Bhalak (0.80). If we compare the allocative efficiency of the farmers (involving

prices of the resources), Tarkhani distributary was leading with maximum (0.74). As far as economic efficiency was concerned, Khikhi distributary was at the top with an economic efficiency of 0.66 as compared to Tarkhani (0.52) and Bhallak (0.55). Although, Khikhi distributary is at the tail end facing acute shortage of surface water and suffering from salinity, but high economic efficiency illustrates that the tail ender are using water efficiently. This implies that if Khikhi distributary is provided with better quality water through already worked out redistribution scenarios (i.e. Scenario 3, as reported in Culas et al., 2015), or by investing in infrastructure rehabilitation and institutional mechanism for improved water use efficiency, this can improve the productivity and economic returns for the farmers.

9. We recommend that the Punjab Irrigation Departments, Groundwater Division produce a Groundwater Status Report annually to apprise PID's management team on the status of groundwater in each doab. This will assist in providing information on the current state of the groundwater system to Resource Managers in PID as well as allow policy makers to make informed decisions.

10. A vital recommendation emanating from the experience in this and the previous ACIAR project is that PID is strongly encouraged to make a concerted effort to have a strong team in place for the new ACIAR project on Improving Groundwater Management (LWR/2016/036) as it will offer significant opportunity to mid-career and early career professionals to engage, learn and contribute to improved groundwater management in the case study areas in Punjab. This project offers an opportunity to participate in training and capacity development, and to work alongside various in-country professionals, International professionals (ICARDA) and Australian professionals in groundwater management, socio-economics and community engagement. It offers a real opportunity for professionals to understand challenges that farming communities face and to develop strategies for improved groundwater management and for improving livelihoods.

3 Introduction

Agricultural productivity in Pakistan is relatively low compared to other countries and it is limited by availability of water and water quality. The main sources of water for agriculture in the doabs of Punjab are rainfall (10-20%), canal/ surface water (40-50%) and groundwater (40-50%). However, water scarcity is a major issue in Pakistan due to increased cropping intensity which results in over extraction of groundwater, deepening of groundwater table and saline intrusion. The issues confronted are estimating (net) water availability, equitable distribution of water, and incentives/policy instruments for capacity building of the water sector and farmers.

Groundwater extraction in the Punjab has increased exponentially particularly in the past 30 years. This has allowed increased cropping intensity and improvement in livelihoods, but it has come at a cost. In parts of the major doabs, groundwater depletion is occurring, and in some areas farmers are forced to use marginal quality groundwater due to inequity in supply from the surface water system. Moreover, institutional capacity requires enhancement so that irrigation departments can gain the skills and experience to monitor, model, and manage groundwater resources. Management of groundwater in the Pakistan is also constrained as there is a lack of a regulatory and groundwater policy framework for guiding the sustainable use of groundwater.

An integrated approach has been followed for the completed ACIAR project, in which the socioeconomic expectations of the farmers have been analysed in econometric models and for optimal water use scenarios in relation to improving crop yield and equitable water allocations. Remote sensing and GIS approaches also supported the spatial and temporal aspects of ground water recharge, crop water requirements and the net water availability of the locations in the study area (Rechna Doab). The groundwater and solute transport models were utilised to undertake water use scenarios to 2030 to provide PID guidance on possible impacts of various surface water and groundwater use scenarios.

3.1 Background to the Study

The aims of proposed SRA activities are to handover project outcomes and also provide training for the Pakistani stakeholders for capacity building for the management of canal and groundwater resources resulting from ACIAR Project (LWR/2005/144) workshop held in Lahore, Pakistan during Dec 2014. The major project outcomes are: (i) remote sensing techniques used to estimate spatial and temporal distribution of rainfall and ET; (ii) surface water and groundwater interaction model for the Rechna Doab to address problems of sustainable groundwater and surface water use; (iii) development and application of solute transport models for assessing salinity impacts; and (iv) econometric model to explore options for more equitable, economically efficient distribution of water resources.

Remote sensing techniques for estimation of potential and actual evapotranspiration were utilised for improved spatial and temporal estimation of evapotranspiration. The use of improved spatial and temporal assessment of rainfall and evapotranspiration has greatly assisted in providing accurate inputs for the groundwater model. A Google API tool was developed for estimating crop water use for various locations within the study area.

A regional groundwater and solute transport model for Rechna Doab in Punjab Pakistan was developed for PID. The model is a significant enhancement over previous models carried out in Pakistan which were based on seasonal time steps covering Kharif and Rabi seasons. The Rechna Doab study model was developed at monthly time steps which offer PID an opportunity to better understand the temporal and spatial surface water and groundwater dynamics. The regional model was utilised to create sub-models at a finer spatial scale for detailed studies of canal and groundwater interaction. Examples of these are the LCC East and Rakh Branch sub-models for PID.

A socio-economic study was also undertaken for LCC East (Lower Chenab Canal Command). The results of the water user scenario analyses, resulting from econometric as well as hydrological modelling approaches, will assist PIDA and Farmer Organisations for implementing more equitable, economically efficient and improved water quality options in the study areas.

The SRA activities has focused on enhancing capacity of PID and PIDA to undertake groundwater modelling and socioeconomic modelling, utilising the models for additional focussed scenario runs, development of sub-regional models using the Rechna Doab model, training in GIS/remote sensing and crop water use estimation, and assistance for policy support materials. The training activities in Pakistan are also designed to enhance capacity and benefit students at UAAR and UAF.

3.2 Aim and Objectives

i. Develop training and report for the groundwater-surface water models and the econometrics model for PID, PIDA and UAAR.

ii. Develop and run drought and increased pumping scenarios with the Rechna Doab model to assess impact on groundwater resources.

iii. Develop a simplified TMR model for Rakh Branch and provide training to PID, PIDA, and UAF staff.

iv. Develop a framework for a decision support system based on evapotranspiration, crop water needs, land cover, land use change and ground water quality.

v. Develop a framework and guidelines to produce an annual groundwater status report for PID management

vi. Provide training on spatial ET0 calculation using developed models (hands on exercise)

vii. Provide training on using satellite imagery to estimate actual crop evapotranspiration.

viii. Provide monthly and ad hoc back up sessions via Skype and face to face after 6 months

ix. Assist in preparation of policy support materials and introduce a framework for groundwater status report.

3.3 Outputs and Activities

The outputs from this SRA cover groundwater modelling training; Rechna Doab model enhancement; additional drought and pumping scenario analysis; GIS and Remote sensing training; use of web based tools for crop water prediction; socioeconomic modelling training; and socioeconomic model scenarios:

i. Training in groundwater modelling for PID, UAAR and UAF for enhancing capacity to model and improve management of groundwater systems.

ii. Develop strategies for the application and use of the groundwater-surface water model and the econometrics model for Rechna Doab. The documentation will reference the modelling report and the Socio-economics reports produced for Rechna Doab. The report will also provide guidance on how the existing models can be improved by PID. This guidance is essential for PID as they envisage developing groundwater models for the remaining doabs. A significant enhancement of the work undertaken for Rechna Doab is the development of the models at a monthly time step which will also complement CSIRO work on surface water modelling that is being undertaken at the basin level. This enhancement also provides PID with an opportunity to closely examine their monitoring strategy and to better target the monitoring to provide a basis for impact assessment.

iii. Utilising the models for scenario analysis to understand how management practices can be improved would be a significant uptake of the work. Other than the scenarios already undertaken in the Rechna Doab model we propose four additional scenarios that will be useful to PID for sustainable management of surface and groundwater resources in Rechna Doab. The four scenarios need to simulate the impact of successive droughts and the impact of increased pumping of fresh groundwater resources. This involved consultation with PID on the pumping trends and the decrease in surface water availability during drought.

iv. Develop framework for a web based decision support system to guide PIDA and other stakeholders to enable them for selection of crops to be cultivated based on specific crop water needs, evapotranspiration.

v. Training in spatial modelling techniques for PIDA, UAF, UAAR to include: (a) Hands on training on Spatial ET0 calculator; and (b) focussed training on estimating actual ET using satellite image processing and meteorological data. This will be targeted to specific users such as spatial modellers with GIS capabilities.

vi. Training on appropriate utilisation and application of the groundwater model will be undertaken for PID staff and to increase capacity in groundwater management for PID, UAAR and other participants. The additional staff in-kind commitment of up to 5 positions to support groundwater modelling in the PID groundwater group will need to be part of the training to maximise benefits for PID. The focus here is on developing competencies and capabilities within PID for application of groundwater modelling tools, and to apply these tools for sustainable management of groundwater resources. It targets the key agency which has responsibility for management of water resources by building linkages between them and Australia through training and capacity building. The inclusion of Universities (UAAR, UAF etc) will improve in-country capability and awareness for the need for groundwater modelling and governance.

    The training is planned over two sessions 4 months apart. The first session will cover 8 days and this will be followed by a second training session approximately 4-6 months later and will cover 7 days. The training program is designed in two parts to provide maximum value and benefit to PID and PIDA and universities. It will also provide an opportunity to practice what they have learnt in the first session and to meet face to face again to strengthen the learning process.

    The desired outcome will be targeted strengthening of the key institution responsible for water resources management and building in-country capacity to initiate pro-active management of groundwater resources subject to prevailing socio-economic constraints.

vii. Provide information on how the different water use scenarios were tested using the socio-economic data collected from the three distributaries and inform on how the econometric models were tested to simulate the water reallocation impact on salinity, crop productivity and farmers income (in relation to the major crop wheat). Informing the model framework developed and how that could be extended to other crops and areas having more or less similar socio-economic conditions.

Providing an assessment of economic value for implementing existing water policies and identifying alternative policy options in water distribution that can result in better socio-economic outcomes.

Demonstrating, evaluating and exploring adoption pathways regarding on-farm canal and groundwater management strategies and water saving technologies in relation to water scarcity conditions arising from increased pumping/ground water use and droughts.

viii. Skype meetings with PID and UAAR on a monthly basis to provide assistance with groundwater and socio-economic modelling. The aim here is to have on-going communication with PIDA and UAAR.

ix. Consult with PID on preparation of policy and guidelines for managing groundwater resources in Rechna Doab, and seek advice and guidance from PID to assess feasibility of implementation.

x. Develop a framework and guidelines to produce an annual groundwater status report for PID management. This would allow PID to assess the monitoring and groundwater conditions.

3.4 Project Team

The project team consisted on Dr Jay Punthakey (groundwater modelling lead); Dr Mobushir Riaz Khan (GIS/Remote Sensing lead), Dr Irfan Baig (socioeconomic survey design) and Dr Richard Culas (socioeconomic modelling lead), Dr Muhammad Riaz (surface water monitoring), Dr Muhammad Javed (groundwater monitoring), and Dr Ghulam Zakir Hassan (research)

3.5 Study Approach and Capacity Development

Spatial Modelling and Groundwater Modelling Capacity Development

The team developed various scenarios for the groundwater-surface water models and the econometrics model for PID, PIDA and UAAR, along with guidelines for improving the current model and for extending the calibration of the model. The current model covers 66 months from May 2008 to October 2013. The data available from PID for calibration ends in 2012, so there is scope for checking the 2013 data within the framework of the existing model. Additionally PIDA's future efforts should focus on extending the model calibration every 5 years permitting resources are available. This would also provide guidance on model strengths and weaknesses and help improve the model.

The main purpose of a groundwater model is not to have only a calibrated model. Rather the application and use of the groundwater model provides a useful framework for assessing groundwater conditions, and will allow PID to improve and enhance their current monitoring and management of the doab. The training component will focus on this aspect of the modelling process by utilising the Rechna Doab model to develop and run four scenarios: (i) long duration drought scenario with varying drought periods; and (ii) increased pumping scenarios to assess impact on groundwater resources (quantity and quality impacts).

The documentation for spatial ET0 calculation will be prepared which will also include instructions and documentation for using the software developed by UAAR. Hands on training will be provided in the labs for using the software in the training sessions. Location specific surface and ground water data, crops grown and the modelling input will be linked using geo-spatial overlay analyses.

Provide two training sessions in Pakistan. This will comprise initial training for PID, PIDA, and Universities – UAF, UAAR. The first session will focus on the development of the Rechna Doab model as a case study from examining and understanding the monitoring data to model development and calibration stage.

This will be followed approximately 4-6 months later by a second training session for PIDA, Centre of Excellence Water Engineering, and Universities – UAF, UAAR. This second training component will focus on understanding water balances, and model reliability, and developing an understanding of sustainable yields. This second session will cover the scenario modelling phase so that the training can reinforce the use of the model for developing management strategies.

Socioeconomics

Provide information on how the different water use scenarios were tested using the socio-economic data collected from the three distributaries and inform on how the econometric models were tested to simulate the water reallocation impact on salinity, crop productivity and farmers income (in relation to the major crop wheat). Informing the model framework developed and how that could be extended to other crops and areas having more or less similar socio-economic conditions.

Providing an assessment of economic value for implementing existing water policies, and identify alternative policy options for water redistribution that can result in better socio-economic outcomes.

Demonstrating, evaluating and exploring adoption pathways regarding on-farm canal and groundwater management strategies and water saving technologies in relation to water scarcity conditions arising from increased pumping/groundwater use and droughts.

Training sessions will be held focussing on the econometric model and using the model to test different water use scenarios in the LCC. Examples of how the modelling results can provide improved outcomes for policy support will be demonstrated.

Communication

The team will be available to provide monthly and ad hoc back up sessions via Skype and will meet with the team twice in Pakistan before and after each training session.

Policy Support

The challenge will be to develop a framework for discussing how the model can be used to support policy and to make an impact. We aim to use the results from scenario modelling for explaining various options available. This will provide a platform to discuss policy options and to assist in preparation of policy support materials given existing socio-economic constraints. Moreover, to assist in the policy debate we aim to use examples from Australia to develop a framework and guidelines to produce a groundwater status report on an annual basis. This would allow PID to assess monitoring and groundwater conditions and will provide a platform to discuss the need for developing policy options for preserving fresh groundwater sources.

4 Training in groundwater modelling, remote sensing/GIS and econometric modelling

Understanding of groundwater management issues can be enhanced when the socioeconomics of famers, and their perspectives and benefits are also taken into consideration. In Pakistan farmers have ownership of tube wells, though by definition groundwater is a common property resource, and Government can facilitate groundwater management towards its sustainable use. Increased groundwater extraction by hundreds of thousands of tubewells results in declining groundwater levels and increases the risk of salinity intrusion into fresh groundwater areas. PID has prioritised improved management of groundwater resources which requires use of groundwater flow and solute transport models. The aim of the present capacity enhancement is to increase capabilities in groundwater and socioeconomic modelling for mid-career professionals within PID.

The training program covered groundwater modelling and remote sensing and GIS training. A parallel training program was also conducted in household survey design and socioeconomic modelling. As part of the training program a field visit was organised at Pubberwala Distributary near Faisalabad including meeting with farmer organisation and field demonstrations on flow measurements undertaken by PID staff.

4.1 Training in groundwater flow and transport model for Rechna Doab

The aim of the groundwater modelling training was to enhance capacity in Punjab Irrigation Department (PID), UAAR and UAF to capitalise on the previous ACIAR project which developed the Rechna Doab regional groundwater model and the Lower Chenab Canal (LCC) subregional model. Training programs were held in Lahore in August 2015, and at UAF in Faisalabad and Lahore in April 2016. The groundwater and remote sensing training was held together to demonstrate how spatial data sets can be used to develop a Modflow model.

The education background of the PID staff participating in groundwater modelling, remote sensing and GIS training was civil engineering with good knowledge of surface water and varying skills levels and understanding of groundwater modelling. Some had been exposed to simple groundwater models during their studies.

The initial training program covered an overview of MODFLOW and the packages used in developing a MODFLOW model. Next, the training covered a comprehensive overview of the development of the Rechna Doab model. The development covered each of the packages used in developing the Rechna Doab model and the data needs as well as how the data were analysed for model development. Additionally training was provided in the development of a solute transport model for Rechna Doab using MT3D for estimating salinity trends and spatial distribution of salinity.

This was followed by demonstrating how the LCC East model was developed using Telescopic Mesh Refinement (TMR) package in MODFLOW. TMR allows a sub-model to be extracted from the regional model at a finer scale, thus allowing for focussed modelling in an area of interest. The feedback from this training course by senior officers of PID was that the participants would benefit from additional training on the Modflow model and setting up a simpler model to help mid-career professional’s better understanding of how to develop and calibrate a model. This would assist participants to better grasp the complexities of the Rechna Doab model.

The feedback from the first training session was used to design the second training program. The training in April 2016 included an introduction to Modflow, followed by a lecture on designing a conceptual model with suitable examples of conceptual model. This was followed by designing a simple Modflow models. The series of lectures on designing a simple groundwater model started with the problem statement, background data, formulating a conceptual model, and designing the grid and entering aquifer parameters. This model was progressively built on with more features such as wells, rivers, evapotranspiration, recharge, adding a second layer and boundary conditions to give the trainees hand-on experience in building models. The training also covered using groundwater models to assess impacts and support policy using scenario analysis. An additional sub-model for the Rakh Branch was demonstrated using the Rechna Doab regional groundwater model to create a TMR sub-model of the Rakh Branch in LCC west.

Discussion during the training also focussed on the need for a strategic monitoring program with identification and instrumentation of key bores with loggers that can continuously record water level and salinity data. This would require dedicated monitoring bores, however, there are over 700 monitoring bores in Rechna doab so having dedicated monitoring bores is possible. What is lacking is most of these bores are not deep enough to monitor the deeper aquifer which is a significant gap in data collection.

4.2 Training in remote sensing and GIS for Rechna Doab

The SRA training sessions were developed in consultation with PID. The main focus was on:

- Interpolation and validation of Water Quality data
- Remote Sensing & GIS based Analysis for Mapping Crop Areas and their Performance
- Developing web based system for crop water requirements

The training covered the following areas with examples and hands-on training for participants. Future training would be more effective if more emphasis is paid to the use of remote sensing and image analysis as participants were lacking this background. The following was covered in the training program:

1. Overview of Rechna Doab ET and prediction of ET
2. Introduction to Remote Sensing image analysis and linking with crop calendar and crop statistics for mapping crop areas (to estimate crop coefficients)
3. Using Spatial ET0 calculator and remote sensing results to estimate ETA
4. Using Google API, Web-GIS and spatial ET0 calculator for decision support system to calculate crop water requirements
5. Remote Sensing applications for crop monitoring and crop water management included:
    i. Developing Decision support system based on evapotranspiration, crop water needs, land cover land use change and ground water quality
    ii. Spatial ET0 calculation using developed models
    iii. Remote Sensing & GIS based Analysis for Mapping Crop Areas and their Performance
    iv. Estimation and Mapping of ETA

4.3 Training in household survey design and socioeconomic modelling for Rechna Doab

The professional background of the PIDA extension staff was mostly sociology/social science. Though, the students from UAF had good agricultural economics background. Hence the trainees had a mix of views and understanding of the groundwater problem in Pakistan. The training sessions covered the following areas with examples, their applications and feedback.

1. General rules for writing survey questions for socioeconomic analysis in the context of groundwater management in Pakistan. This included examples of closed ended question, Likert scale and open ended questions. The trainees were asked to write sample questionnaires and given feedback.

2. Survey methods, optimal sample selection and selecting study areas with reference to groundwater management issues. The examples from LWR/2005/144 were discussed.

3. How to manage a survey, ethics in survey, sample size (using sample size calculator), data collection, data coding/decoding, and designing variables (data base) for analysis.

4. Data management using Excel spreadsheets and SPSS statistical programme.

5. Descriptive statistics of data, conducting regression analysis, dealing with qualitative data, and aspects of cross-sectional, time series and panel data and how to use them. The session also covered the need for pre-testing of survey data for all strata.

Survey Designs

Participants of the training were familiarized with the basic concepts of the survey designs in the second half of the first day training. The concept was important as survey instrumentation is very important in socioeconomic research. For evaluating or assessment of the impacts of irrigation projects, new technology, improved water resource management or water distribution scenarios, it is essential to have complete, correct, and up to date information about the affected persons, families and the total population.

To obtain this information, different types of surveys are needed to be conducted which require varying skills among the persons who will carry out these surveys. To provide the concerned staff of PIDA to conduct socioeconomic surveys in an effective manner, a session was arranged to familiarize these officials with definite and specific guidelines that must be prescribed for the conduct of various socio-economic surveys.

A presentation was shared with the participants covering the basic concepts including survey design, sampling frame work and management and logistics arrangements for conducting a field survey. They were made familiar with the objectives of the survey in specific context of the recently completed combine project of PID/PIDA, UAF, UAAR and CSU funded by ACIAR. Structure of the different sections of the questionnaire was also discussed. To make the session more interactive, detailed project questionnaire was shared with the participants and they were asked to generate their opinion over the nature of the different key questions. Questionnaire design in specific context of sampling framework was discussed and the participants were appraised of the process of team selection for the data collection and training of the enumerators. The investigators engaged for data collection must be properly trained. They must know how to probe, and to clarify the nature of the question so to have similar response from the respondents. The enumerators should have to build good rapport among the respondents.

Participants also discussed how to assign appropriate codes to record the responses of the survey questions and they were also made familiar with the coding scheme by giving different examples from the project questionnaire. Different types of questions that could be asked from the respondents while conducting the field surveys from the farmers were also deliberated. Use of close ended, Likert scale and open ended questions was shared with the socio-economic trainees of the PID and PIDA. Participants discussed the different types of the styles of asking the questions that could bring biasness in the recorded responses. It was emphasized that the enumerator should also be trained so to avoid any conflict with the respondents during the interviews. Investigators should not take sides or be biased in any way by the agitations.

Importance of the background information about the area, respondents, social taboos and production practices could prove very handy for conducting a successful survey. Apart from pilot surveys different other methods like Focus Group Discussion (FGD), review of the literature and secondary data sources could be very useful in proving these a priori information.

After discussing the importance of the sample and data collection tools, key concepts of survey management including task identification, coordination, monitoring, quality assurance, and compiling and reporting were also discussed. Data editing and coding should preferably be done on daily basis during the collection stage so if any discrepancy is found it could be rectified immediately even by going back to the respondents and it should be avoided later on. Supervisor must ensure these tasks and corrections if any should be undertaken on a daily basis. In this regard, holding a daily team meeting could achieve desired results.

Participants of the training program were also made aware of the importance of an effective monitoring program. It should be developed in a way that it could be capable of identifying deviations from the proposed action and any important unanticipated impacts. A monitoring plan should be developed to track project and program development and compare real impacts with projected ones. Another modern concept in data collection process is to introduce different information technology gadgets to improve the quality standards of the survey and collected data.

In the last step of an effective survey design, importance of the community ownership for a successful survey and importance of the community was discussed with the trainees. They were introduced to get the ownership of the community by:

- Making them aware of the study objectives
- Methods of data collection (consistent with norms)
- Awareness regarding data usage and output
- Respect gender, age and religious issues

Participants were introduced with the binary response modelling of the survey data. In binary response modelling, the respondents were informed, researchers try to analyse the binary response dependent variable (e.g. low or high, yes or no) in the presence of quantitative and dummy variables. In this regard, PROBIT and LOGIT modelling examples from the survey data were shared with the trainees and provided training on setting up the model. They were also made familiar with the statistical software that has been used for the analysis of the data in different socio-economic surveys that is SPSS.

4.4 Assessment of training and capacity building by participants and pathways for delivering effective training

At the end of the training the participants were asked to complete an evaluation and provide feedback on the outcome of the workshop. The responses are summarised as from 14 completed evaluations (evaluation form attached as appendix). Overall the participants were positive on the objective of the training in enhancing their knowledge, the training sessions that were delivered, demonstration of the issues, modelling and data management, and the field trip (see, Table 1).

Table 1: Number of responses from the trainees on evaluation of training outcomes

Rate your overall satisfaction with the workshop and the training provided:	Unsatisfactory	Satisfactory	Good	Exceeds expectations	Excellent
Were the training objectives met?		1	7	3	3
Did the training enhance your knowledge of the issues?			5	5	3
Would you recommend this training to others?			5	4	6
Will you be able to apply the information to your job?		3	4	2	5
Rate your satisfaction with the presentations (deliveries and demonstrations/ examples applied).			5	6	3
How do you consider the knowledge/skills that you gain from the field trip as useful?			4	6	3
Are you satisfied with the catering and other facilities provided during the workshop?		1	4	4	5

Comments from the trainees on the training outcome/impact and consideration for future training include the following:

1. More focal group discussion at different distributaries and with FOs.
2. Dissemination of results in local language to famers and other stakeholders.
3. Learned the socioeconomic and econometric models for redistribution of water.
4. Development and calibration of hydrological model with limited data and explanation of such model in relation to other models developed for other countries.
5. Farm scale model with more precise information should be developed with guidance from farmers.
6. Crop mapping with ET relation and CWR on web based model emphasized to conduct field survey and to avoid traditional method.
7. Practical examples of MODFLOW application.
8. Socioeconomic modelling can be linked with discussion meeting with farmers

9. Holding workshop in field and interview of farmers about their understanding of the problems and expectation.

10. Providing famers latest technologies like laser levelling and best crop management practices.

11. Remote sensing technique and interoperability between groundwater management software and GIS has been very fruitful.

12. Socioeconomic models with application of water use scenarios and farmers can be included in the training so that they can get better knowledge of the issues.

13. Model for yield and income estimates are more valuable.

14. Disseminate water saving techniques in the field area and should build coordination between aligned departments (agricultural extension with on farm water management and livestock department).

15. For farmers changes in cropping management can be due to availability of water with less groundwater usage.

16. Improve farmers' awareness for reduced number of tube wells.

17. Install 5 CS' tube at head of the water courses (outlets).

18. Government may provide subsidized electricity bill.

19. Improve the groundwater quality.

20. Groundwater modelling, management of groundwater issues of farmers and providing groundwater management technology like laser level, drip irrigation, water saving crops and water course lining.

Comments from the participants on the outcome and impact of the workshop and suggestions for the groundwater management issues include the following:

1. Remote sensing and hydrology integration is very useful. Famers' interaction and actual information required.

2. Modelling training was well taught. Data collection looks inappropriate. In field there are variations consider proper sampling. Sampling should represent the actual variations in the fields.

3. Econometric modelling was fine.

4. Participants should be involved in the implementation of the projects results. The results should be disseminated with stakeholders with agricultural department.

5. Farm sizes are reduced; tube wells number should be restricted and only at water course basis (not with individual rights).

6. Capacity building of farmers.

7. Farmers awareness of the issues.

8. Research results should be contributed to farmers.

9. Learned on how to interpret the data/results and how the data were selected for analysing the models.

10. Groundwater modelling is good should increase the farmers awareness; go to farm level and help farmers; on groundwater declining should advise farmers.

11. Learned on new remote sensing techniques but agricultural department's role should be useful for farmers.

12. Interaction with farmer should be priority.

13. New things learned in relation to techniques/methods/models for groundwater models and socioeconomics.

14. Capacity building of PIDA staff is important. Recently workshops have been conducted in Khikhi and Kamalia distributories.

15. Completion of ACIAR project and SRA training is good.

16. MODFLOW and modelling are very useful.

17. Links between socioeconomics and hydrology was missing in the past project and it should be considered in new project.

4.5 Policy support and opportunities for enhanced engagement

Econometric modelling was considered to redistribute water between the distributaries, in relation to changed proportions of ground- and surface water, to minimize the effects of salinity on crop yield. However salinity development overtime can be unavoidable in the irrigated areas unless the pumping of groundwater is reduced. Therefore groundwater management through water saving technologies, improving soil conditions and crop agronomy practices are equally important. Participants at the training gave the above viewpoints in relation to their capacity.

The issues for groundwater management can be overuse of groundwater as well as the ways in which any surplus water is shared. Policies dealing with these issues should consider efficient use of water through creating formal/informal water markets (trading), and subsidized water pricing or allocation of water for poor farmers on equity grounds. The participants were taught the basics of economics of water use in relation to private- and social costs and related policies that can be effective.

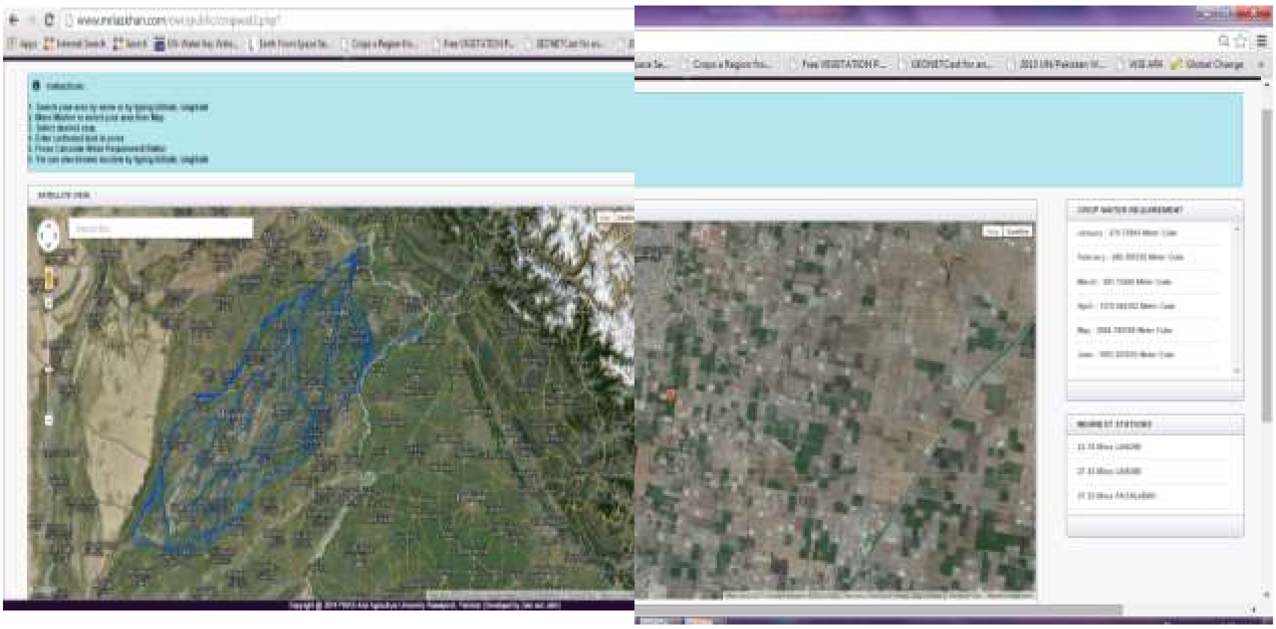
The question whether the Rechna Doab system can be maintained at sustainable levels requires the use of various scenarios. Groundwater modelling scenarios were undertaken to demonstrate the impact on sustainable yields during drought and increased pumping scenarios. One additional year of data was obtained from PID in order to extend the calibration of the groundwater model to 2014. Similarly remote sensing was used to extend the temporal distribution of rainfall and actual evapotranspiration for 2014 which provided inputs to the groundwater model. These scenarios showed that despite increasing pumping during drought situations the system is resilient and can recover when pumping is reduced back to sustainable levels. The scenarios also showed that increased pumping over 30% will result in groundwater depletion with storage becoming negative indicative of outflows from the system being greater than inflows. This should be avoided and policies to manage groundwater resources within a sustainable framework encouraged.

5 Remote sensing and GIS and DSS tools for Rechna Doab

5.1 Developing Decision support system based on evapotranspiration and Crop water needs

- A web based decision Support tool was developed at PMAS-AAUR to assist researchers, policy makers and farmers to calculate the crop water requirements at field level
- The tool uses google API. Individual farms can be easily located by using Lat long or through navigation pan.
- After selection of crop to be grown, the tool provides monthly water requirements for the specific crop both tabular and graphical.
- The DSS will assist the policy makers, PIDA officials and Farmer's organizations to make optimal decisions viz-a-viz surface water (and ground water) availability)

Figure 5.1 Google API showing regional area, farm and crop water requirements



Further Development:

1. Helpline where farmers can call from any phone and select options in their own preferred languages needs to be undertaken in the future
2. Further development of this App may be undertaken with guidance from PID and Fo's and farmers. It would be particularly beneficial if the App can be enhanced with surface water allowances for each farm, and access to groundwater and quality for each farm, this would greatly assist farmers and FO's with water planning at the farm level.

5.2 PMAS – AAUR Crop Water Estimation System - Algorithm

- The system will calculate the final ETo by averaging the ETo of all three nearest stations.
- Final ETo per month will be multiplied with a crop coefficient.
- To get actual crop water requirement in Meter Cube / Month.
- Final Crop Water Req = (CWR / 1000) * (crop area * 4047)

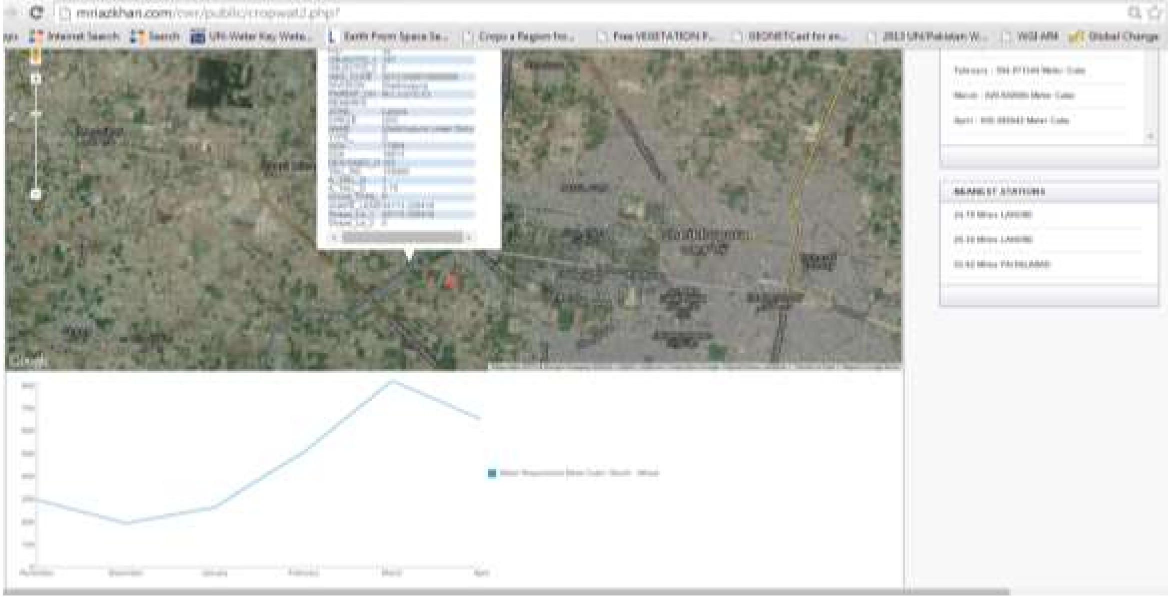
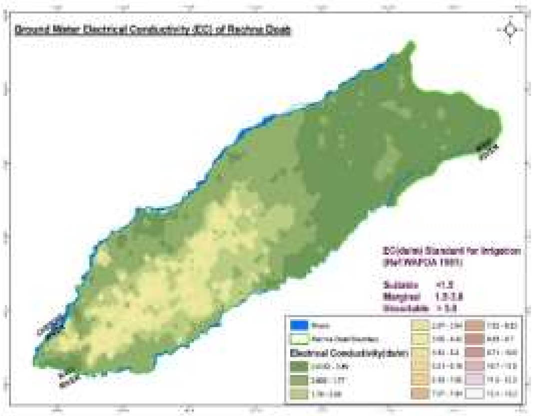


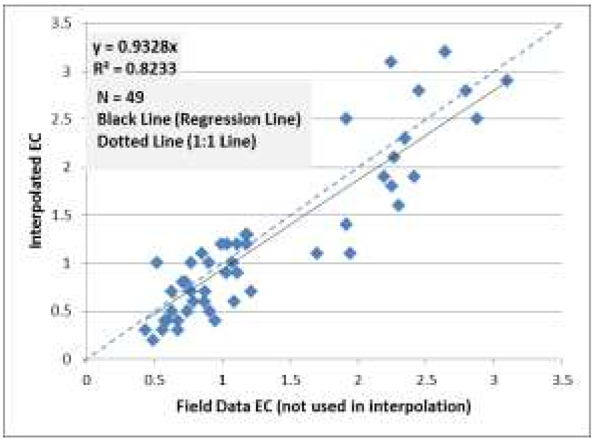
Figure 5.2 Google API showing location details and crop water requirements

5.3 Ground Water Quality

The participants were acquainted with how to spatially interpolate the sample data and ground truth of the interpolation scheme. They were already trained on obtaining ground survey data of piezometer and during the two SRA trainings, various interpolation methods were used and compared for accuracy within a GIS environment.

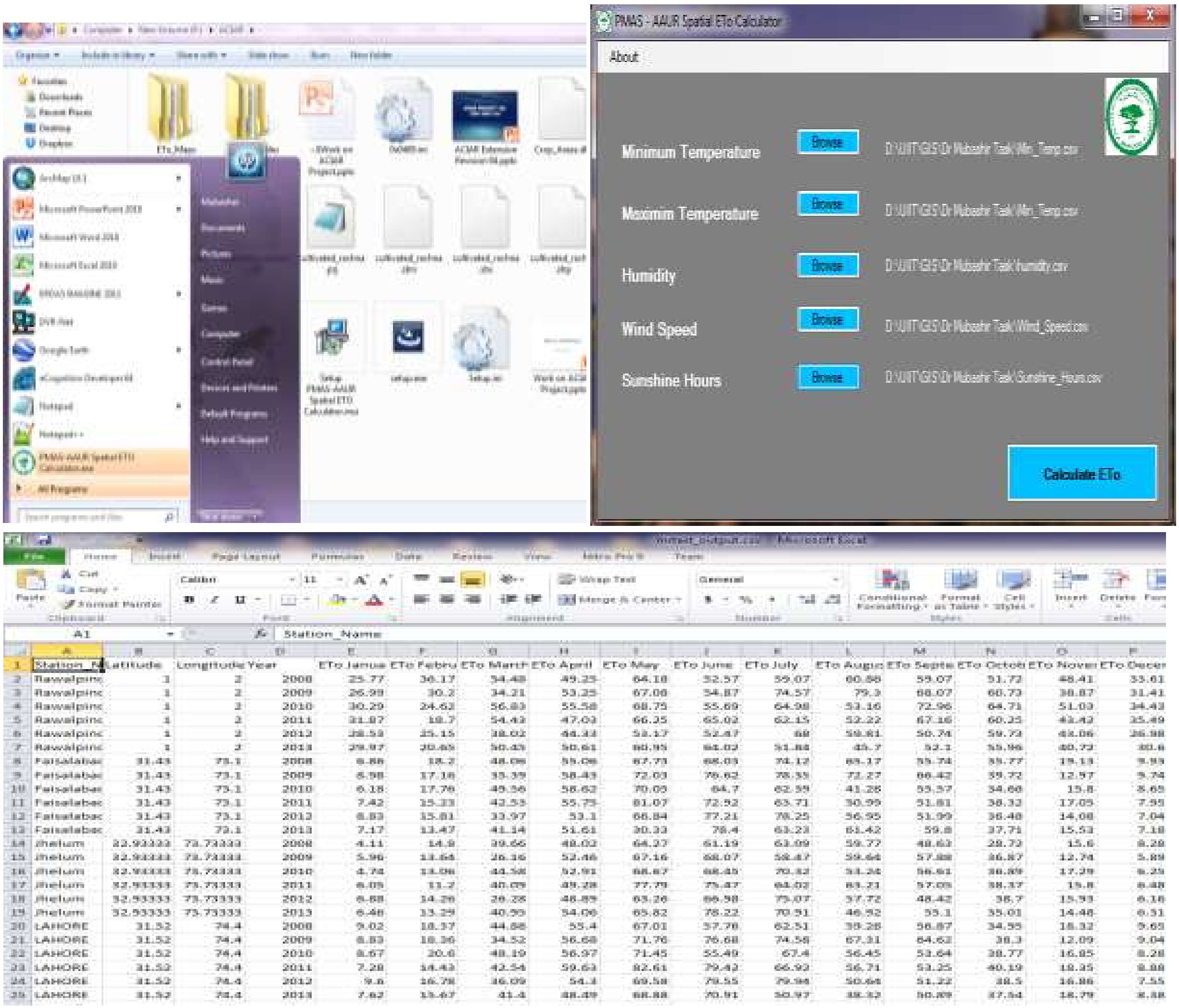
During interpolation, ninety percent of the values were used whereas the remaining ten percent were used for validation. The predicted values for the corresponding validation data set were obtained using an overlay function in ArcGIS and scatter plots were used to check the accuracy of the interpolation results.





5.4 Spatial ET0 calculation using developed models

Spatial ET0 calculator was prepared by UAAR team, which also includes a manual for using the software developed. Hands on training was provided in the labs for using the software in different training sessions. Location specific surface and ground water data, crops grown and the modelling input are linked using geo-spatial overlay analysis.



5.5 Remote Sensing & GIS based Analysis for Mapping Crop Areas and their Performance

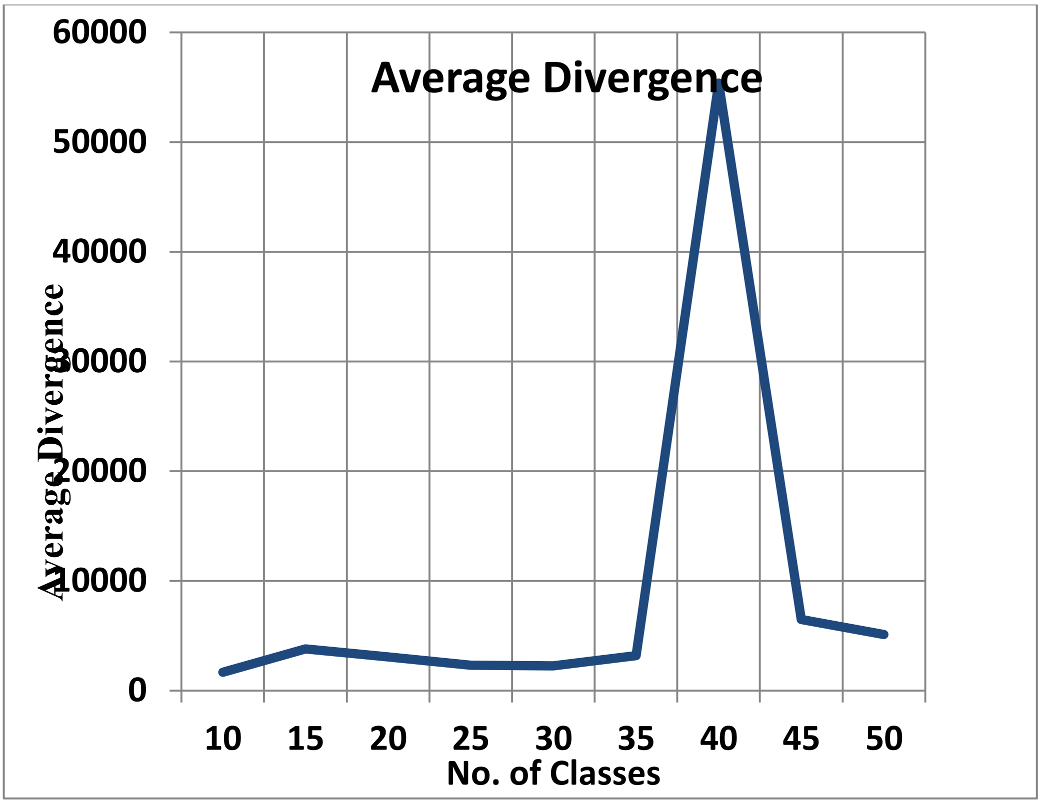
The participants from Punjab Irrigation Department and Universities were given training on the followings:

a. Downloading and preprocessing the remote sensing images:

MODIS NDVI (MOD13Q1) data from 2008 till 2013 was available after every 16 days of temporal resolution with 250 meter resolution was acquired from the Glovis website to prepare spatially explicit crop maps. After downloading satellite images stacking and mosaicking process were used.

b. Cluster analysis:

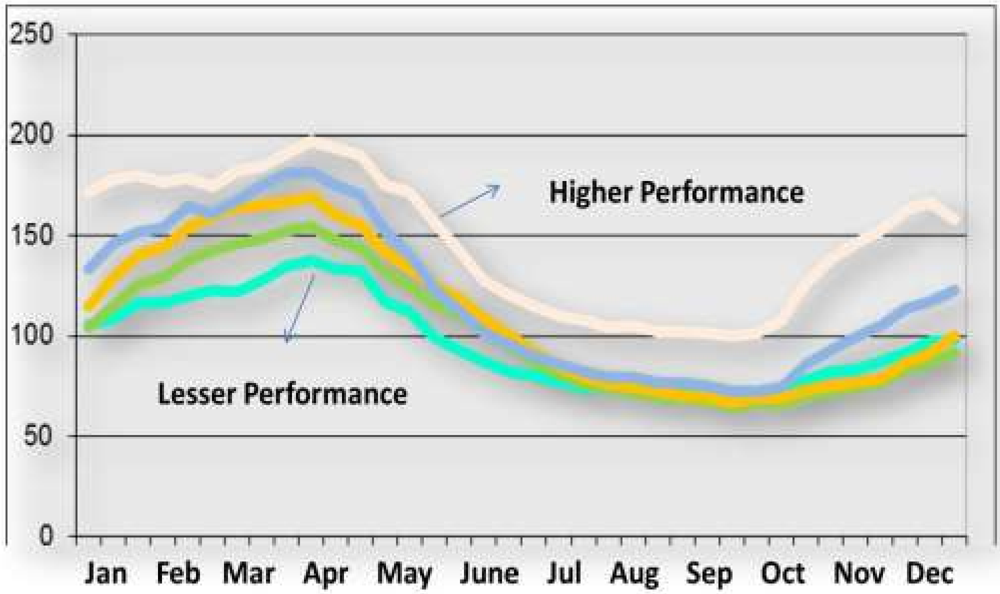
Remote sensing was used to map various crops in space and time. Unsupervised classification was implemented using the ISO DATA clustering method to identify crop patterns in Rechna Doab. The minimum user inputs for ISODATA clustering were number of iterations which were set to 50 and the convergence threshold which was set to 0.95 for every classification run (Khan et al., 2010). A total number of 20 classification runs were executed starting from 5 classes up to 100 classes with an increment of 5 classes in each run. The output of each classification run was a classified image and its corresponding signature. Optimal classification was selected by using divergence statistics (Sawin, 1973).



The above figure shows that in this case 40 classes are optimal which means that there are 40 different types of land covers or mix of land covers in the study area. Participants were given practical training on how to make above figure using RS software.

c. Linking crop calendar with output of cluster analysis/unsupervised classifications to map various crops:

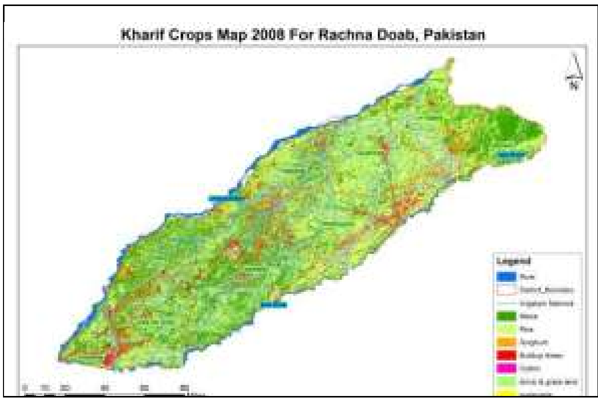
After selection of optimal classification the corresponding signature was used and matched to the practiced crop calendar of the study area and each class was related to the crop calendar. Individual crop areas were then identified both in Rabi and Kharif seasons by linking the results of image processing and the crop calendar information. Next the crop Kc values were obtained for each month by consulting FAO table (FAO 56).

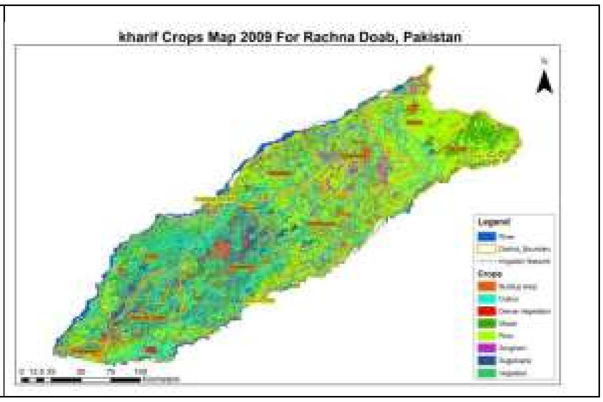


The above figure demonstrates two aspects:

First, it is a winter crop and in this case it was wheat crop as the participants of the training also undertook ground truthing.

Second, the performance of wheat in the study area varies spatially as some profiles are greener as compared to other profiles.



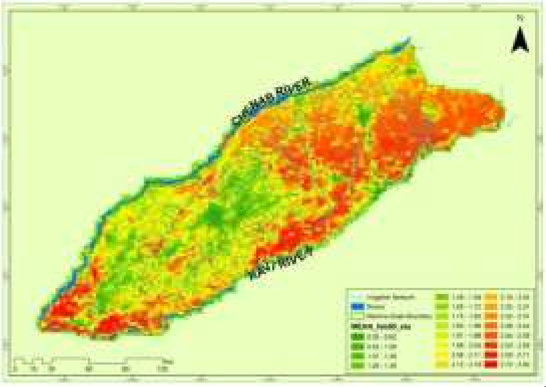


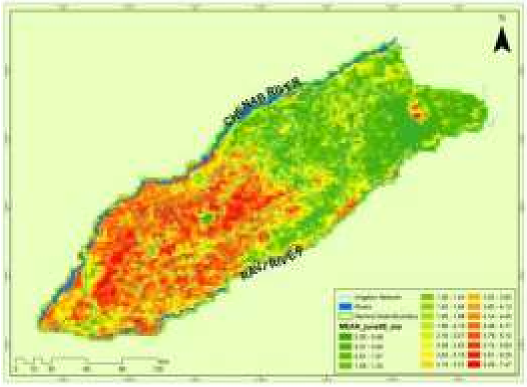
d. GIS operations to compute ETA using crop maps and potential evapotranspiration:

ET0 and Kc were used to calculate the ETa by using following equation:

$ETa = kc\ ET0$

The outputs of ET0 (Figure 3) and Crop area Maps (Figures 6 & 7) where used to calculate the actual evapotranspiration using the Equation 3. The results were actual evapotranspiration maps from 2008 till 2013.


CHENAB RIVER
RAVI RIVER


CHENAB RIVER
RAVI RIVER

6 Pumping and drought scenario analysis using the groundwater flow and transport model for Rechna Doab

This section focuses on increased pumping scenarios and drought scenarios. Long term simulation of the Rechna Doab groundwater model under the no-plan scenario indicates a sustainable yield for Rechna Doab to be $10{,}100\times10^6 m^3$/yr. To allow for adaptive management of the Rechna Doab we suggest the sustainable yield should be allowed to vary by $\pm$ $1{,}000\times10^6 m^3$/yr. The trend in Rechna Doab has been an increasing trend in groundwater pumping with over 200,000 tubewells currently using groundwater. This brings into question the resilience of the system, given that PID at present does not have the institutional structure nor the regulatory framework in place to enforce the recommended sustainable yield. It is therefore prudent to understand the limitations of the current system as pumping rates increase. To this effect two pumping scenarios are presented with pumping increasing by 20 percent and 30 percent. Additionally two drought scenarios are also tested, one with two successive medium term droughts of 3 years, and one long duration drought lasting 10 years similar to the millennium drought experienced in Australia.

6.1 Increased Pumping by 20 percent for Rechna Doab

The enhanced pumping scenarios used climate data from 2008 to 2014 which was reused to simulate conditions from 2014 till 2030. All the model parameters remained the same with the exception of pumping and evapotranspiration. This scenario assumes that agricultural pumping in Rechna Doab increases by 20%, from an average of $10{,}100\times10^6 m^3$/yr to $12{,}200\times10^6 m^3$/yr. For these scenarios evapotranspiration is assumed to remain unchanged, however, a substantial increase in pumping would be a result of agricultural intensification, thus the net storage may decrease further with increased consumptive use.

The water balance for scenario 2 with 20% increase in groundwater from 2014 to 2030 is presented in Table 6.1. All values are in million m^3 (MCM)/year (GL/yr) and are averaged over the 16.5 years of simulation.

Table 6.1 Water balance for all model layers for 20% increase in groundwater use scenario from 2014-2030

Stresses	Inflows MCM/yr	Outflows MCM/yr	Net MCM/yr
Recharge	10,314	0	10,314
River & canals	4,248	70	4,179
Wells	0	12,206	-12,206
Evapotranspiration	0	712	-712
Boundary flows	237	1,482	-1,245
Storage	**14,799**	**14,469**	**330**

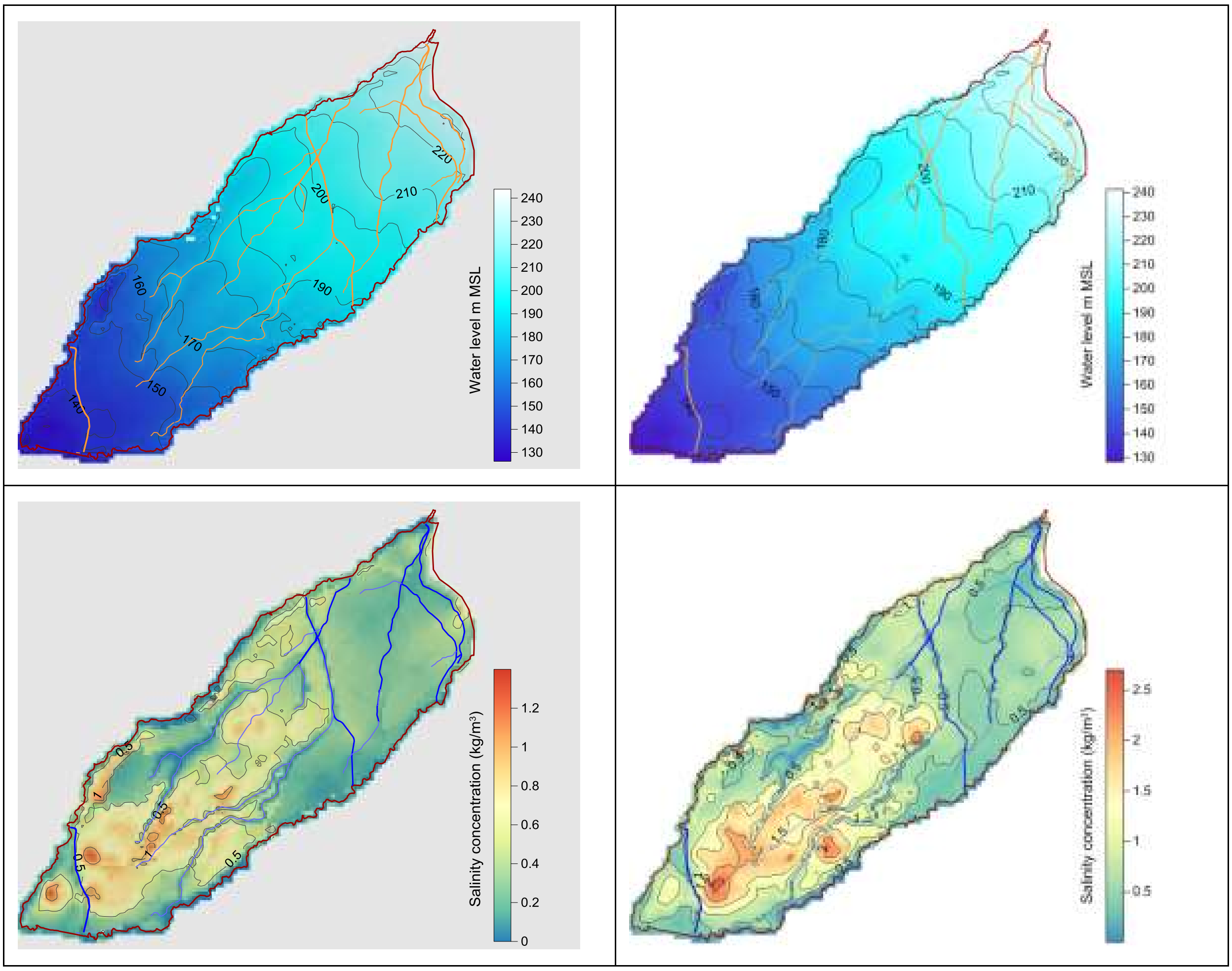
This scenario indicates that if groundwater usage was increased by 20 percent to 12,206 MCM/yr, then the net storage term decreased from 2,781 MCM/yr for the no-plan scenario to 330 MCM/yr which is substantially lower than for the no plan scenario. It is important to understand that whereas the increase in pumping results in a small net surplus this can very easily become negative if surface water deliveries were to decrease or if there is a prolonged dry period resulting in decreased rainfall, and decreased surface water supplies. We recommend that PID undertake further investigations to improve specified boundary conditions along the eastern boundary of Rechna Doab. For improved accuracy of boundary flows we recommend using transient boundary conditions as additional data becomes available.

Moreover, given the data uncertainties and unknowns such as groundwater usage from 200,000 tubewells presently operating in Rechna Doab, it would be prudent to manage the system such that there is a surplus net storage. We further recommend that water balances based on selected zones be conducted by PID where declining groundwater levels are of concern. This will help in understanding where groundwater depletion zones warrant further management. It is equally important for PID to ascertain the status of groundwater resources along the river boundaries, particularly to the east in the Bari Doab where significant groundwater pumping is taking place.

Water level and salinity contours for the aquifer at the end of simulation (2030) are shown in Figure 6.1 for layers 1 and 2. Water level contours are similar at the end of April 2030, however, salinity concentrations differ between layers 1 and 2. Salinity concentrations in layer 2 are higher in the lower mid sections of the doab in the eastern part of LCC west and along the western boundary of LCC east. The salinity stratification in the Indus is such that salinity increases with depth, thus for layers 3 and 4 salinity increases further. The lack of monitoring data from deeper layers of the basin is a significant shortcoming and is likely to influence salinity predictions. However, the immediate concern is the first two layers representing the top 60 m where most of the pumping in Rechna Doab is taking place. Salinity hotspots are simulated in a number of locations. However, the most prominent is in the Bhagat and Tarkhani districts where salinity increases with depth. Managing pumping so that salinity does not increase either by lateral intrusion and/or by upconing is fundamental to the sustainability of groundwater pumping particularly in the lower mid sections of the doab.

The water level response of selected bore hydrographs for layers 1 and 2 is shown in Figure 6.2 and Figure 6.3. In areas where pumping intensity has increased by 20 percent water levels are declining as shown in LCW4, LCW30, and JG38 for layer 1 and 42UN KWL21 and KWL22 for layer 2. Some bores show stable water levels despite the increased pumping such as LCW253 in layer1. However, there are also areas showing rising water level trends as shown in LCE346 in layer 2. There are two factors that are likely to be affecting rising trends; distance from canals and lower intensity of pumping in the area.

Figure 6.1: Increased pumping (20%) Scenario : Simulated heads and salinity concentration for aquifer layer 1 (left) and layer 2 (right)



Salinity concentrations for selected tubewells for layer 1 are shown in Figure 6.4, and for layer 2 in Figure 6.5. The trends for layer 1, are either stable or decreasing slightly suggesting that for the tubewells selected the salinity concentrations are not increasing. This is a somewhat surprising result and a preliminary conclusion would suggest that the Rechna Doab is a very resilient system however, there are several other considerations, the period in which the model was calibrated had above average rainfall and flooding (such as the 2010 floods). Repeating this same sequence of rainfall and surface water availability patterns may have resulted in a more optimistic result. Moreover, increased pumping near canals resulted in increased head gradients, which tends to enhance freshwater flow out of the canals to the groundwater system. The selection of tubewells for monitoring salinities also tends to be biased towards the freshwater zones. These are areas within canal command areas where there is significant seepage from canals and distributaries as well as significant irrigation recharge. However, the most significant influence is the underlying salinity in the deeper layers. Where salinities in the deepest layer are high the vertical transport of salts is enhanced. A combination of increased pumping rates and high underlying salinity increases the risk of salinity concentrations increasing as shown by tubewells 182 and 627 in Figure 6.5.

Figure 6.2: Increased pumping (20%) Scenario: Simulated heads (mMSL) for piezometers in Layer 1

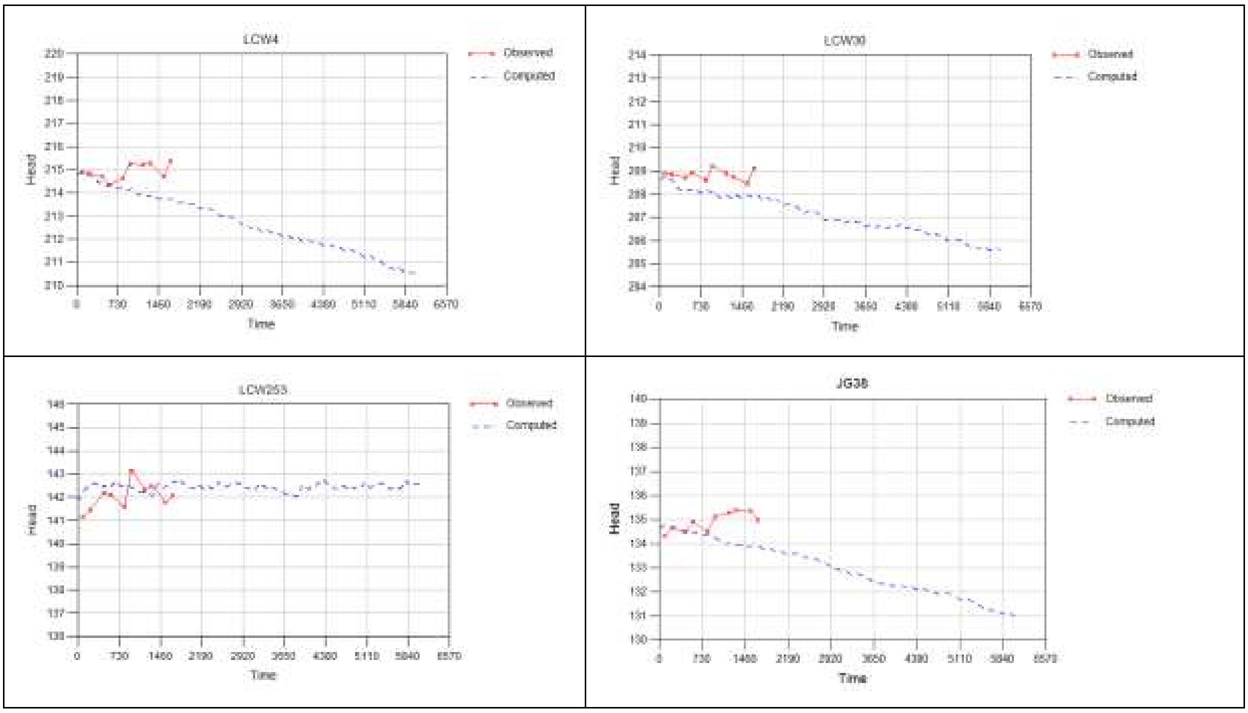
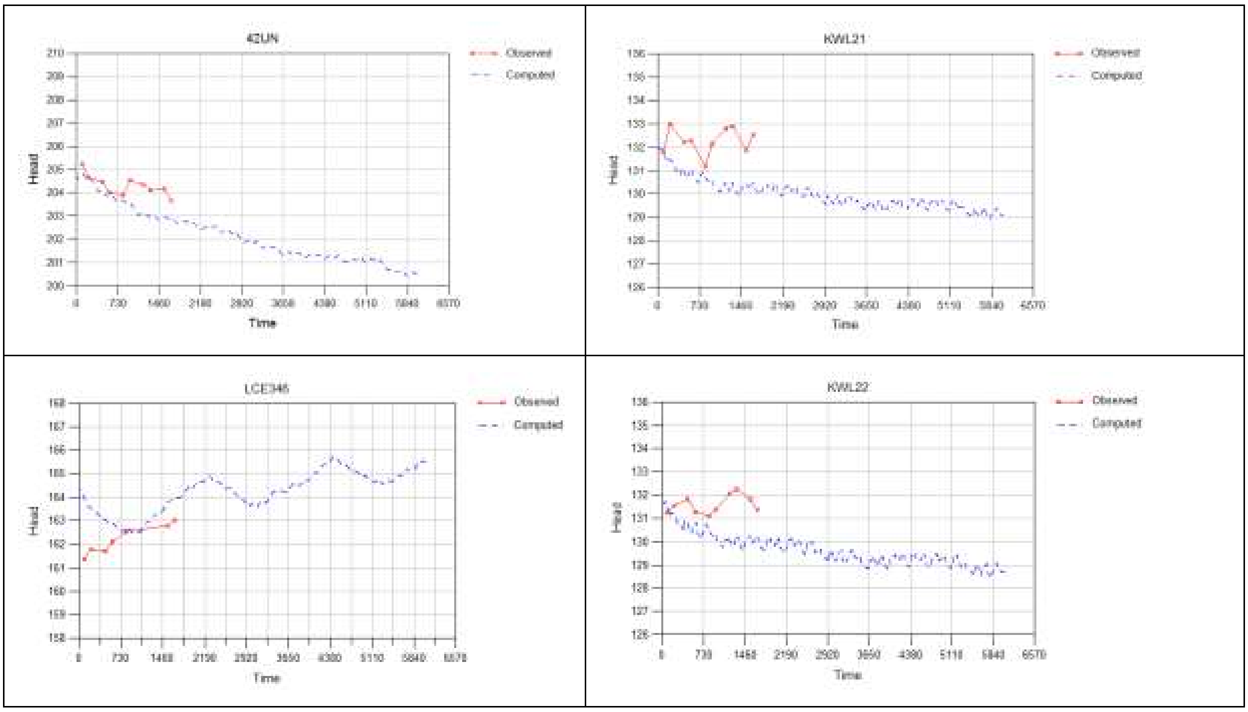


Figure 6.3: Increased pumping (20%) Scenario: Simulated heads (mMSL) for piezometers in Layer 2



Our recommendation would be for PID to extend the calibration of the model over at least a 10 year period and also institute strategic monitoring of water levels and salinity. Continuous monitoring using water level and salinity loggers would improve understanding of the salinity dynamics. Moreover, monitoring salinity changes with depth, particularly where salinities are rising would help to improve model conceptualisation.

Figure 6.4: Increased pumping (20%) Scenario: Simulated concentration (kg/m3) for piezometers in Layer 1

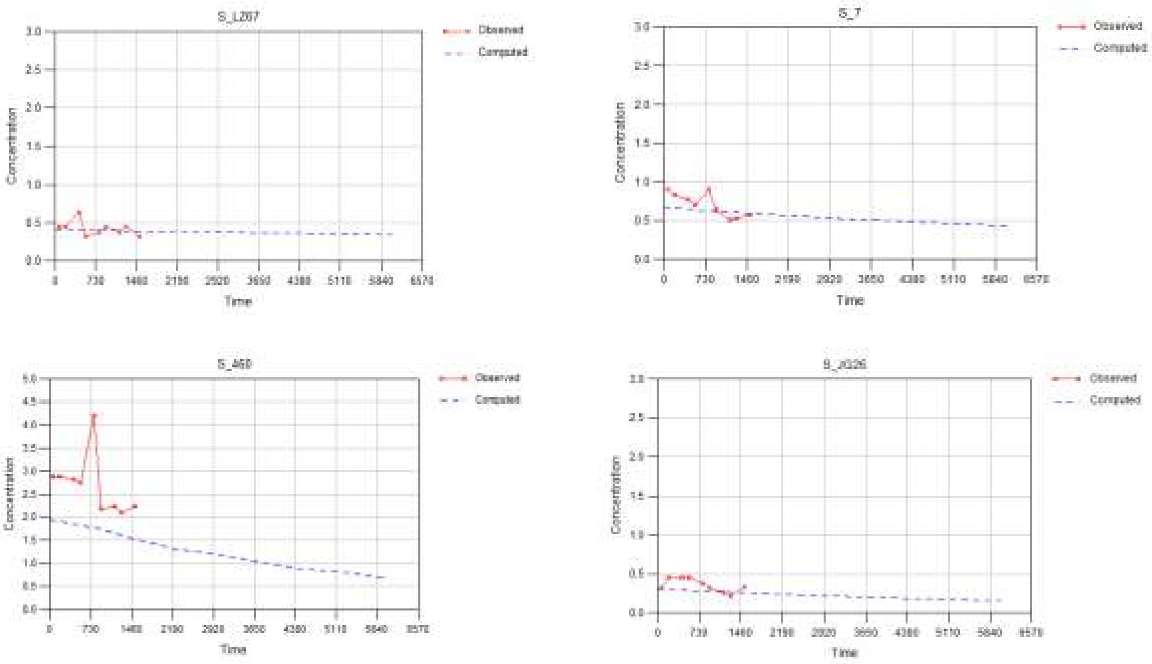
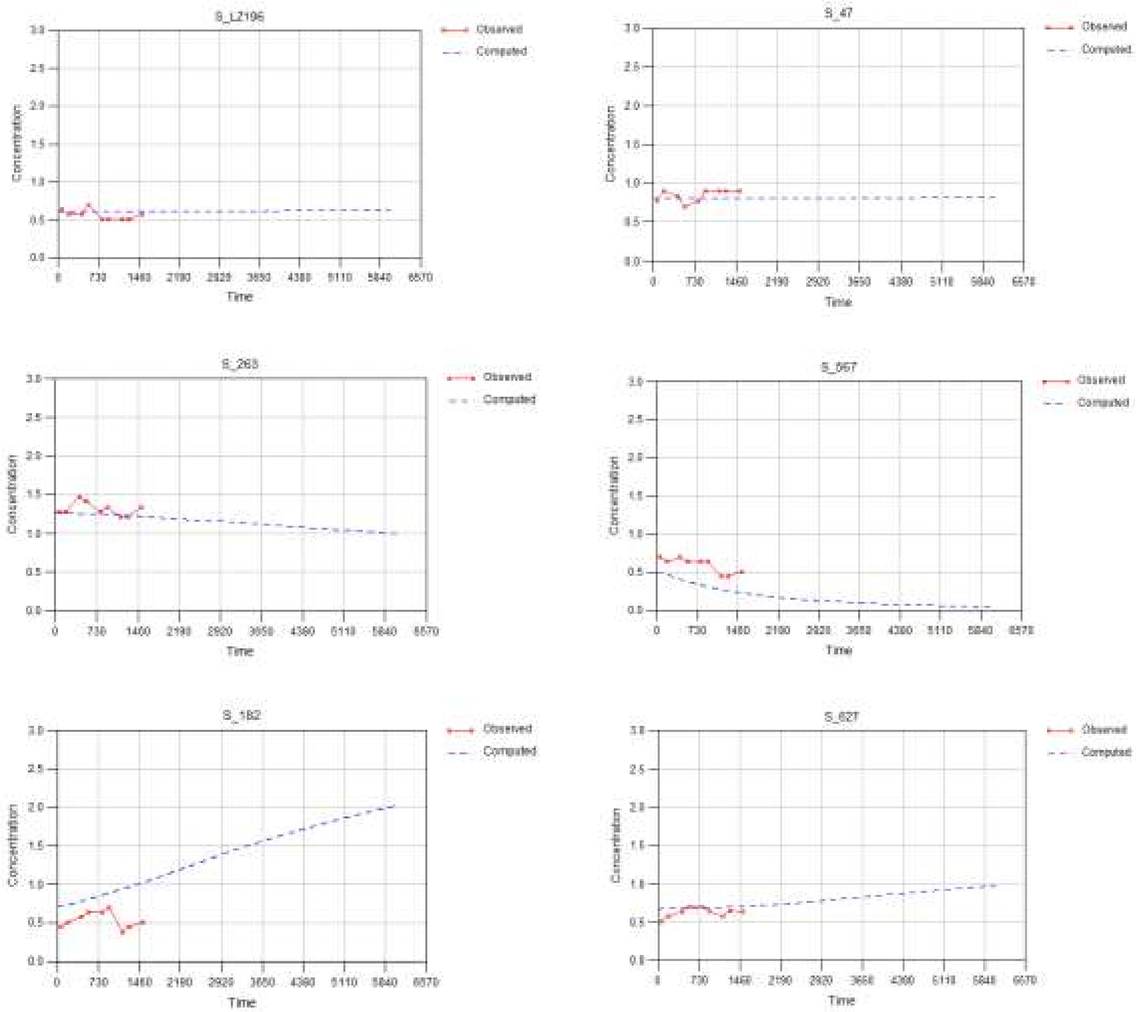


Figure 6.5: Increased pumping (20%) Scenario: Simulated concentration (kg/m3) for piezometers in Layer 2



6.2 Increased Pumping by 30 percent for Rechna Doab

The enhanced pumping scenarios used climate data from 2008 to 2014 which was reused to simulate conditions up till 2030. All the model parameters remained the same with exception of pumping and evapotranspiration. This scenario assumes that agricultural pumping in Rechna Doab increases by 30%, from an average of 10,100×10^{6}m^3/yr to 13,100×10^{6}m^3/yr respectively.

The water balance for scenario 2 with 30% increase in groundwater from 2014 to 2030 is presented in Table 6.2. All values are in million m^3 (MCM)/year (GL/yr) and are averaged over the 16.5 years of simulation.

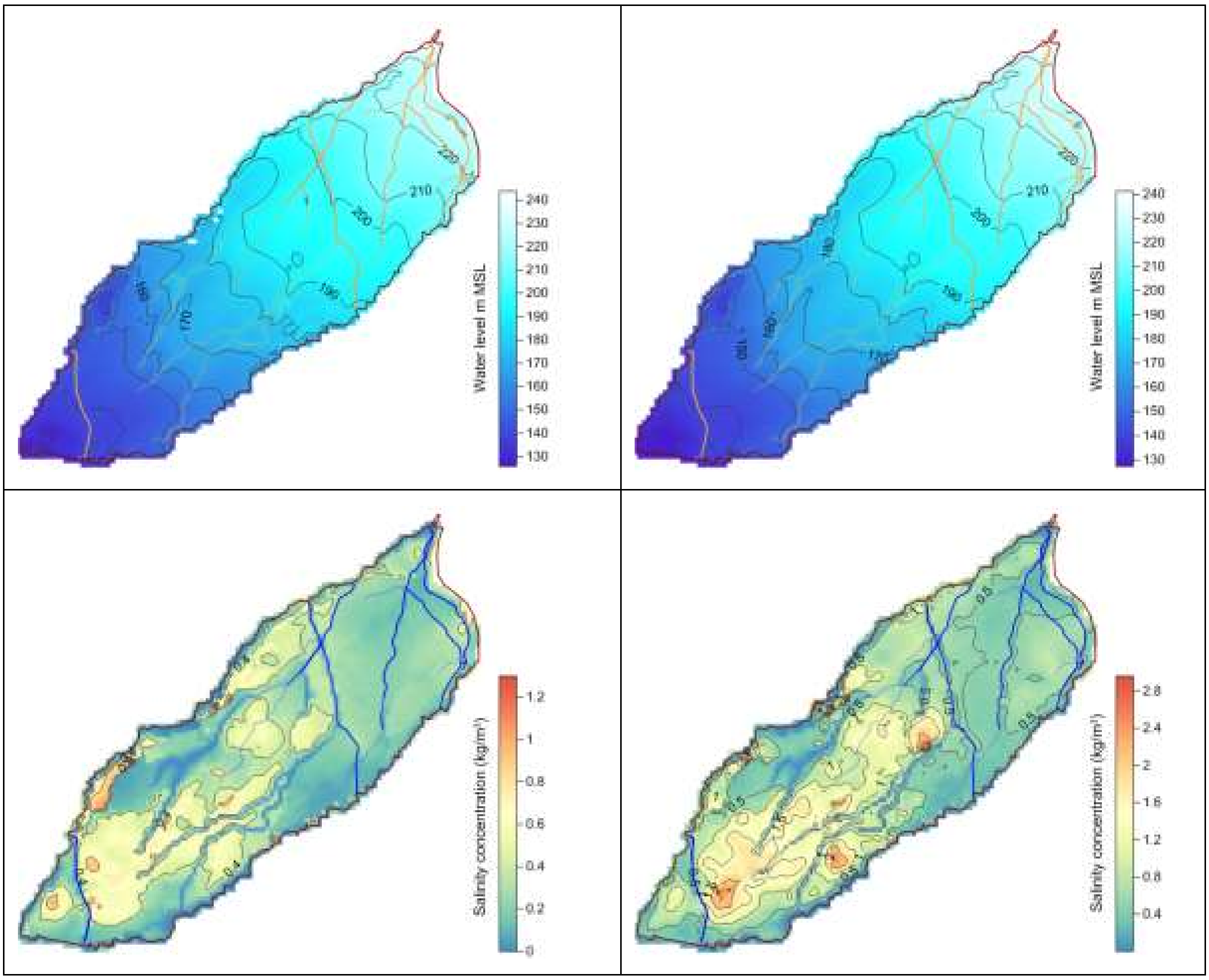
Table 6.2 Water balance for all model layers for 30% increase in groundwater use scenario from 2014-2030

Stresses	Inflows MCM/yr	Outflows MCM/yr	Net MCM/yr
Recharge	10,314	0	10,314
River & canals	4,287	567	4,219
Wells	0	13,136	-13,136
Evapotranspiration	0	603	-603
Boundary flows	254	1442	-1,188
Storage	**14,855**	**15,248**	**-393**

This scenario indicates that if groundwater usage was increased by 30 percent to 13,136 MCM/yr the net storage term decrease from 2,781 MCM/yr to -393 MCM/yr, which is substantially lower than for the no plan scenario. This simulation shows increased pumping by 30% will result in a deficit and if surface water deliveries were to decrease or if there is a prolonged dry period resulting in decreased rainfall the decline in storage would result in particular areas suffering rapidly declining water levels and associated salinity impacts. Moreover, given the data uncertainties and unknowns (e.g. Groundwater usage from 200,000 tubewells) it would be prudent to manage the system such that there is a surplus net storage. We further recommend that water balances based on selected zones be conducted by PID where declining groundwater levels are a concern to ascertain the vulnerability of each zone to groundwater level decline as well as salinity. This would allow PID to exercise more flexible management of the Rechna Doab taking into account local area conditions.

Water level and salinity contours for the aquifer at the end of simulation (2030) are shown in Figure 6.6 for layers 1 and 2. Water levels are similar at the end of April 2030, however, salinity concentrations differ between layers 1 and 2. In the eastern part of LCC west and along the western boundary of LCC east, salinity concentrations in in layer 2 are higher in the lower mid sections of the doab. Salinities approaching 3 kg/m^3 make groundwater unusable for irrigation. The salinity stratification in the Indus is such that salinity increases with depth, thus salinities are higher for layers 3 and 4. However, the immediate concern is the first two layers representing the top 60 m where most of the pumping in Rechna Doab is taking place. Salinity in the top layer does not exceed 1.22 kg/m^3 however this is most likely a result of enhanced leakage from the canal system and also directly related to the climate data used which covered a wetter than average period. In the second layer, salinities are rising in some areas where pumping intensities are high and or where the underlying salinity in the deeper layers is high. Salinity hotspots are simulated in a number of locations. However, the most prominent is in the Bhagat, Tarkhani and Tandlianwala districts, and a zone covering the lower mid regions of the doab, where salinity increases with depth. Managing pumping so that salinity does not increase either by lateral intrusion and/or by upconing is fundamental to the sustainability of groundwater pumping particularly in the lower mid sections of the doab and also as tubewells are deepened to access groundwater The twin impact of increased pumping intensity and pumping from deeper layers of the aquifer will significantly increase salinity risk in the Rechna Doab. An important recommendation for PID is to design a program to monitor vertical salinity profiles at strategic locations.

Figure 6.6: Increased pumping (30%) Scenario : Simulated heads and salinity concentration for aquifer Layers 1 and 2



The water level response of selected bore hydrographs for layers 1 and 2 are shown in Figure 6.7 and Figure 6.8. In areas where pumping intensity has increased by 30 percent water levels are declining as shown in LCW4, LCW30, and JG38 for layer 1 and 42UN, KWL21 and KWL22 for layer 2. Some bores in layer1 such as LCW253 show stable water levels despite the increased pumping. However, there are also areas showing rising water level trends as shown in LCE346 in layer 2. There are two factors that are likely to be affecting rising trends; distance from canal and lower intensity of pumping in the area.

Figure 6.7: Increased pumping (30%) Scenario: Simulated heads (mMSL) for piezometers in Layer 1

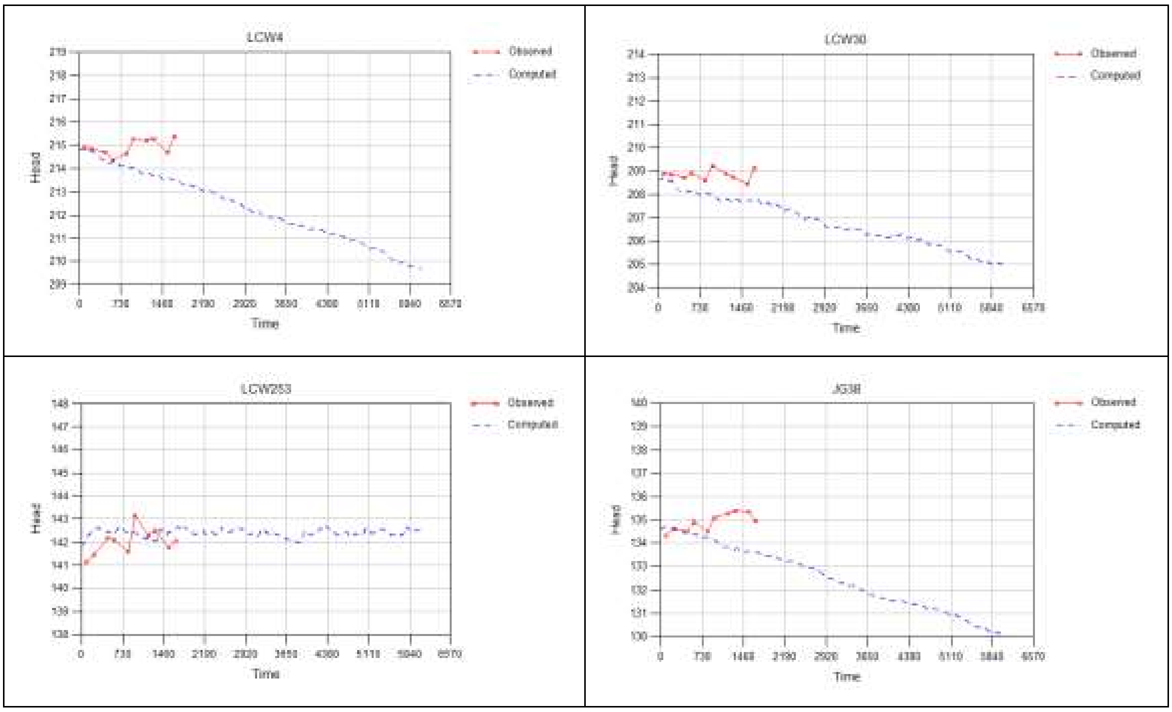


Figure 6.8: Increased pumping (30%) Scenario: Simulated heads (mMSL) for piezometers in Layer 2

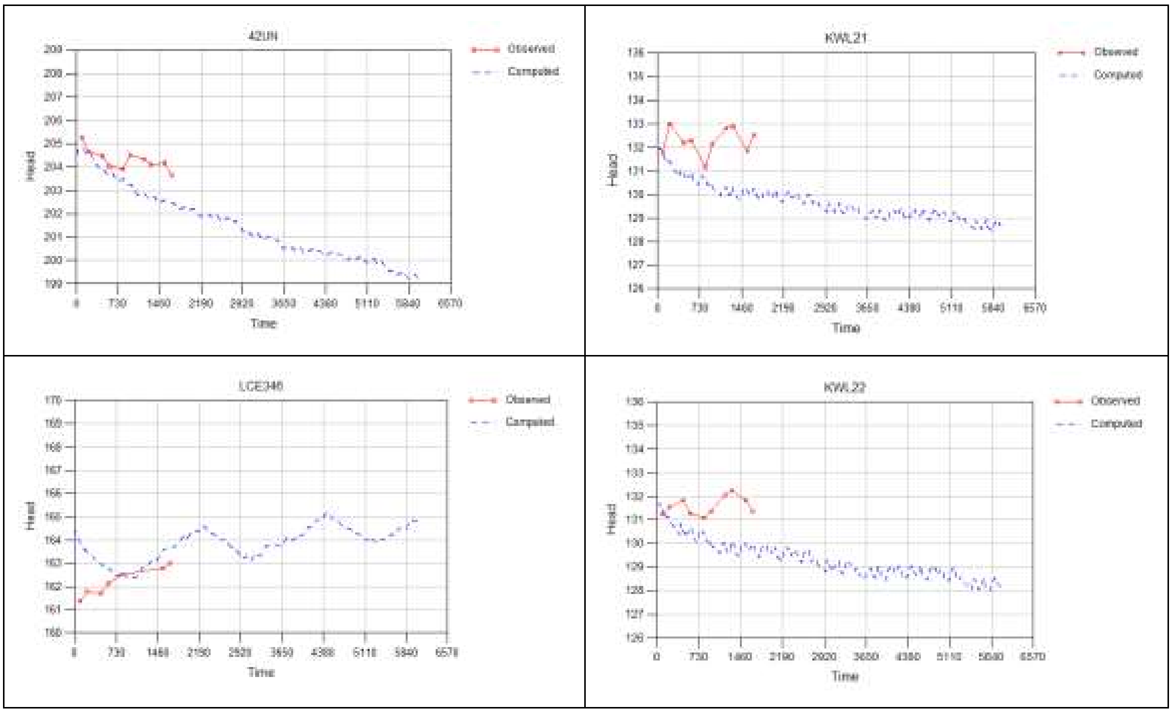


Figure 6.9: Increased pumping (30%) Scenario: Simulated concentration (kg/m3) for piezometers in Layer 1

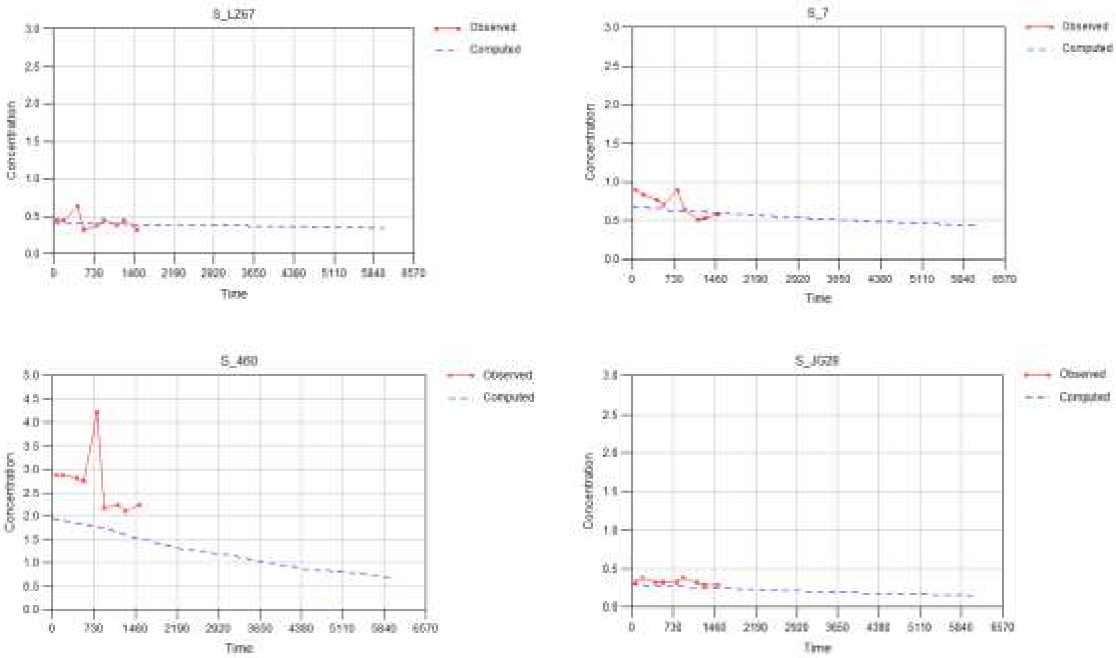
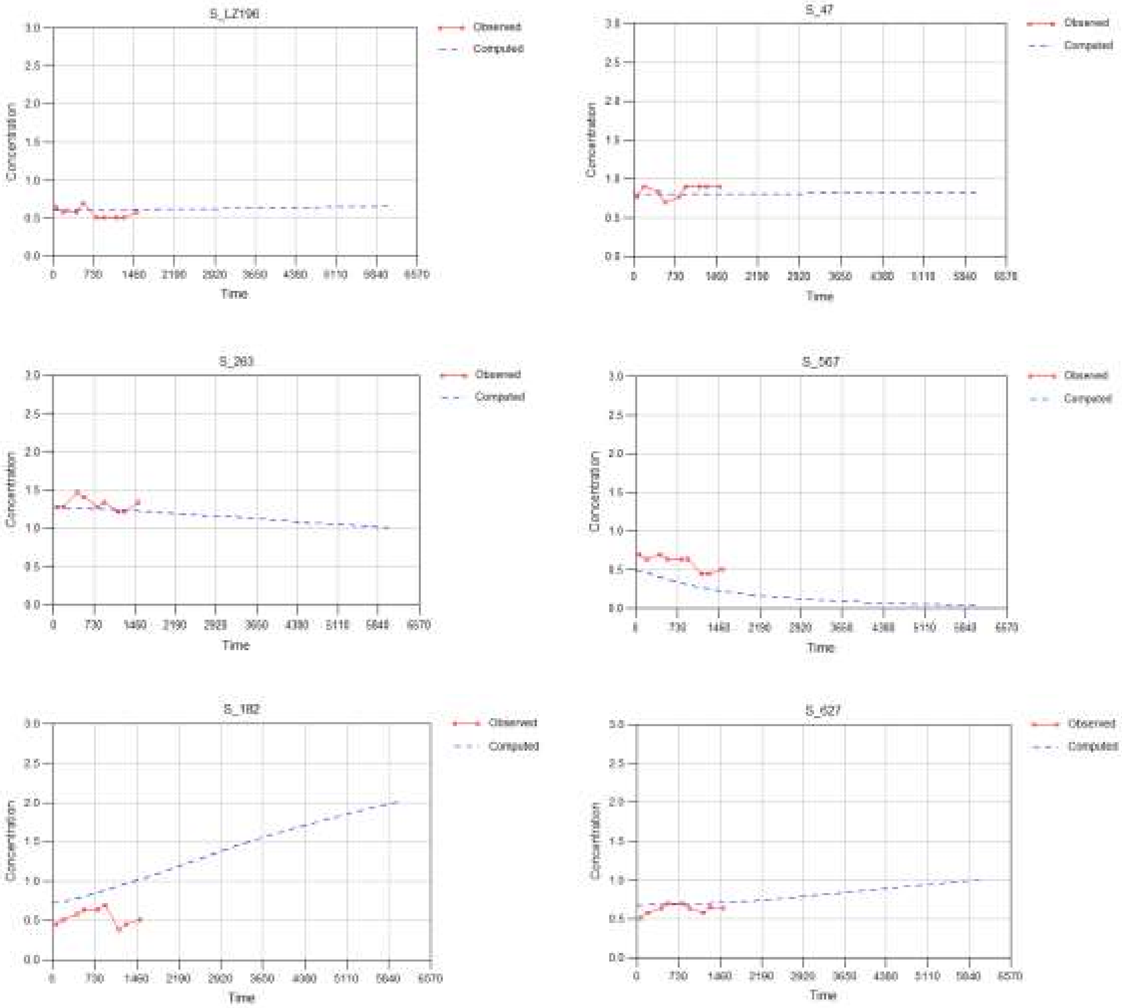


Figure 6.10: Increased pumping (30%) Scenario: Simulated concentration (kg/m3) for piezometers in Layer 2



Salinity concentrations for selected tubewells for layer 1 are shown in Figure 6.9, and for layer 2 in Figure 6.10. The trends are either stable or decreasing slightly in some bores, suggesting that for the tubewells selected the salinity concentrations are not increasing. This is a somewhat surprising result and a preliminary conclusion would suggest that the Rechna Doab is a very resilient system. However, there are several other considerations, the period in which the model was calibrated had above average rainfall and flooding (such as the 2010 floods). Repeating this same sequence of rainfall and surface water availability patterns may have resulted in a more optimistic result. Moreover, increased pumping near canals resulted in increased head gradients, which tends to enhance freshwater flow out of the canals to the groundwater system. However, the most significant influence is the underlying salinity in the deeper layers. Where salinities in the deepest layer are high the vertical transport of salts is enhanced. A combination of increased pumping rates and high underlying salinity increases the risk of salinity concentrations increasing as shown by tubewells 373 and 603 in Figure 6.10. There are also very slight increased salinity trends for tubewells LZ196 and 47. The area’s most at risk are portions of the mid and lower doabs.

Continuous monitoring water level and salinity loggers would improve understanding of the salinity dynamics. An additional consideration is that calibration of the solute model may need to be revisited when additional data becomes available as a 4 year period for calibration with only 2 measurement points per year is inadequate for robust calibration. Our recommendation is for PID to extend the calibration of the model over at least a 10 year period and also institute strategic monitoring of water levels and salinity. Continuous monitoring water level and salinity loggers would improve understanding of the salinity dynamics. To improve salinity predictions improved data on salinity concentrations in the deeper parts of the doab is vital. A program of monitoring deeper parts of the doab should be instituted so that a better understanding of pumping risk can be ascertained.

6.3 Short duration drought scenario with pumping increased by 30 percent during drought for Rechna Doab

The enhanced pumping scenarios used climate data from 2008 to 2014 which was reused to simulate conditions up till 2030. Two drought periods each of 3 years duration (2020 to 2022 and 2027 to 2029) were selected as drought periods. During the drought rainfall was assumed to be 20% of normal rainfall, and pumping during drought years was assumed to increase by 30 percent in response to lower surface water availability. Additionally river and canal supply was reduced by 10 percent to simulate lower supply conditions. All the model parameters remained the same.

The water balance for scenario 3 with the two drought periods during 2014 to 2030 is presented in Table 6.3. All values are in million m^3 (MCM)/year (GL/yr) and are averaged over the 16.5 years of simulation.

Table 6.3 Water balance for all model layers for two drought periods extending over 3 years from 2014-2030

Stresses	Inflows MCM/yr	Outflows MCM/yr	Net MCM/yr
Recharge	9,835	0	9,835
River & canals	4,088	71	4,018
Wells	0	11,141	-11,141
Evapotranspiration	0	782	-782
Boundary flows	226	1473	-1,246
Storage	**14,151**	**13,466**	**685**

This scenario indicates that groundwater usage was increased to 11,141 MCM/yr to allow for increased pumping during drought and the net storage term decreased from 2,781 MCM/yr to 685 MCM/yr which is lower than for the no plan scenario, however, it has exceeded the recommended sustainable yield for Rechna Doab (10,100 ± 1000 MCM/yr). This simulation shows that the net storage remains positive even as surface water supplies are decreased by 10 percent and pumping increased by 30% during the two drought periods each extending for 3 years. However, tail enders are likely to experience greater water stress as they will be affected by both lower surface water deliveries and increased risk of salinity as tail enders will make up the shortfall by pumping greater volumes of groundwater which is likely to be of higher salinity. Additionally, decline in storage for the tail enders and for those in the lower mid portions of the doab would result in particular areas suffering rapidly declining water levels and associated salinity impacts. Moreover, given the data uncertainties and unknowns (e.g. Groundwater usage from 200,000 tubewells) it would be prudent to manage pumping within the guidance provided for sustainable yield, at least until this estimate is revised in the future when the model is extended and improved. We further recommend that water balances based on selected zones be conducted by PID where declining groundwater levels are a concern to ascertain the vulnerability of each zone to groundwater level decline as well as salinity. This would allow PID to exercise more flexible management of the Rechna Doab taking into account local area conditions.

Water level and salinity contours for the aquifer at the end of simulation (2030) are shown in Figure 6.11 for layers 1 and 2. Water levels are similar at the end of April 2030, however, salinity concentrations differ between layers 1 and 2. In the eastern part of LCC west and along the western boundary of LCC east, salinity concentrations in layer 2 are higher in the lower mid sections of the doab. Irrigation water salinity in excess of 3000 mg/L result in increased soil salinity and sodicity which impacting crop productivity. The salinity stratification in the Indus is such that salinity increases with depth, thus salinities are higher for layers 3 and 4. However, the immediate concern is the first two layers representing the top 60 m where most of the pumping in Rechna Doab is taking place. In the second layer, salinities are rising in some areas where pumping intensities are high. Managing pumping so that salinity does not increase either by lateral intrusion and/or by upconing is fundamental to the sustainability of groundwater pumping particularly in the lower mid sections of the doab and also as tubewells are deepened to access groundwater The twin impact of increased pumping intensity and pumping from deeper layers of the aquifer will significantly increase salinity risk in the Rechna Doab.

Figure 6.11: Simulated heads and salinity concentration for aquifer Layers 1 and 2 for two drought periods extending over 3 years from 2020-22 and 2027-29.

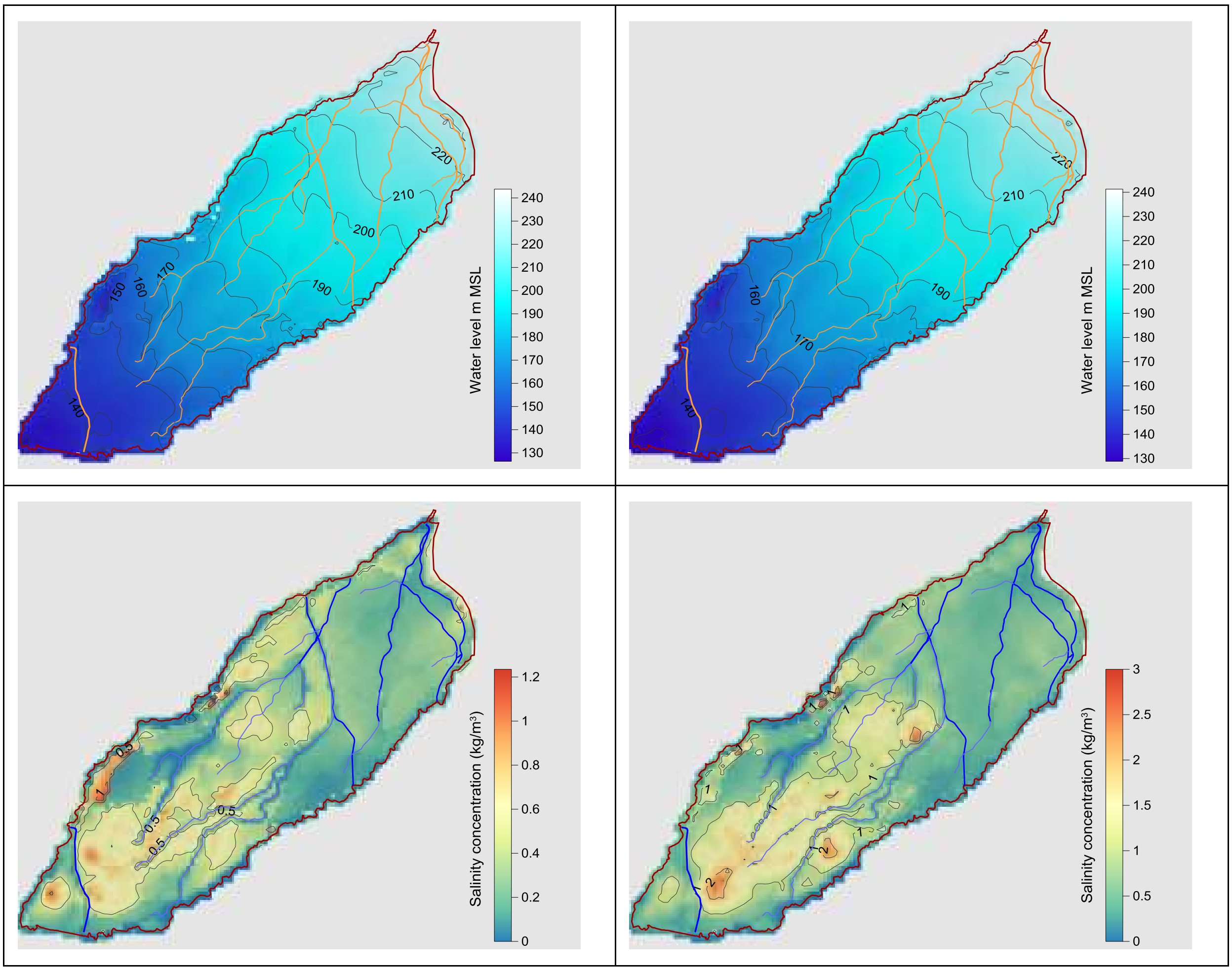


Figure 6.12: Simulated heads (mMSL) for piezometers in Layer 1 for two drought periods extending over 3 years from 2020-22 and 2027-29

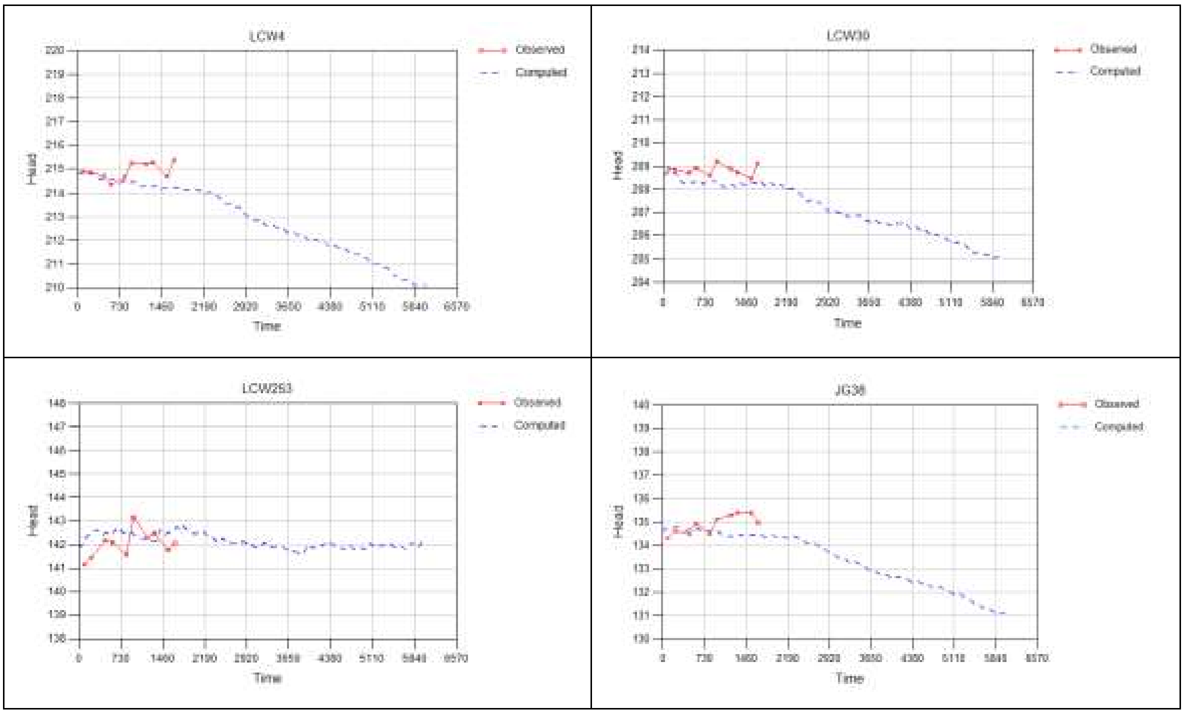
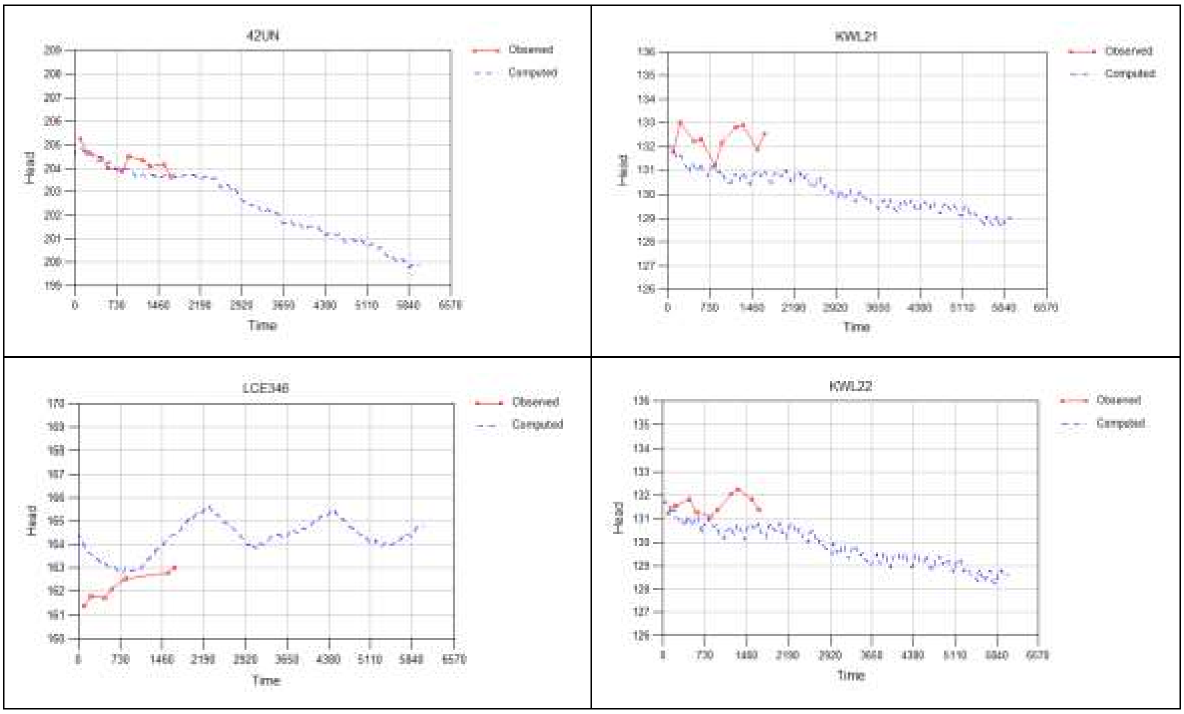


Figure 6.13: Simulated heads (mMSL) for piezometers in Layer 2 for two drought periods extending over 3 years from 2020-22 and 2027-29



The water level response of selected bore hydrographs for layers 1 and 2 are shown in Figure 6.12 and Figure 6.13. In this scenario a combination of factors affects the water level response; these include increased pumping intensity during drought periods, reduced recharge due to lower surface water availability, and reduced total inflows as shown by the water balance in Table 6.3 which results in declining water levels in bores LCW4, LCW30, and JG38 for layer 1 and 42UN and KWL21 for layer 2. Some bores in layer1 such as LCW253 show stable water levels despite the increased pumping. However, there are also areas showing rising water level trends as shown in LCE346 in layer 2. There are two factors that are likely to be affecting rising trends; distance from canal and lower intensity of pumping in the area.

Figure 6.14: Simulated concentration (kg/m3) for piezometers in Layer 1 for two drought periods extending over 3 years from 2020-22 and 2027-29

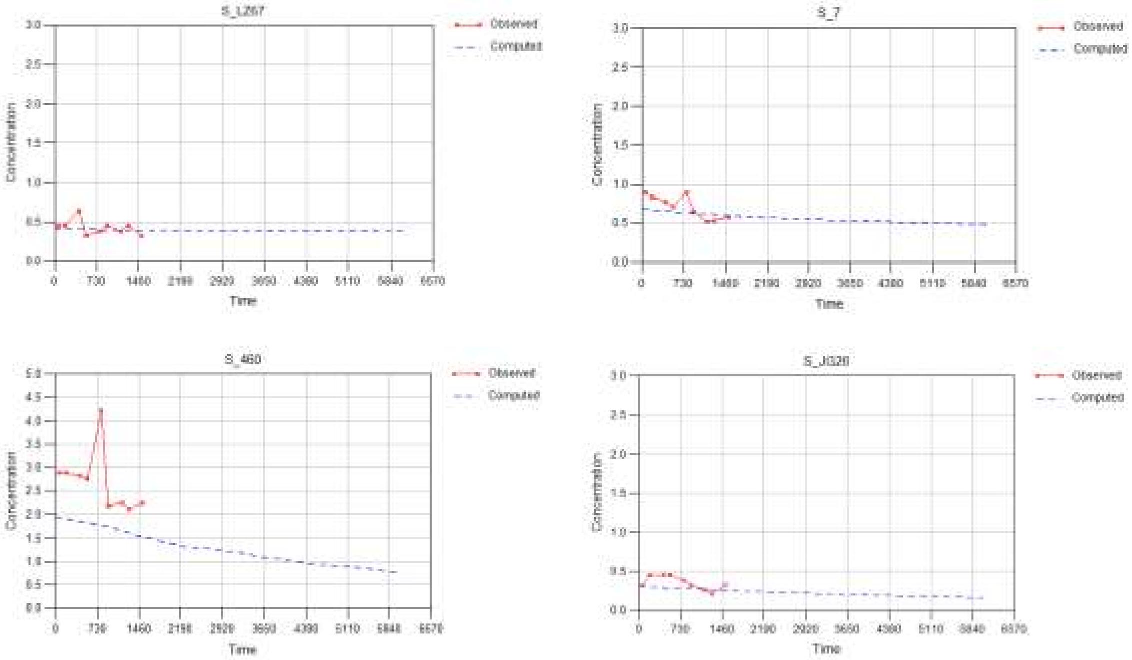
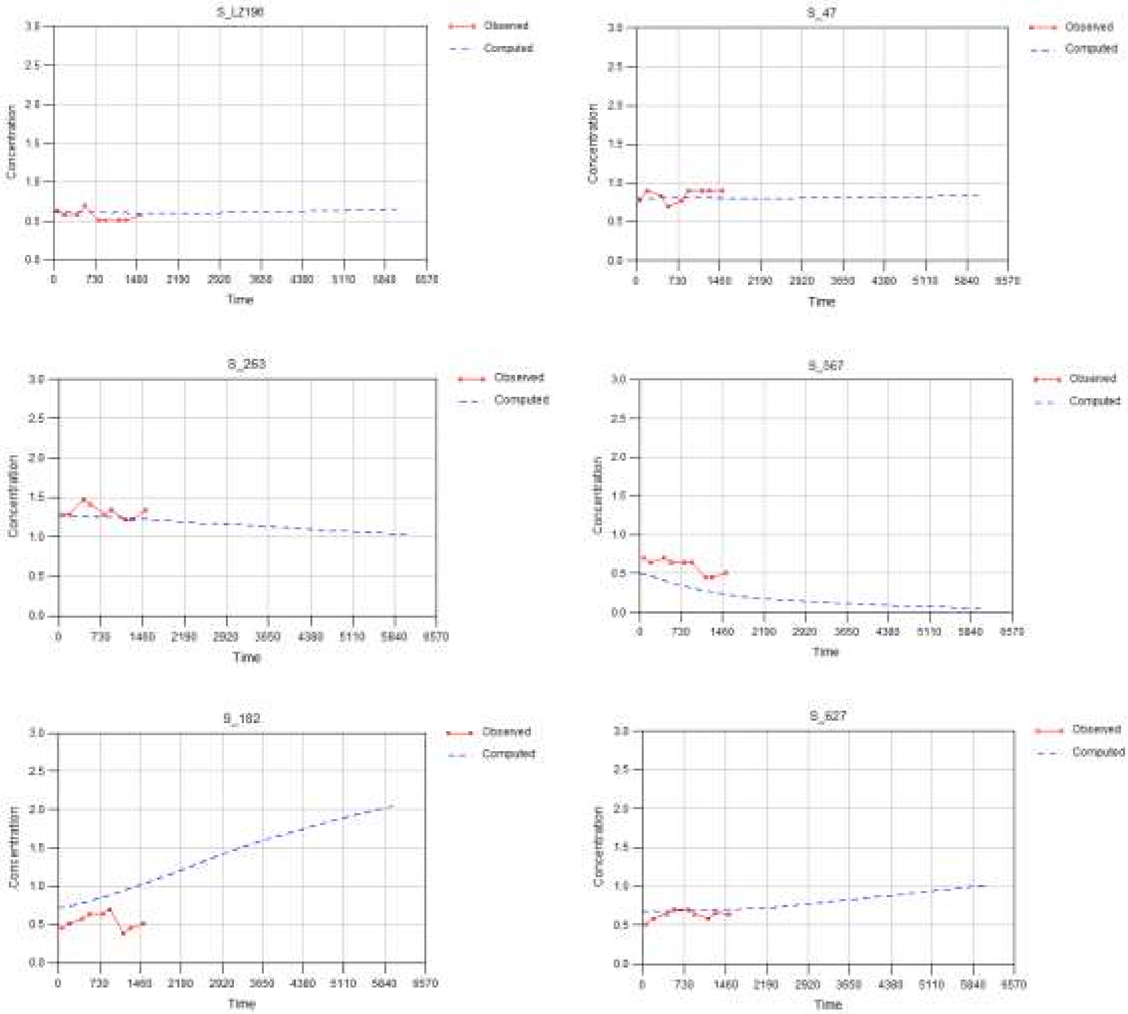


Figure 6.15: Simulated concentration (kg/m3) for piezometers in Layer 2 for two drought periods extending over 3 years from 2020-22 and 2027-29



Salinity concentrations for selected tubewells for layer 1 are shown in Figure 6.14, and for layer 2 in Figure 6.15. The trends are either stable or decreasing slightly in most tubewells in layer 1, suggesting that for the tubewells selected the salinity concentrations are not increasing. However, the most significant influence is the underlying salinity in the deeper layers. Where salinities in the deepest layer are high the vertical transport of salts is enhanced. A combination of increased pumping rates and high underlying salinity increases the risk of salinity concentrations increasing as shown by tubewells s182 and s627 in Figure 6.15. The areas most at risk are portions of the mid and lower doabs. The area in the district of Bhagat is most at risk with underlying salinities increasing with depth.

Continuous monitoring water level and salinity loggers would improve understanding of the salinity dynamics. To improve salinity predictions improved data on salinity concentrations in the deeper parts of the doab is vital. A program of monitoring deeper parts of the doab should be instituted so that a better understanding of pumping risk can be ascertained.

6.4 Long duration drought scenario with pumping increased by 30 percent for Rechna Doab

The enhanced pumping scenarios used climate data from 2008 to 2014 which was reused to simulate conditions up till 2030. A single long drought period of 10 years duration (2020 to 2029) was selected as the drought period. Rainfall during the drought years was assumed to be 20% of normal rainfall, and pumping during drought years was assumed to increase by 30 percent in response to lower surface water availability. Additionally river and canal supply was reduced by 10 percent to simulate lower supply conditions. All the model parameters remained the same.

The water balance for scenario 3 with the two drought periods during 2014 to 2030 is presented in Table 6.3. All values are in million m^3 (MCM)/year (GL/yr) and are averaged over the 16.5 years of simulation.

Table 6.4 Water balance for all model layers for two drought periods extending over 3 years from 2014-2030

Stresses	**Inflows MCM/yr**	**Outflows MCM/yr**	**Net MCM/yr**
Recharge	9,540	0	9,540
River & canals	3,801	66	3,735
Wells	0	11,794	-11,794
Evapotranspiration	0	593	-593
Boundary flows	252	1337	-1,085
Storage	**13,593**	**13,790**	**-197**

This scenario indicates that groundwater usage was increased to 11,794 MCM/yr to allow for increased pumping during the 10 years of drought. The net storage term decreased from 2,781 MCM/yr for the no plan scenario to -197 MCM/yr, which indicates the severity of the 10 year drought. This simulation shows increased pumping by 30% during the ten year drought period would need to be managed carefully as the pumping is likely to exceed the recommended sustainable yield limit, and the net storage term has depleted to -197 MCM. This means that reduced surface water supplies coupled with reduced rainfall recharge during the drought years has decreased total inflows which will impact on increased levels of salinity in the Rechna Doab. In particular, tail enders are likely to experience greater water stress as they will be affected by both lower surface water deliveries and increased risk of salinity as tail enders will tend to make up the shortfall by pumping greater volumes of groundwater which is likely to be of higher salinity. Additionally, decline in storage for the tail enders and for those in the lower mid portions of the doab would result in particular areas suffering from declining water levels and increased salinity impacts as upward gradients from the lower layers will mobilize higher salinity groundwater. Moreover, given the data uncertainties and unknowns (e.g. Groundwater usage from 200,000 tubewells; and the relatively short period for calibration of 6 years) it would be prudent to manage pumping within the guidance provided for sustainable yield, at least until this estimate is revised in the future when the model is extended and improved. Another area where model simulations could be improved is along the boundary of the Ravi river. These boundary conditions could be improved by analysing monitoring data in the adjacent Bari Doab where there is considerably more pumping occurring. We further recommend that water balances based on selected zones be conducted by PID where declining groundwater levels are a concern to ascertain the vulnerability of each zone to groundwater level decline as well as salinity. This would allow PID to exercise more flexible management of the Rechna Doab taking into account local area conditions.

Water level and salinity contours for the aquifer at the end of simulation (2030) are shown in Figure 6.16 for layers 1 and 2. Water levels are similar at the end of April 2030, however, salinity concentrations differ between layers 1 and 2. In the eastern part of LCC west and along the western boundary of LCC east, salinity concentrations in layer 2 are higher in the lower mid sections of the doab. Irrigation water salinity in excess of 3000 mg/L results in increased soil salinity and sodicity which impacts crop productivity. The salinity stratification in the Indus is such that salinity increases with depth, thus salinities are higher for layers 3 and 4. However, the immediate concern is the first two layers representing the top 60 m where most of the pumping in Rechna Doab is taking place. In the second layer, salinities are rising in some areas where pumping intensities are high. Managing pumping so that salinity does not increase either by lateral intrusion and/or by upconing is fundamental to the sustainability of groundwater pumping particularly in the lower mid sections of the doab and also as tubewells are deepened to access groundwater. Cumulative impacts of increased pumping intensity, lower surface water supplies, lower rainfall due to drought, and increased pumping from deeper layers of the aquifer will significantly increase salinity risk in the Rechna Doab.

Figure 6.16: Simulated heads and salinity concentration for aquifer Layers 1 and long duration drought (2020-2029)

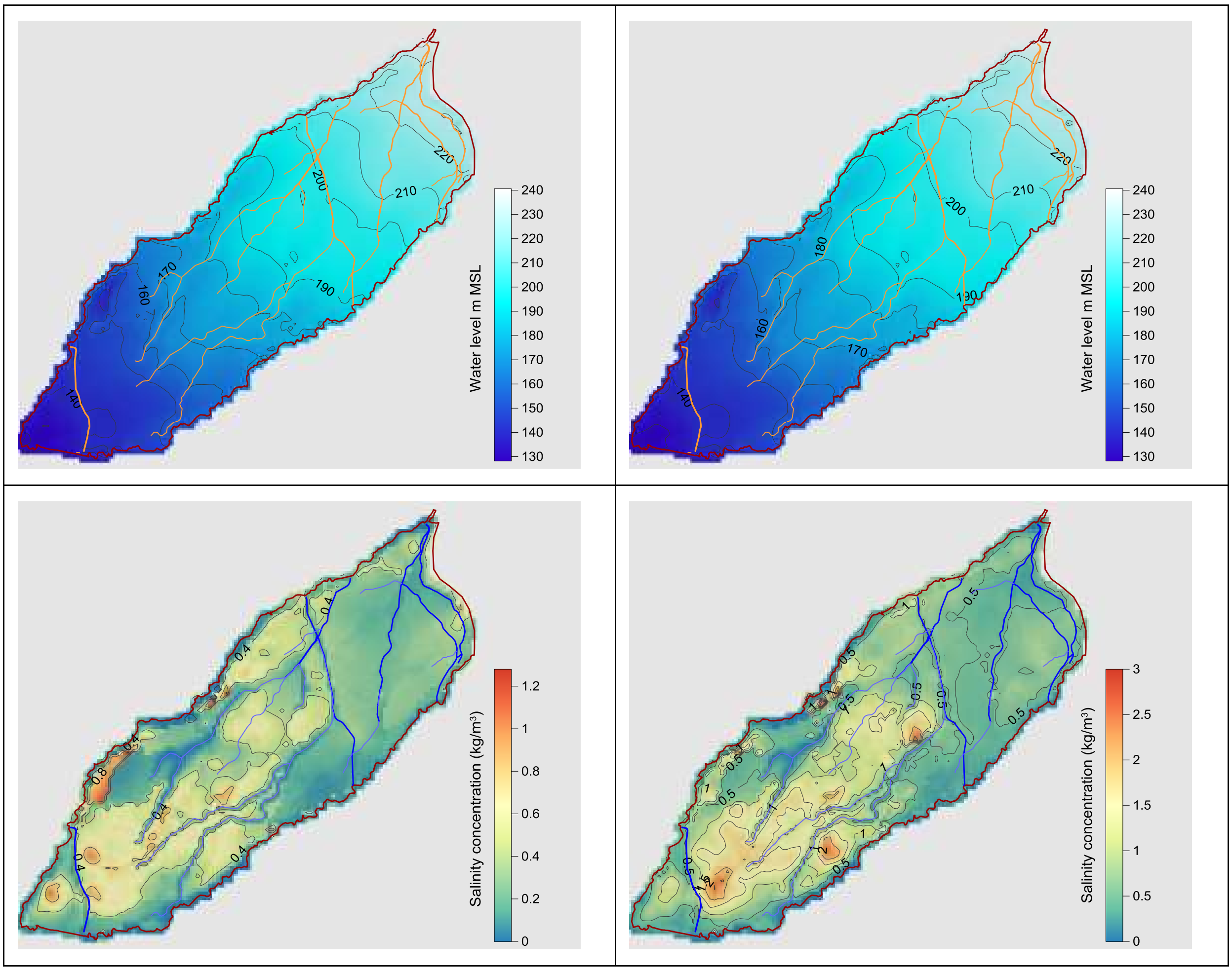


Figure 6.17: Simulated heads (mMSL) for piezometers in Layer 1 for a long duration drought (2020-2029)

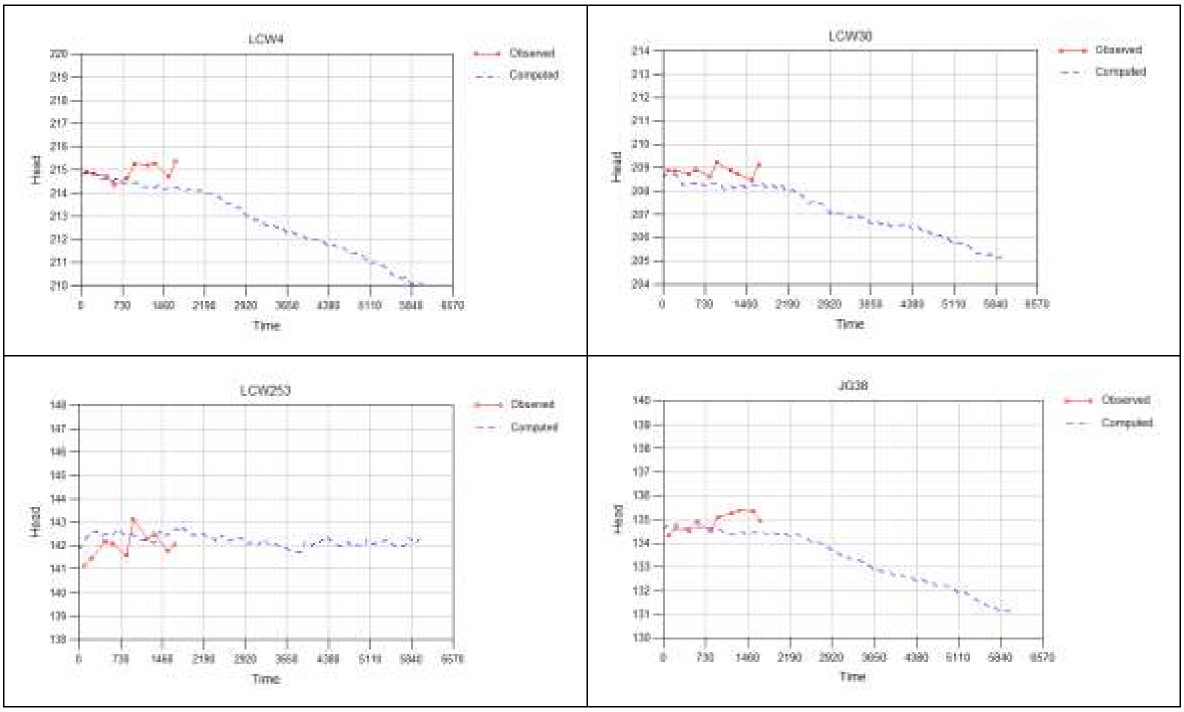
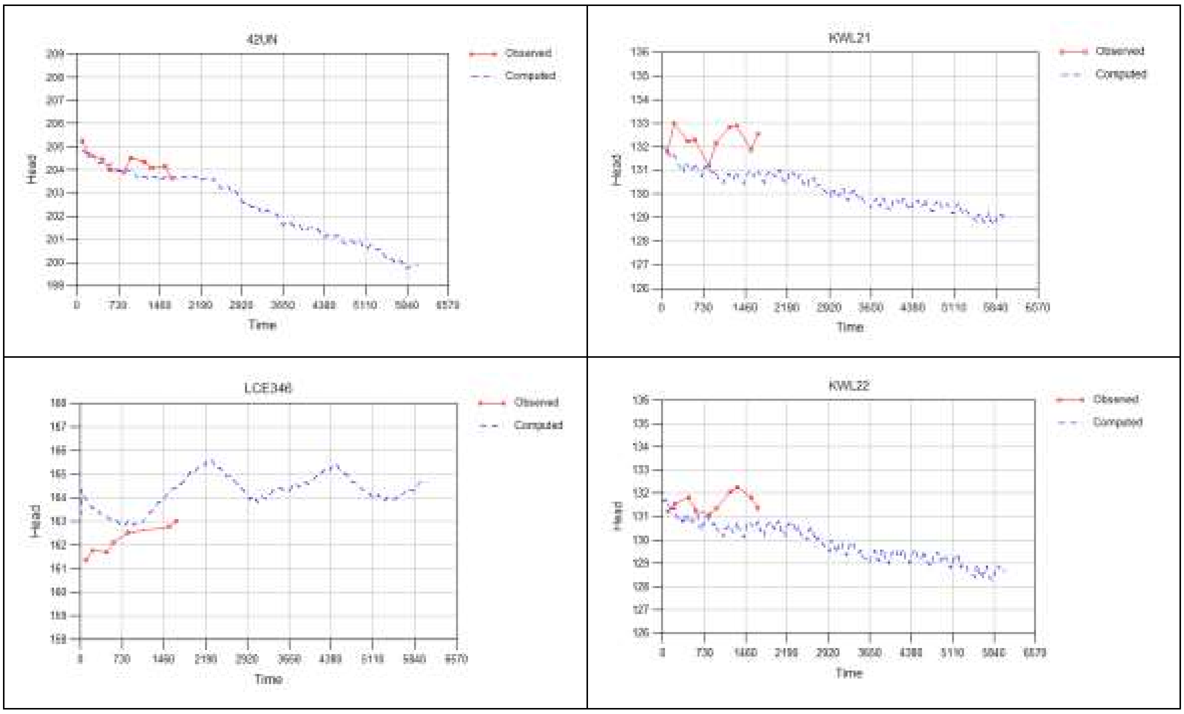


Figure 6.18: Simulated heads (mMSL) for piezometers in Layer 2 for a long duration drought (2020-2029)



The water level response of selected bore hydrographs for layers 1 and 2 are shown in Figure 6.17 and Figure 6.18. In this scenario a combination of factors affects the water level response; these include increased pumping intensity during drought periods, reduced recharge due to lower surface water availability, and reduced total inflows as shown by the water balance in Table 6.4 which results in declining water levels in bores LCW4, LCW30, and JG38 for layer 1 and 42UN, KWL21 and KWL22 for layer 2. Some bores in layer 1 such as LCW253 show stable water levels despite the increased pumping. However, there are also areas showing rising water level trends as shown in LCE346 in layer 2. There are two factors that are likely to be affecting rising trends; distance from canal and lower intensity of pumping in the area. Areas where surface water supplies are adequate and where pumping intensities are low may experience rising water levels.

Figure 6.19: Simulated concentration (kg/m3) for piezometers in Layer 1 for a long duration drought (2020-2029)

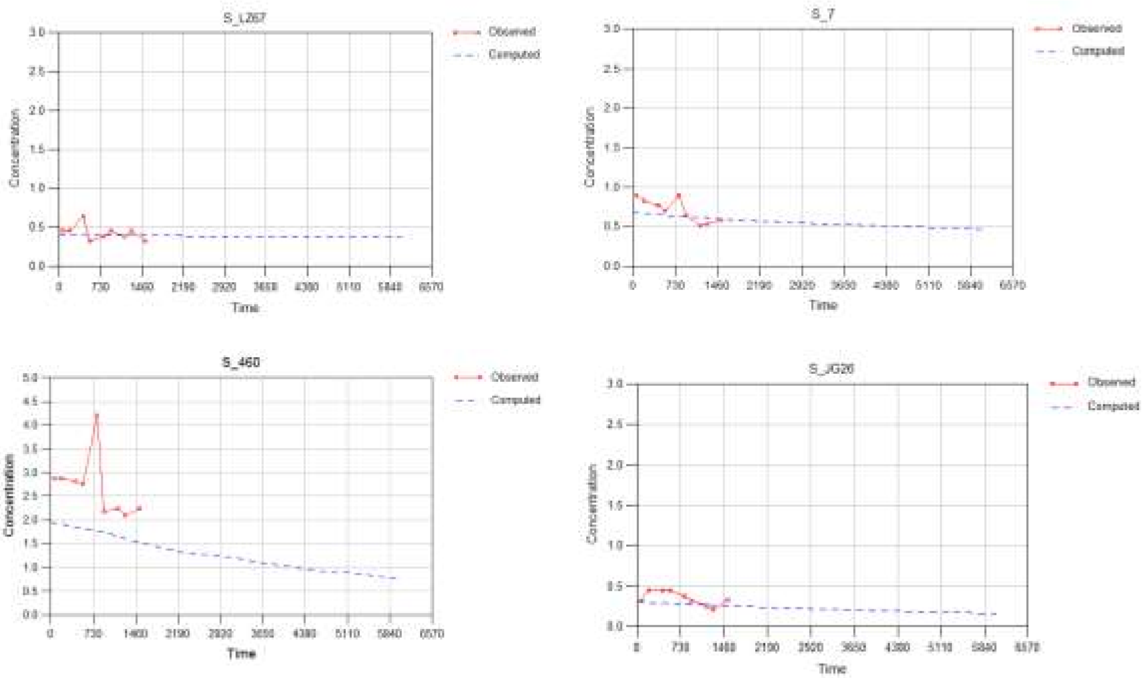
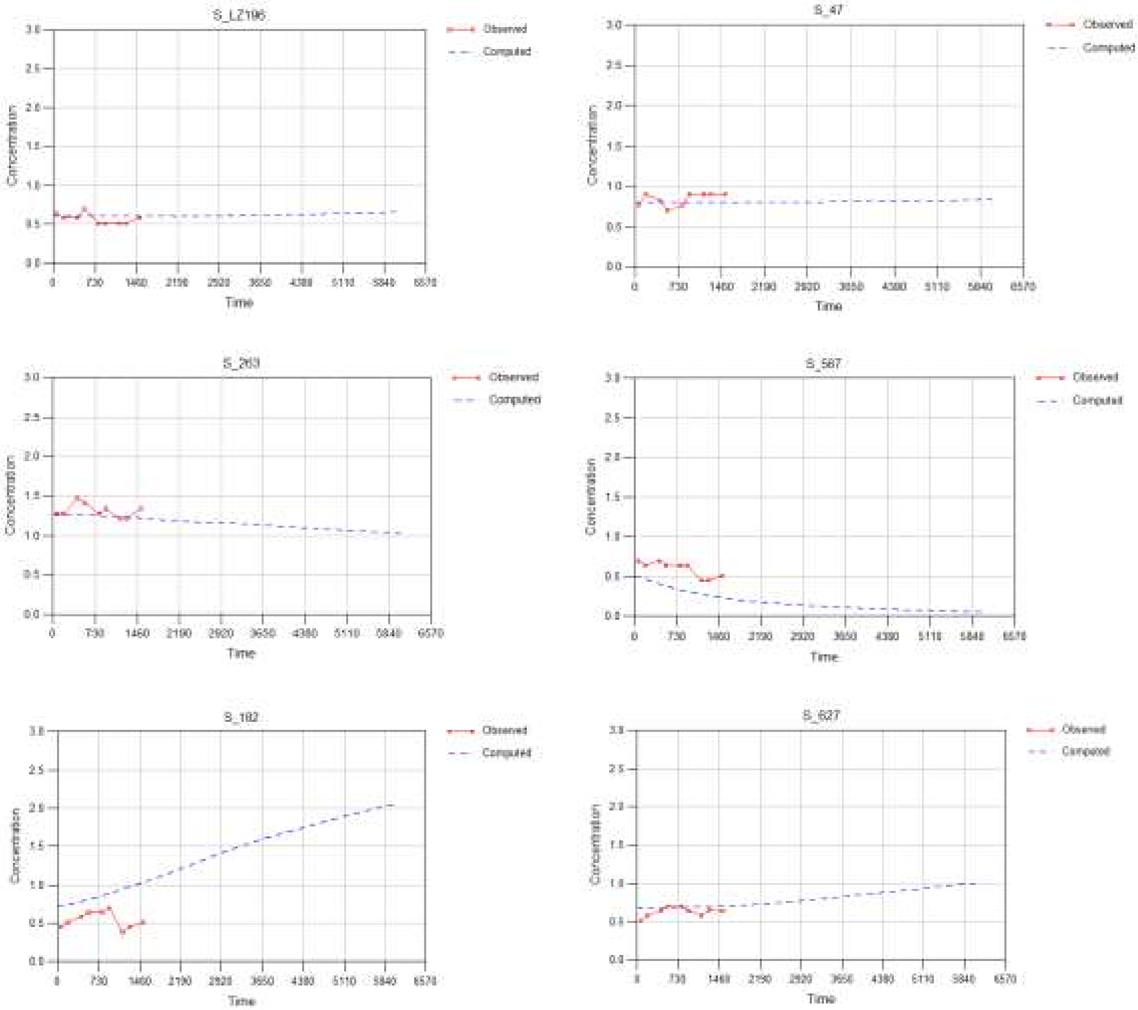


Figure 6.20: Simulated concentration (kg/m3) for piezometers in Layer 2 for two drought periods extending over 3 years from 2014-2030



Salinity concentrations for selected tubewells for layer 1 are shown in Figure 6.19, and for layer 2 in Figure 6.20. The trends are either stable or decreasing slightly in some bores, suggesting that for the tubewells selected the salinity concentrations are not increasing. Another reason why salinities may not be rising despite increased pumping is due to seepage of freshwater from canals and irrigation recharge in layer 1, as the layers are highly connected there is fresh water from layer 1 being drawn into layer 2. However, the most significant influence is the underlying salinity in the deeper layers. Where salinities in the deepest layer are high the vertical transport of salts is enhanced. A combination of increased pumping rates and high underlying salinity increases the risk of salinity concentrations increasing as shown by tubewells s182 and s627 in Figure 6.20. The areas most at risk are portions of the mid and lower doabs. The area in the district of Bhagat, Aminpur, Tandlianwala and Tarkhani are most at risk with underlying salinities increasing rapidly with depth.

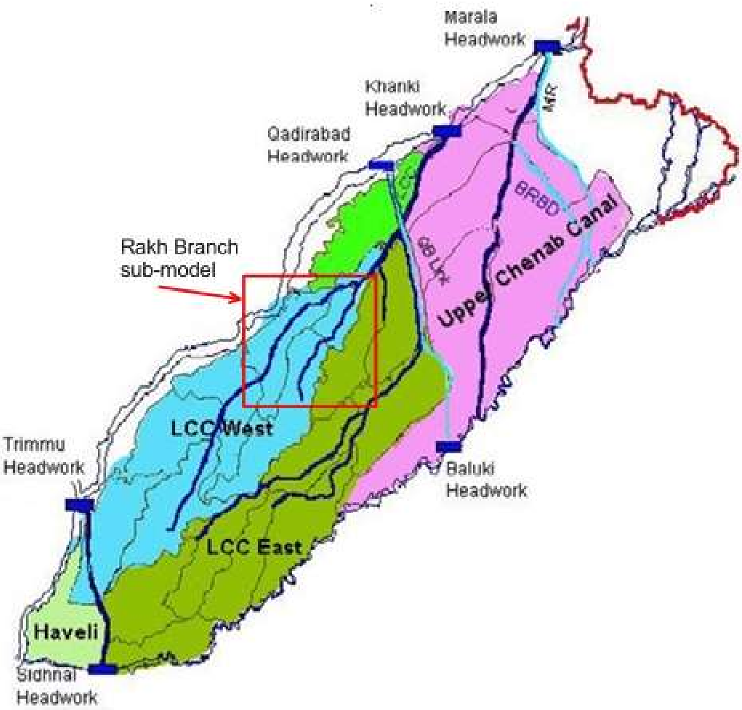
Continuous monitoring with water level and salinity loggers would improve understanding of the salinity dynamics. To improve salinity predictions improved data on salinity concentrations in the deeper parts of the doab is vital. A program of monitoring deeper parts of the doab should be instituted so that a better understanding of pumping risk can be ascertained.

7 TMR model of Rakh Branch

The regional model for Rechna Doab was utilised to develop a sub-model of Rakh Branch to demonstrate how the regional model can be used to provide in-depth analysis for a sub region. The Rakh Branch sub-model also provided a useful training exercise to demonstrate the application of the TMR package in MODFLOW.

The LCC system is one of the oldest irrigation systems in the Punjab, constructed as an inundation canal in 1887. It was converted into a perennial canal in 1892 upon completion of Khanki weir on the Chenab River. It serves a Canal Command Area (CCA) of 1.24 Mha in 6 districts of central Punjab, with a population of 4.2 million. The major canal irrigation systems in Rechna Doab are shown in Figure 7.1, along with the outline for the Rakh Branch sub-model.

Figure 7.1: Canal Irrigation Network in Rechna Doab, Punjab

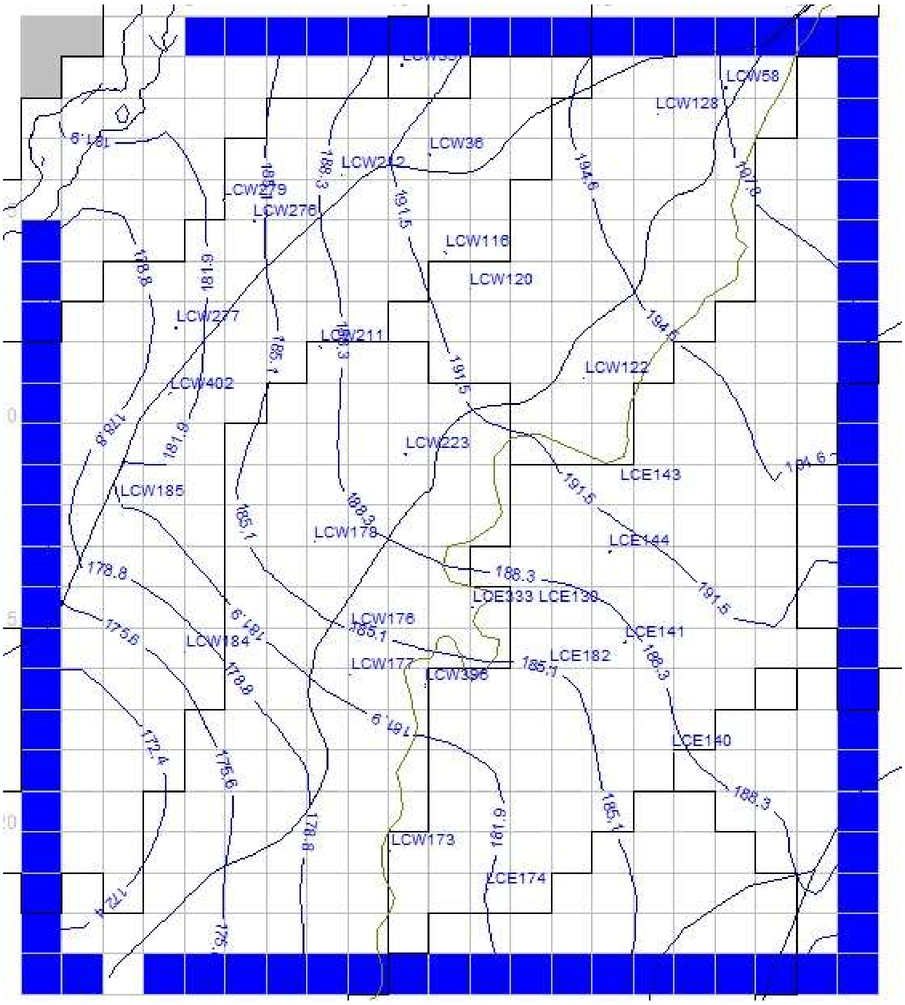


The LCC system has been bifurcated into LCC East and LCC West. The sub-model under study comprises a portion of the LCC West area which is located between the Chenab river and the mid portion of the Rechna Doab. The major canals within the system include the Jhang Branch, and Rakh Branch canals. There is also an extensive network of distributaries, minors and watercourses covering LCC West. The Rakh branch sub-model falls partly under the jurisdiction of Sangla, Kot Khuda Yar and Uqbana districts.

The Rakh Branch subregion model in this study covers approximately 315,000 ha and makes up about 10.6 percent of Rechna Doab as shown in Figure 7.1. The Rakh branch sub-model was modelled using the TMR package in Modflow. This sub-model is largely based on the existing regional groundwater model. The TMR model for Rakh Branch was extracted from the regional Rechna Doab model using a grid scale of 2500x2500 m. The model consists of 24 rows and 21 columns and 36,089 active cells. The Rakh Branch sub-model was developed specifically as a training exercise hence to allow for simplicity the grid scale was kept the same as for the regional model. However, the sub-model can be used as the basis for further refinement by transforming the sub-model to a finer grid. A smaller grid size as that used in the LCC East model allows for a much finer definition of the river and canal system which not only contributes to improved accuracy of river recharge and discharge but in future model enhancements it allows the incorporation of the canal distributary network. However, the simpler TMR model is beneficial as a training tool.

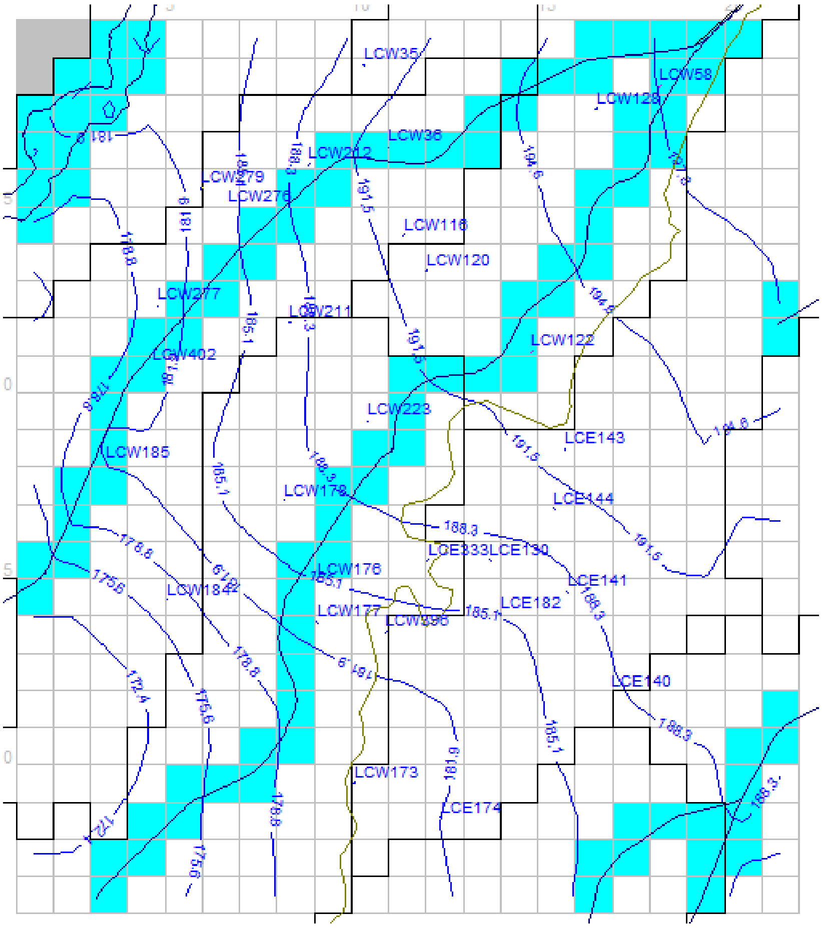
In the first instance the TMR sub-model for Rakh Branch was checked to ensure that the data had been imported correctly into the sub area model. The river cells specified in layer 1, and the constant head boundaries were checked as the TMR package has created time varying constant head boundaries surrounding the Rakh branch sub-model. An important factor to note that all TMR models require boundary conditions along all boundaries as TMR models are a subset of the larger regional model. The constant head boundaries created by the TMR package are shown in Figure 7.2. The northwest cells do not have any constant head boundaries as this boundary condition is defined by the Chenab River, and similarly the boundary condition for the Rakh Branch canal is used in row 24 and col 3 shown in Figure 7.3.

Figure 7.2 Constant head boundary conditions for Rakh Branch sub-model



Similarly the rivers and canals, pumping, recharge, evapotranspiration were obtained from the regional model. The river and canal network for the Rakh Branch sub-model is shown in Figure 7.3.

Figure 7.3 River and canal network for the Rakh Branch sub-model



The Rakh branch sub-model presented here is the first step in building a detailed model that can be further developed and used for predictions. The current Rechna Doab model incorporates the main canals, branch canals and link canals. In future work with the Rakh branch sub-model or for a sub-regional model for LCC West, it is recommended that the river package be extended to the distributary level. It is also recommended that future work with the Rakh Branch sub-model re-evaluate the pumping which would also entail reworking the spatial estimates of ET0 and ETA at a finer spatial scale.

The water balance for the Rakh Branch sub-model presented in Table 7.1, shows the largest component of the water balance is recharge from rainfall and irrigation recharge which represents 80.5 percent of all inflows for the Rakh Branch sub-model. Canal inflows constitutes 17.9% of all inflows. The Rakh branch is lined so one would expect lower inflows, thus most of the inflows are from Jhang Branch canal. The largest outflow is groundwater pumping which constitutes 79% of all outflows. The net storage is a surplus of 664 MCM.

Table 7.1 Water balance for Rakh Branch sub-model

Stresses	Inflows MCM/yr	Outflows MCM/yr	Net MCM/yr
Recharge	1,310	0	1,310
River & canals	291	0	291
Wells	0	762	-762
Evapotranspiration	0	55	-55
Constant Head	26	145	-1,19
Storage	**1,627**	**963**	**664**

The purpose of this sub-model was to examine the Rakh Branch from its starting point along its south-westerly course to the end of the Rakh Branch. The head contours for layers 1 and 2 in Figure 7.4 show a south-westerly flow direction. Drawdown for the Rakh Branch sub-model show some interesting differences between layer 1 and 2. Pumping hotspots are shown by areas which are dark red, maximum drawdown over 5 m shown in Figure 7.5. In layer 2 the drawdowns are negative indicating that water levels have risen over most of the area.

Figure 7.4 Head Contours for layers 1 and 2 in Oct 2013

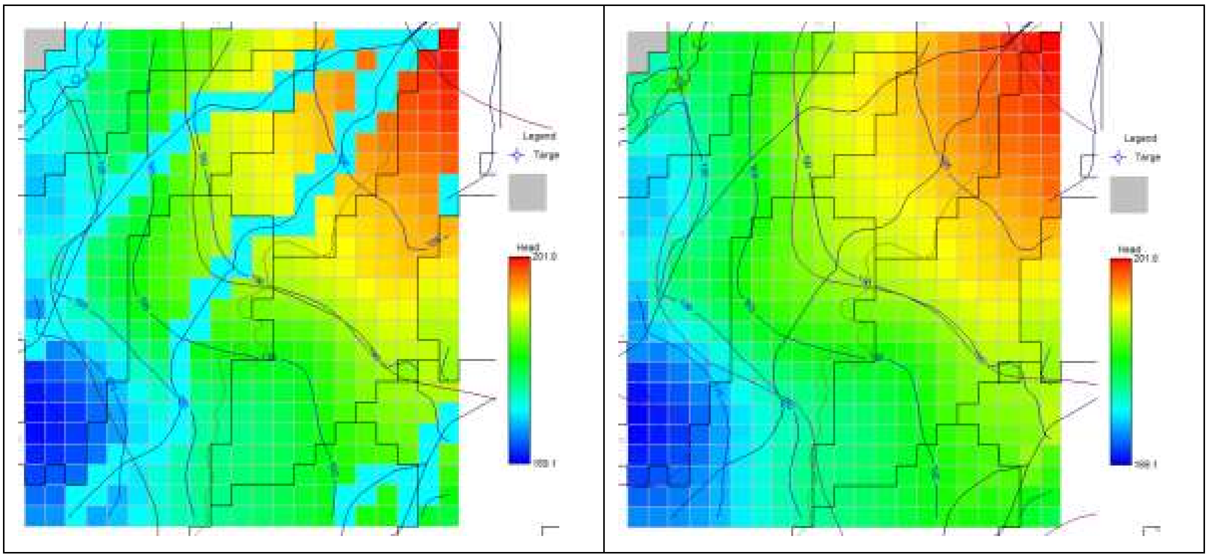
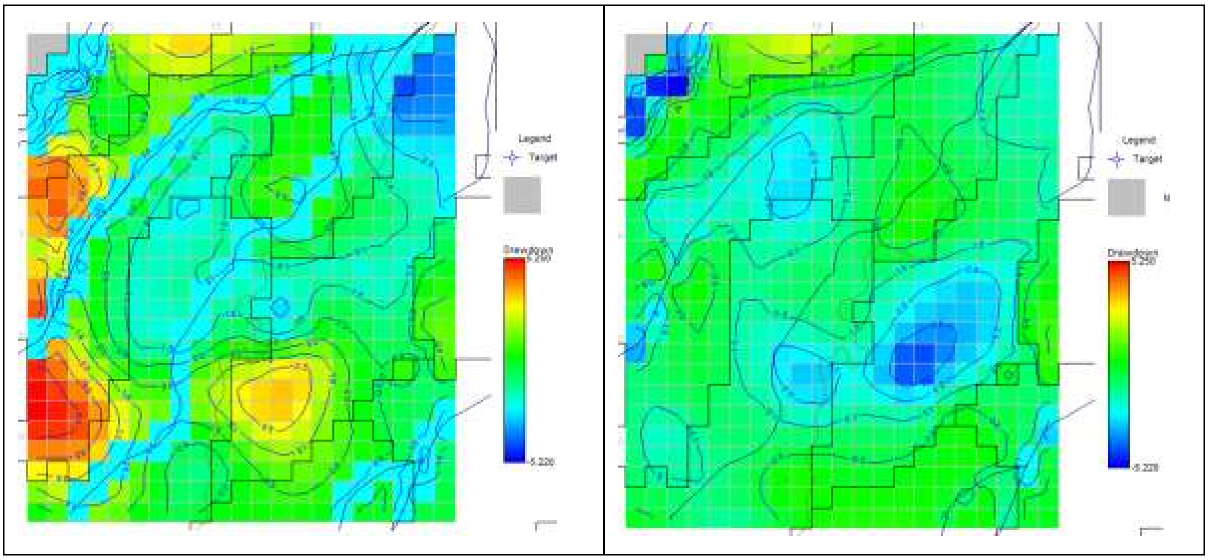


Figure 7.5 Drawdowns for layers 1 and 2 in Oct 2013



Simulated heads for selected piezometers in Layer 1 are shown in Figure 7.6. Rising, stable and falling trends are shown. The rapid drop in some of the piezometers during the start of the simulation as shown in LCE182 needs further investigation. Pumping intensity in the vicinity of large drawdowns needs to be evaluated. For instance WASA wells are not incorporated in this study and if significant pumping is occurring from WASA wells these need to be incorporated.

Simulated heads for selected piezometers in Layer 2 are shown in Figure 7.7. The trends generally are either stable or rising, which is also in general agreement with measured values. A shift from manual measurements taken biannually to the use of automatic loggers would improve accuracy, reduce errors in recorded measurements, and more importantly allow the groundwater managers to improve their understanding of water level trends in the region.

Figure 7.6: Simulated heads (mMSL) for piezometers in Layer 1

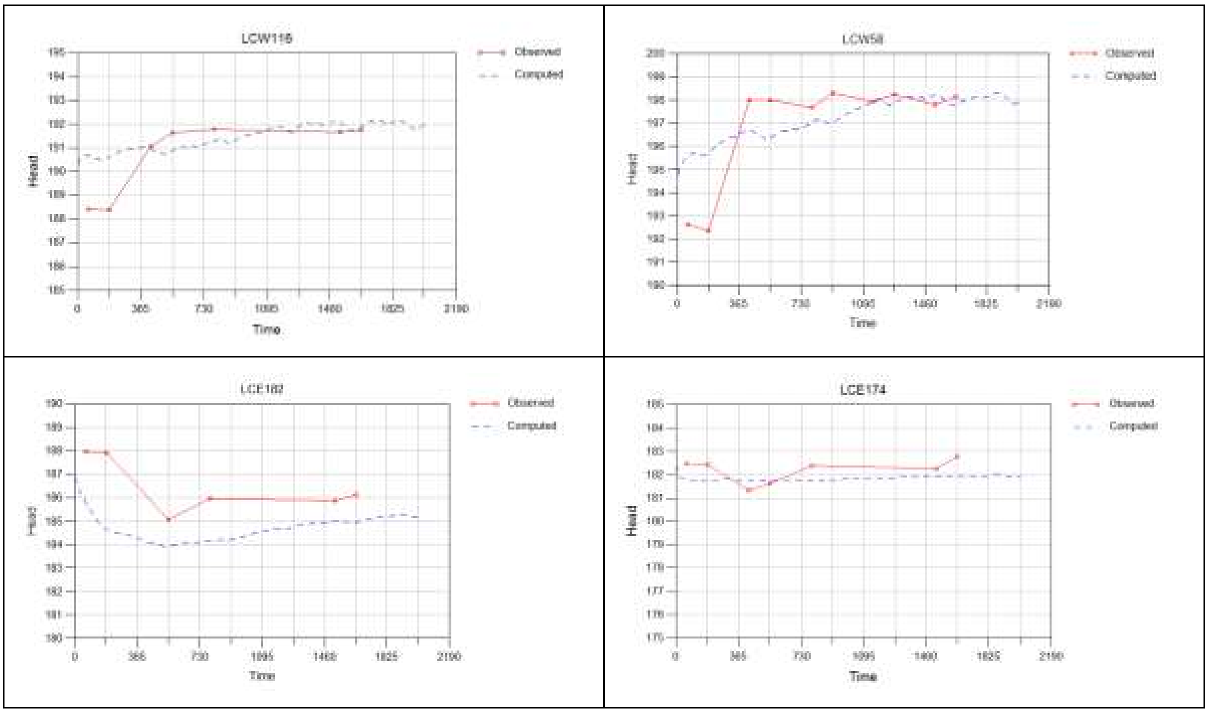
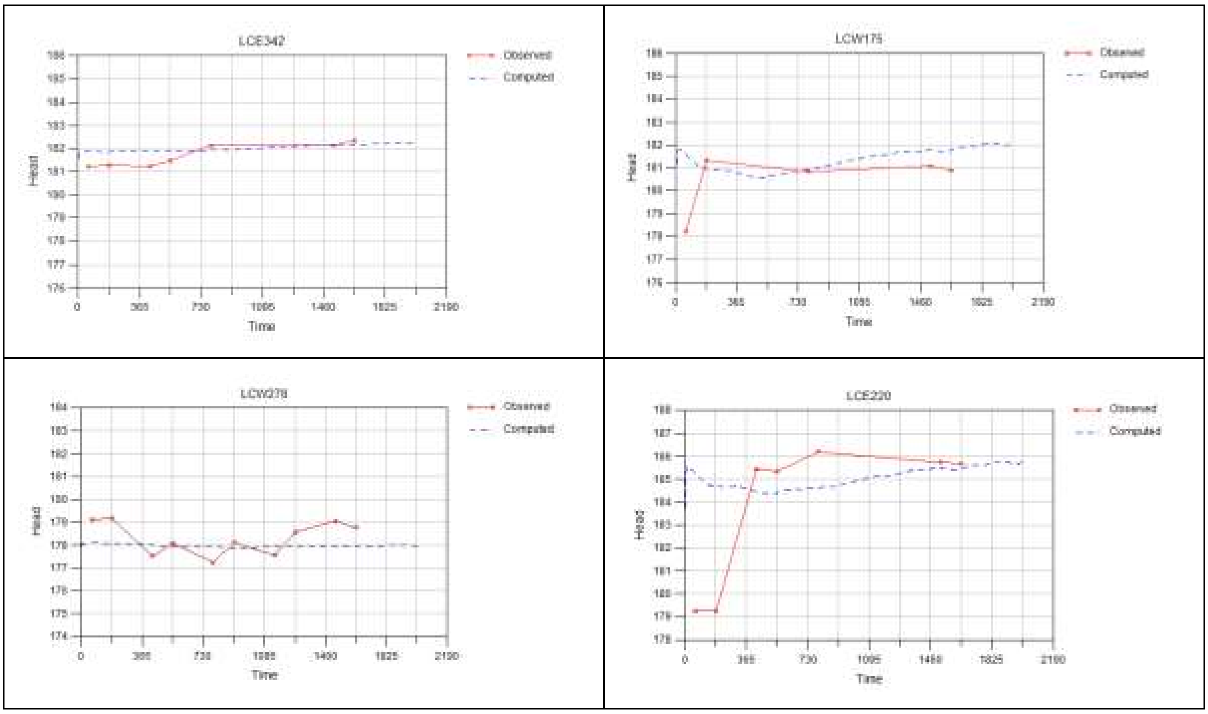


Figure 7.7: Simulated heads (mMSL) for piezometers in Layer 2



Simulated salinity concentratons for layer 1 and 2 are shown in Figure 7.8. Freshwater zones along the Chenab river, Jhang Branch and Rakh Branch canals are prominent In layer 1. There is a small zone of high salinity along the middle reach of Rakh Branch and on the right bank. Generally salinities are low in layer1. In layer 2 freshwater zones are prominent along the Chenab and along Jhang Branch only. The area along Rakh branch and also to the southeast shows higher salinity concentrations. High salinity zones are shown clearly and including elevated salinities in layer 2 at the tail end of Rakh Branch

Figure 7.8: Simulated salinity concentrations for layer 1 and 2 in Oct 2013

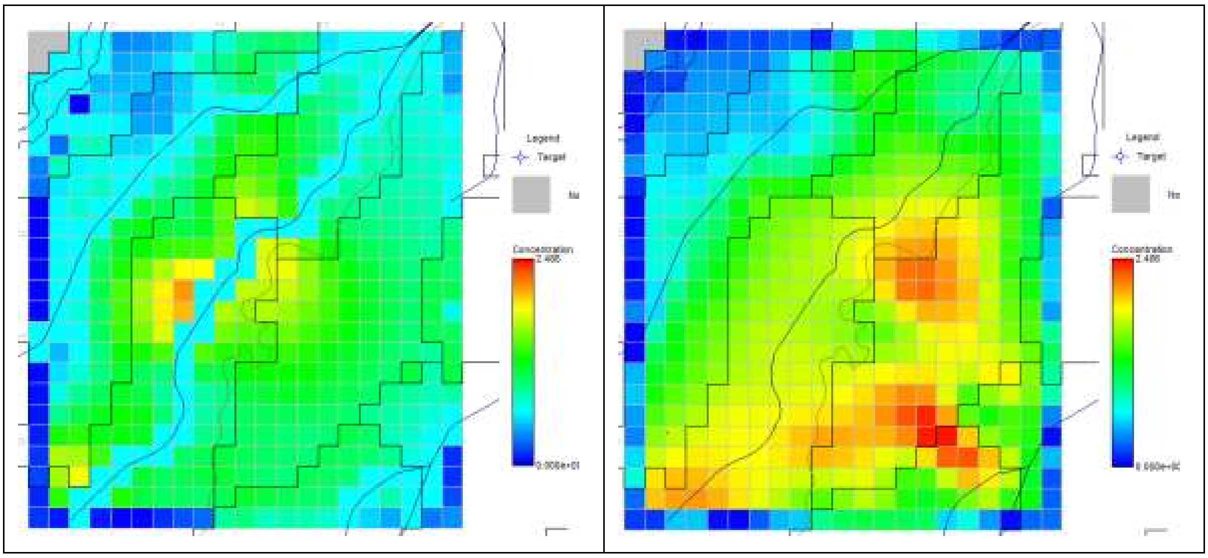
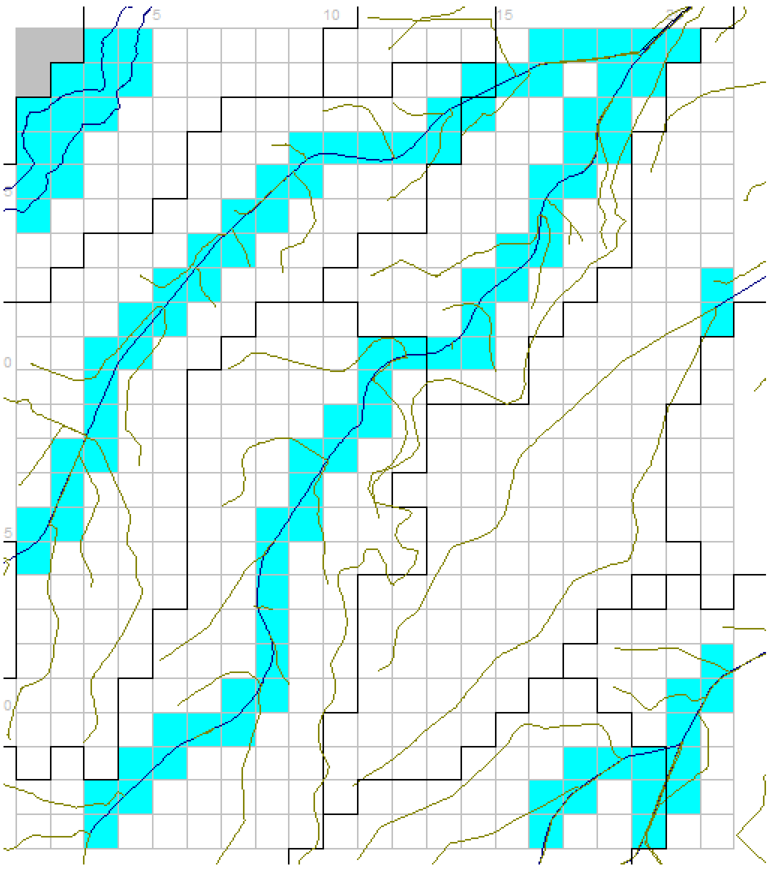


Figure 7.9: Rakh Branch sub-model showing distributaries



The Rakh Branch sub-model demonstrates how one can develop a TMR model to gain a better insight into a specific region of the larger regional model. However, this phase is only the first step. The basic premise for developing a TMR sub-model is to gain improved insight of system behaviour at a finer spatial scale with additional features such as modelling distributaries and minors. The Rakh Branch model showing distributaries at the regional scale is shown in Figure 7.9. The next step would be to enhance the present sub-model to work on a finer grid scale (eg. 400 or 500 m grid) and to add in the distributaries and important minors (sub-regional scale). This would entail refining the river package to include a network of main canals, branch canals, distributaries and minors. Similarly, pumping, recharge and evapotranspiration processes would need to be reassessed at the finer spatial scale.

TMR can also be used to develop a very detailed sub-model, for instance at 50 or 100 m grid scales. At that scale the modeller may need to include minors, sub-minors, water courses, essentially a farm scale model. Lastly, with a finer scale and detailed model the questions that need to be asked and the various scenarios that may be needed will also require careful consideration.

8 Framework for a Groundwater Status report

We recommend that the Punjab Irrigation Departments, Groundwater Division produce a Groundwater Status Report annually to apprise PID's management team on the status of groundwater in each doab. The framework for the groundwater status report is provided as a starting point for consideration. The report can be tailored to meet the needs of a particular region, the aim being to propose a framework for a Groundwater Status Report that needs to be provided to management annually to enhance planning and decision making within the Department.

8.1 Purpose

The purpose of this report is to:

- Provide stakeholders with a brief, factual statement of the status of groundwater conditions in Rechna Doab. Stakeholders include PID, PIDA, FO's and farmers and other government stakeholders.
- Response of water levels and salinity for key bores and pumping history and trends to understand impacts on the aquifer.
- Highlight the current level of key trigger parameters and compare them to the relevant trigger levels.
- Recommend action in relation to these trigger parameters.
- Current status of the aquifer and guidance for management of the aquifer.

8.2 Report Structure

8.2.1 Key Locations

A brief statement covering the area and key monitoring bores.

Several monitoring bores have been selected to be key representative locations. They have been selected to represent the various aspects of the dynamics of the groundwater regime and the quality of the water in the shallow and deeper regions of the aquifer.

The plots of water levels at these locations over the relevant time period shows how the aquifer is responding when subjected to various stresses, the most important of these being rainfall, evapotranspiration, local pumping for irrigation or municipal supply purposes and, in some cases, the storage history of nearby dams. Selected hydrographs which are useful for the reader to understand impacts on the aquifer should be shown here.

Depending on how many monitoring points are available, how big the status report ought to be, and what resources are available for its preparation, we would suggest selecting as follows:

i. downstream of each barrage, both sides of river (where appropriate)
    - close to the river,
    - midway between river and aquifer boundary,
    - part way along each weir pool, same pattern as above

ii. along main, branch and link canals and selected major distributaries

iii. near aquifer boundary (where inflows/outflows are expected)
iv. areas where water levels are declining, and control points
v. areas where salinity is increasing, and control points
vi. areas where cropping intensity, rice, sugarcane and other high water use crops are grown each season.

This is an ideal arrangement, and practical monitoring would require strategic decisions on where to monitor and how many monitoring points are affordable. The guidelines can be used when selecting which of the existing monitoring points should be included when compiling data for the status report. If there are obvious locations where monitoring data would add crucial information to the report, additional wells should be contemplated.

8.3 Climatic and Land Use Context

8.3.1 Climate

During the period covered by this report, figures of the important climatic factors (including rainfall and evapotranspiration tabulations) should be shown.

8.3.2 Land use

Changes in land use (or land management) during the past year should be detailed in the report including any changes to the pumping regime.

The report should include tabulations of pumping data, and any relevant information about the withdrawal of groundwater from the aquifer.

8.4 Current Status - Storage

8.4.1 Calculated volumes

The most objective parameter available for determining the current overall status of the groundwater storage is the volume of saturated alluvium. This value can be estimated by using the underlying bedrock surface and the number of water level measuring points available. A numerical model can be used to estimate the change in aquifer volume over time.

The groundwater status report would generally include a figure showing the time series for calculated volume of saturated alluvium extended to the reporting date. Additionally, the calculated volume of saturated alluvium is reported at particular times such as in the Rabi and Kharif seasons, and an explanation is provided to help understand the status of the aquifer.

8.4.2 Cross sections

For some regions or types of aquifers it is also useful to present a cross sections with a profile of the water table shown on each cross section, to help with visualization of the current status of the aquifer.

Key locations: Hydrographs from monitoring bores at key locations should be shown with appropriate discussion.

8.4.3 Trigger Points

Insert a discussion of which trigger points, if any, have approached or exceeded the trigger value, what the implications are, and what action is recommended. The discussion should also include how trigger points have been selected and communicated to farmers, groundwater users and rural households.

8.5 Current Status – Quality

Spatial distribution of key water quality parameters in particular EC, nitrate, and other water quality parameters (eg. Arsenic), should be shown as spatial graphs accrss the doab. If enough data are not available for contouring color-coded dots can be shown. Similarly time series data from the monitoring sites needs to be included to help understand changes to water quality parameters at specified locations in the aquifer.

For the report to be useful for decision and policy makers, the report should include a t a discussion of the current distribution of these parameters, with reference to any trigger points that have been established. For instance Pakistan water quality standards could be used to establish upper limits. An important aspect is to ensure a discussion is included in respect to water quality hot spots that have been monitored, and remedial/management action that needs to be undertaken should be recommended.

A comparison of current levels and distribution of these parameters to preceding data needs to be presented to demonstrate effectiveness of current management strategies. This should follow a discussion of programs and/or interventions that have been undertaken during the year, in the ongoing effort to minimize the impact of nitrogen on the groundwater quality.

In the future, strategic monitoring can provide better water quality information which can be used to develop a nutrient management plan and adoption of best practices may be highlighted. The important point here is to benchmark improvement in groundwater quality.

8.6 Conclusions and Recommendations

i. Assess changes to the volume of groundwater in storage within the Rechna Doab Aquifer – where has it increased or decreased since the previous Status Report.

ii. Is the variation within the expected range or not.

iii. Assess the operation of the aquifer: No change to operating procedures is recommended or groundwater withdrawal rates should be decreased by a specified percentage.

iv. Assess if trigger points have been breached. No volumetric trigger points have been exceeded, or the following volumetric trigger points have been approached/exceeded.

v. Recommend action to be implemented as recommended in the Groundwater Management Plan for implementation if a trigger level is breached should be implemented as follows:

vi. Recommendations following assessment of the pattern and occurrence of salinity and other water quality parameters such as nitrates and arsenic in the Rechna Doab aquifer.

vii. Recommended actions in accordance with the Groundwater Management Plan.

viii. The next annual Status Report should be prepared as provided for in the Groundwater Management Plan.

9 Socioeconomic scenarios

For the purpose of scenario analysis of groundwater management and subsequent socioeconomic analysis, a sample of farm household data collected during the period 2009-2012 were used. The survey questions included close-ended and open-ended questions. When collecting data, pre-testing should be done to verify the reliability of the collected data for its representation of the population. The scenario analysis also implemented for distributary and locational differences within distributaries by using qualitative (locational dummy) variables in the models following Culas et al. (2015). The analysis are based on cross-sectional data, and the trainees were taught about the statistical characters of the data used and also running the models with SPSS programme. An explanations for the descriptive statistics of the sample data analysed and interpretations of the models were given to the trainees. The following aspects were covered during the training:

i. Crop productivity (yield) analysis in relation to agricultural inputs, designing water use scenarios and setting up variables for salinity impact on crop yield.

ii. Modelling the optimal water use scenarios for distributaries in the canal and for head, middle and tail locations within each distributaries.

iii. Impact of water user allocations (redistribution of water) on crop yields and estimating the famers' income (gross margins) and deciding the optimal water use scenario.

iv. Discrete choice models for analysing groundwater management options available to famers, and based on their socioeconomic characters, water saving technologies and institutional variables, analysing the farmers' adaptation options for water reallocation.

v. Theoretical perspectives on the private and social costs of groundwater use, subsidizing water prices (by direct measures or indirectly through subsidized energy process), water policy and governance issues pertinent to Pakistan.

9.1 Scenario analysis using socioeconomic models for Rechna Doab

As one of the objective of the SRA was to carry out an additional scenario for water use,

the socioeconomic analysis has undertaken to estimate the technical, allocative and economic efficiency for the study area with respect to the crops produced.

Efficiency of resource use under different scenario gives us an idea, how farmers are using the scarce resources in different settings. These analysis sometimes are carried out to measure the relative technical, allocative (price) and economic efficiency of the decision making units (DMUs), in our case farmers carrying out farming practices under different set of conditions. Technical efficiency (TE) relates to producing maximum quantity of output from a given set of inputs whereas allocative efficiency (AE) is the ability to use inputs in optimal proportions given their respective prices and production technology (Coelli et al., 2005). In order to find the economic efficiency (EE) from those of technical and allocative efficiency, a knowledge of production frontier is necessary which can indicate the maximum outputs given the set of inputs and the production technology.

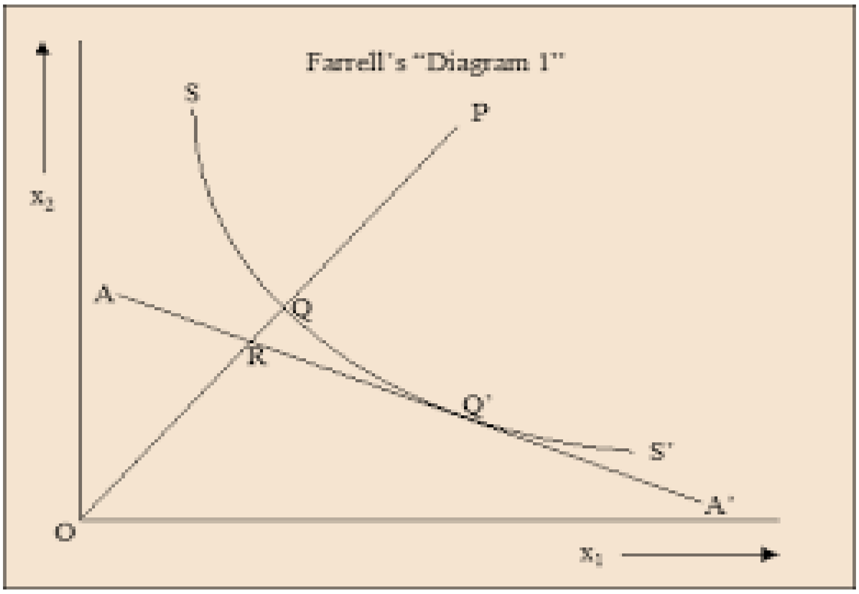


Figure 9.1: Technical, allocative and economic efficiency (adopted from Farrell, 1957)

Following Farrell (1957) we can demonstrate efficiency measurement using the input oriented approach with two inputs (*X1* and *X2*) to produce an output (Q) as shown in the Figure 1. Farrell (1957) was concerned with relative efficiency: the measurement of the difference between efficient and inefficient points. *SS'* is an isoquant representing combinations of inputs X1 and X2 with 100 percent technical efficiency. *AA'* is a market price line whose slope is the ratio of the market prices of the inputs. Production of quantity, *q*, of the output at *Q'* (where *AA'* is tangent to *SS'*) is both technically efficient and allocative efficient. *Q'* represents the combination of the inputs which results in the production of quantity, *q*, at the lowest cost.

A producer operating at *P* is both technically inefficient and allocative inefficient at the market prices implicit in *AA'*. *P* can improve its technical efficiency by reducing its usage of either or both of the inputs. Assuming proportionate reductions in each input, *P* would operate technically efficiently at *Q*. However to be as cost efficient as *Q'* at the market prices implied by *AA'* would require *P* to be operating at *R* if it were possible for *P* to further proportionately reduce its use of the inputs.

Alternatively, *P*, operating at *Q* would be allocative efficient if *AA'* were tangent to *SS'* at *Q*. If a producer on *SS'* is allowed to select its own "market prices" such that *AA'* is tangent to *SS'* where the producer sits on *SS'* then the producer will be both 100 percent technically and 100 percent allocative efficient. In other words, if a producer is allowed to choose its own market prices and it can achieve 100 percent allocative efficiency at those prices, then it is 100 percent technically efficient.

Farrell takes the ratio *OR*/*OQ* as the measure of AE of *P* and *OQ*/*OP* as the measure of TE of *P*. The overall efficiency EE of *P* is the AE*TE = *OR*/*OQ* * *OQ*/*OP* = *OR*/*OP*. Both TE and AE are known as "radial" measures since they are derived from the ratio of the lengths of radii – lines from the geometric origin. Reduction from *P*'s usage to *Q*'s usage involves reductions in X1 and X2 proportional to their actual usage, since *PQO* is a straight line. This quality is known as "equi-proportional reduction".

Actual examples of the production of output Q from inputs X1 and X2 can be plotted as a series of points, rather than a continuous curve. Drawing a set of lines between a subset of the points, such that no point was closer to the origin than the lines, would give an estimation of *SS'*. Inefficient producers can then derive an estimated technical efficiency score by reference to the estimate of *SS'*. Farrell addressed a single-output/dual-input case.

An assumption in this approach is that a single output is produced from the two inputs under constant returns to scale (CRS) and with a prior knowledge of an efficient production function.

From the above theoretical illustration, and for our purposes of running an additional scenario of input use in irrigated agriculture, we define the technical efficiency of an observed farm as the ratio of the distance from the point Q to the origin over the distance of the point P from the origin.

TE = OQ/OP

The distance QP represents the technical inefficiency of the observed farm, which is the

amount by which all inputs could be proportionally reduced without reduction in output. The value of TE lies between 0 and 1. A farm is technically efficient if it has TE equal to 1. If the value of TE is less than 1, the farm is technically inefficient. If input prices are given, the allocative efficiency can be calculated. A line AA' is drawn tangent to the isoquant SS' at the point Q'. The line AA' represents an isocost line showing all possible quantities of the two inputs, given their relative market prices that would cost the same amount to the farm.

Slope of the isocost line represents the input price ratio. For output quantity produced at point Q, the best use of inputs is at point Q' because it represents the minimum cost. The allocative efficiency of the firm is defined as:

AE = OR/OQ

At point Q' a farm is both technically and allocatively efficient. Distance RQ represents the reduction in production cost that would occur if production were to occur at allocatively and technically efficient point Q', instead of at technically efficient but allocatively inefficient point Q. Value of allocative efficiency lies between 0 and 1. A value of 1 indicates that the farm is allocatively fully efficient while value less than 1 indicates that the farm is allocatively inefficient.

The economic efficiency of the farm can be defined as the product of technical and allocative efficiency as noted above, i.e.:

EE = TE X AE
EE = OQ/OP X OR/OQ
EE = OR/OP

This implies that the value of economic efficiency is bounded between 0 and 1, where a value of 1 indicates that the farm is economically fully efficient while any value less than 1 indicates that the farm is economically inefficient.

The project study area is in the Punjab Province and is located in the Lower Chenab Canal (LCC) Irrigation System within the Rechna Doab. The Doab has a gross area of 2.98 Mha and about 77% of the area is under cultivation. Three distributaries (one each in head, middle, and tail reach) of the LCC East area have been chosen for our project (Culas et al. 2015). Based on the above criteria, Bhalak, Tarkhani, and Khikhi distributaries have been selected at the head, middle, and tail reach of the LCC East system, respectively. A multistage stratified random sampling method was used to select a sample of watercourses, and farmers within the study area. The sample included 2 watercourses in the head, middle, and tail sections of each of the 3 distributaries covering both the left and right side, giving a total of 18 watercourses.

Data Envelopment Analysis (DEA) was used to analyze the technical, allocative and economic efficiency of Wheat, Cotton and Sugarcane in the study area. Mathematical programming techniques were incorporated in this technique. Specially, a technique of linear programming that uses data on factors (inputs) and products was integrated to build a best practice production frontier upon the data points. The efficiency of each farm is measured by the distance between the observed data points and the frontier. Within the sample, farms on the frontier are the most efficient, while the remaining farms lying below the frontier are inefficient. Their inefficiency increases with the increase in distance from the production frontier.

The total technical efficiency was estimated by an input oriented constant returns to scale DEA model, following Coelli, et al. (2002). For the analysis of allocative efficiency, the procedure described by Haji (2006) and Javeed (2009) was adopted. The standard procedure for the estimation of economic efficiency is first solving the cost minimization problem by DEA and then defining the economic efficiency as the ratio of minimum cost to the observed cost. While allocative Efficiency was obtained by dividing economic efficiency with technical efficiency.

Allocative Efficiency = Economic Efficiency/Technical Efficiency

$$AE = EE/TE$$

Results showed that technical efficiency was higher in salinity hit Khikhi distributary area (0.88) which revealed that farmers were using resources more efficiently as compared to the other two distributaries i.e. Tarkhani (0.69) and Bhalak (0.80). If we compare the allocative efficiency of farmers (involving prices of the resources), Tarkhani distributary was leading with maximum (0.74). As far as economic efficiency was concerned, Khikhi distributary was at the top with an economic efficiency of 0.66 as compared to Tarkhani (0.52) and Bhallak (0.55).

Although, Khikhi distributary is at the tail end facing acute shortage of surface water and suffering from salinity, but high economic efficiency illustrates that the tail ender are using water efficiently. If Khikhi distributary is provided better quality water through already worked out redistribution scenarios, or by investing in infrastructure rehabilitation and institutional mechanism, this will improve their productivity and economic returns among various farmers with improvement in water use efficiency.

10 Field Visits by PID and project team

The field visits were effective in informing the trainees about the actual field level problems in relation to the socioeconomic issues that drives groundwater management problems. Meeting with farmers helped trainees to understand issues from farmers perspective.

10.1 Field Visit to Jhang Branch by PID staff and engagement with farmer organisation

Two workshops were conducted by PID with FO's and Farmers in two distributaries in Rechna Doab. The theme for the workshops were "Awareness Raising and Capacity Building for FO's/Farmers Regarding Groundwater Issues and Management in Punjab". The first workshop was held at Kamalia Distributary on 28 Nov 2015 and the second workshop was held at Khikhi distributary on 20 Feb 2016.

The purpose of both workshops was to create awareness, understanding and capacity building/training among stakeholders regarding groundwater issues in the area and to disseminate the findings of research studies including the ACIAR project on Rechna Doab at the grass roots level. During the workshop brochures were disseminated to farmers on the groundwater situation. A survey was also undertaken with the farmers and drillers.

At Kamalia distributary, about 100 farmers were present as well as Farmers Organisations (FO's) from Kamalia, Waghi, Pir Mahal, Tarkhani and Kabirwala distributaries. Also represented were Agricultural Extension Department, On-Farm Water Management, Livestock Department, WWF-Pakistan, Doaba Foundation and Drillers. Presentation were made by Mr Ghulam Zakir Hassan Sial, Director IRI-PID, and Dr Muhammad Javed, Director SEMU-PID, on groundwater and salinity issues facing farmers in the region. Dr Muhammad Riaz, Director PMIU-PID, presented information on the Rechna Doab project funded by ACIAR which was undertaken jointly with UAAR and CSU. Presenters from PIDA Mr Muhammad Afzal Toor, Deputy General Manager, and Ms Deeba Shaheen, Campaign Coordinator, Indus Consortium covered the issue of canal water theft from the head and middle reaches, which is adversely affecting water for tailenders forcing them to use more groundwater despite the additional costs and the use of water of poor quality. The farmers were explained that if they wanted to save groundwater, theft of water from the upper reaches needs to stop so that tailenders get their fair share of water. Presentations were also made by Mr Javed Iqbal, Manager Doaba Foundation, and Mr Muhammad Irfan, WWF-Pakistan on the issue of groundwater pollution and water quality.

A similar workshop was held at Khikhi distributary which was attended by over 100 farmers, other participants and Farmer Organisations from Khikhi, Dubanwala, Pir Mahal, Bhun, and Yakkar distributaries. Also represented were On-Farm Water Management, University of Agriculture Faisalabad, WWF-Pakistan, Indus Consortium, and Kissan Baithik. Presentations were made by Mr Ghulam Zakir Hassan Sial, Director IRI-PID, on groundwater and salinity issues facing farmers in the region. Mr Mansoor Ahmed, Assistant Director Monitoring, addressed farmers about canal water monitoring and procedures in place for registration of complaints regarding water theft and shortage of water at tail end of canals. The presentation also covered the ACIAR funded project n Rechna Doab. The problems of groundwater quality were addressed by Mr Mushtaq Gill, Ex-DG OFWM/SACAN, Mr Zulfiqar Ali, Manager (IS) LCC East, PIDA, and Mr Muhammad Irfan WWF-Pakistan. Presentations were also made by Mr Faqeer Muhammad, FO-President Khikhi distributary and Mr Iftekhar Hussain FO-Member on steps the FO were taking to control water theft and recover Abiana. They also indicated that although costly and of poor quality farmers have no option but to pump groundwater.

Mr Haroon Rashid, Secretary FO-Khikhi distributary stated that uncontrolled and unplanned pumping of groundwater from tubewells is a major issue which is deteriorating water quality.

The common issues identified included: (i) lack of communication amongst farmers, researchers and Government Departments; (ii) lack of regulation on groundwater; (iii) groundwater users lack ownership; (iv) surface water shortage and distribution, (v) excessive pumping from fresh groundwater areas; (vi) lack of awareness and education amongst farmers and policy makers; (vii) increased cost of installation due to excessive drawdown; (viiii) gaps in groundwater data collection and management; and groundwater quality deterioration due to mixing of saline and fresh water.

10.2 Field visit to Pabberwala Distributary and engagement with farming community

10.2.1 Workshop at Newan Rest House, Jhang Branch, LCC (WEST), Faisalabad 23.04.2016

A workshop was organized by the Irrigation Department under ACIAR project at Newan Rest House, Faisalabad on 23 April 2016. The objective of the workshop is to create awareness among farmers about groundwater issues, its socio-economic effect and management options for groundwater.

In the workshop, international experts, officers from Irrigation Department, Irrigation Research Institute, PIDA, FOs members and farmers of the Pabberwala distributary participated in the workshop.

- Mr.Saeed Ahmad from PIDA welcomed the participants.
- Workshop started with the recitation of Holy Quran. Mr. Muhammad Ijaz
- Mr. Ghulam Zakir Hassan, Director IRI explained to the farmers that purpose of the international experts and Irrigation officers from PID was to listen and understand socio-economic problems, water issues especially groundwater issues and possible options for management.
- Dr. Jay Punthakey from Australia said thanks to the participants especially farmers community to attend the meeting although farmers are busy in harvesting of wheat crops.

Members of FO and farmers of the Pabberwala distributary were asked to share their problems about groundwater.

- Farmers explained that 40% of crop water requirement is met from groundwater while 60% from canal water.
- Groundwater is sweet and its quality is fit for irrigation.
- Muhammad Nawaz from Chak No 134 said that canal water is insufficient to meet their crop water requirement. Therefore tubewell was installed and groundwater is pumped to meet water requirement.
- Muhammd Liaqat Loona, chak 134, said that WASA, Faisalabad installed 25 tubewell of capacity 4 cfs in their area at Dolatpur 1992. These tubewell supply water to Faisalabad city. These tubewell works about 15-17hour a day. Before installation of WASA Well field, groundwater level of the area is about 3 to 10 feet with some areas exhibiting water logged conditions. But now water level of the area has reached 50 to 60 feet and further decreasing.

- Due to heavy rainfall and flood 2014 in River Chenab, water level of the area was raised about 4 to 6 feet.
- M. Nawaz Chak No 136 said that land is not properly levelled. Therefore water losses occur. If laser levelling is provided to the farmers, water efficiency will be increased and about 30 % water can be save.
- Ghulam Murtaza chak No 136 said that due to WASA well field, installation and operation cost of the tubewell has increased. The installation cost has increased from Rs.15,000 to 200,000 from 1990 to 2015 and it was due to the operation of WASA well field which lowered the groundwater. No compensation to the farmers from WASA. Their input cost on crop has increased due to decline of groundwater levels.
- M. Ali from chak No. 134 said that due to water level decline, the tubewell pump is placed at the depth of 40 feet by digging the well. Because by placing the motor and pump on the land surface water cannot be pumped. Digging of well upto 40 to 50 depth is very difficult task for farmers.
- M.Aslam Executive Engineer, Irrigation Department informed that canal water is supply based, not demand based. Water allowances for Pabbarwala distributary is 2.7 cfs. Length of the distributary is 6.4 km and has 22 mogas. The design discharge of the distributary is 22 cfs. The canal command area is 9438 acres.

Pabbarwala Distributary	
FID	1193
IMIS_CODE	30810040020000000
DIVISION	Faisalabad
PARENT_CH	Jhang Branch Upper
REMARKS	
ZONE_	Faisalabad
CIRCLE	LCC West
NAME	Pabbarwala Disty
TYPE_	D
GCA	11167
CCA	6888
DESIGNED_D	21
TAIL_RD	27960
A_TAIL_G	1
A_TAIL_D	4.31
FLOW_TYPE_	P
SHAPE_LENG	8555.954112

- Cost per acre to irrigate from canal and groundwater:
- From canal per acre cost for khari season is about 90 rupees and for rabi about Rs 51. This is the Abiana which is paid for irrigation water.
- For groundwater, cost per acre is about 3000-4000 pending the fuel prices. Irrigation with canal water is cheaper, while irrigation through groundwater is very costly.
- Dr. Ashfaq, Assistant Land Reclamation Officer, DLR, Irrigation Department said that groundwater quality of canal command area Pabberwala is fit for Irrigation.

Groundwater level at head of the distributary is 25 ft while at tail groundwater level is 42 ft. WASA wells are along the middle of the distributary. However, farmers indicated that water levels had declined more than this.

- Input cost for 1 acre wheat crop
  - ✓ Rent for tenet farmers Rs. 30,000 to 40,000 (Pak Rupees)
  - ✓ Ploughing for land preparation = Rs.1,000-1,200 per acre in case of farmer's own tractor
  - ✓ Ploughing for land preparation by renting a tractor is Rs.3,000-4,000 per acre
  - ✓ Wheat Seed purchased = Rs.2,700 for 50 kg
  - ✓ Fertilizers two bag DAP and one Urea

    Two bags DAP = Rs.7,000-8,000

    One bag Urea = Rs.1,900
- Farmers indicated that Potash fertilizer is applied to land which is irrigated by groundwater. No potash is applied when irrigated with canal water
  - ✓ Spray of pesticides and herbicides= Rs.1,200-1,500
  - ✓ Irrigation water by canal = Rs.100
  - ✓ Irrigation water by groundwater= Rs.3,500-5,000 depending on fuel price
  - ✓ Harvesting by harvester = Rs.2,500 but no wheat husk available
  - ✓ Cutting by manual labour = Rs.2,500
  - ✓ Farmers wages/pay for crop season per acre= minimum Rs.5,000
  - ✓ **Output/Production per acre**= 1600-1800 kg = Rs.52,000-58,000.

Dr. Irfan, PMAS UAAR, Rawalpindi asked the question to the farmers about the impact of lining on groundwater. He said that due to lining groundwater level will decrease due to which pumpage cost will further increase.

Dr. M. Javed, PID said that without lining water losses occur and same water is exploited with tubewell. Moreover sweet water from seepage mix with saline water which results in negative impact. Therefore lining of water channel is a good step for water management.

10.2.2 Monitoring demonstration at Pabberwala distributary.

The team from CSU, PID, PMIU, and UAF visited the Pabberwala distributary and measured discharge on site with current meter as a demonstration for farmers. The team from PID Irrigation Research Institute demonstrated on site monitoring of the surface water quality and measuring of groundwater levels from the piezometer with water level reel logger.

10.2.3 Farmer recommendations

Recommendations were proposed by farmers follows:

1. Provision/supply laser levelling services to farm communities.
2. Compensation to the farmers by WASA, Faisalabad
3. Shifting/new WASA well field near bank of River Chenab because old WASA well field has completed life.
4. Reduce the pumpage by WASA tubewell by closing some tubewells or reducing operation hours.
5. Drawdown of groundwater should be fixed for sustainable pumpage
6. Licensing system/certificate for driller and owner should be introduced. No tubwells will be installed without license from Irrigation Department but licensing system should be easy and free of cost

7. Only certified drillers can install the tubewell with prior permission from authority.
8. Lining of Pabberwala distributary and water courses.
9. Public awareness regarding water management techniques and provision of water saving technologies.

There is a need for PID and researchers engaged in water management for greater access to farmers and field sites to understand issues that farmers face. There is also a knowledge gap that researchers can fill by providing outcomes of research to farmer groups particularly targeting issues that are of immediate concern to farming communities. There are always risks when taking research results to farmers, however, this is essential if research results are to be targeted and improved to solve problems in the field.

11 Training Photos

Photos of training sessions, meeting with farmers, and field demonstrations for farmers.

12 Conclusions and recommendations

12.1 Conclusions

12.1.1 Groundwater model for Rechna Doab and scenarios

1. A regional groundwater and solute transport model for Rechna Doab in Punjab Pakistan was developed for PID. The model is a significant enhancement over previous models carried out in Pakistan which were based on seasonal time steps covering Kharif and Rabi seasons. The Rechna Doab model was developed at monthly time steps which offer PID an opportunity to better understand the temporal and spatial surface water and groundwater dynamics. Moreover, the regional model also provides opportunity to create sub-models at a finer spatial scale for detailed studies of canal and groundwater interaction. Examples of these are the LCC East and Rakh Branch sub-models.
2. The SRA was designed to provide training to PID staff to improve knowledge of how the Rechna Doab model was developed, construction of the conceptual model, usefulness of monitoring data for model calibration and verification, water balance analysis and scenario analysis. The training also covered introduction to MODFLOW and MT3D and various example models to help trainees understand how models can be applied to evaluate demands on the groundwater resources. This was followed by training on constructing a sub-model of LCC East and Rakh Branch from the main Rechna Doab model.
3. The trend in Rechna Doab has been an increasing trend in groundwater pumping with over 200,000 tubewells currently using groundwater. This brings into question the resilience of the system particularly as the trend over the past three decades shows a continuous increase in groundwater extractions and an increase in the number of tubewell. It is therefore prudent to understand the limitations of the current system as pumping rates increase. The increased pumping scenarios indicated that if groundwater usage was increased to 12,206 MCM/yr then the net storage term decreased from 2,781 MCM/yr for the no-plan scenario to 330 MCM/yr. And when pumping was increased by 30% to $13,100\times10^6 m^3$/yr, the net storage term decreased to -393 MCM/yr, which indicates extraction rates have exceeded the replenishment rate from rainfall, irrigation and seepage losses. Increased pumping by 30% will result in a deficit and if surface water deliveries were to decrease or if there is a prolonged dry period resulting in decreased rainfall the decline in storage would result in the lower reaches of the doab suffering rapidly declining water levels and associated salinity impacts.
4. Additionally two drought scenarios are also tested, one with two successive medium term droughts of 3 years, and one long duration drought lasting 10 years similar to the millennium drought experienced in Australia. The 2x3 years drought scenario indicates that the net storage term decreased from 2,781 MCM/yr to 685 MCM/yr. The net storage remains positive even as surface water supplies are decreased by 10 percent and pumping increased by 30% during the two drought periods each extending for 3 years. However, tail enders are likely to experience greater water stress as they will be affected by both lower surface water deliveries and increased risk of salinity as tail enders will make up the shortfall by pumping greater volumes of groundwater which is likely to be of higher salinity. Additionally, decline in storage for the tail enders and for those in the lower mid portions of the doab would result in particular areas suffering rapidly declining water levels and associated salinity impacts as salinities are generally higher at the tail end and in the lower mid-section of the doab.

5. The ten year drought scenario indicates that groundwater usage increased to 11,794 MCM/yr to allow for increased pumping during the 10 years of drought. The net storage term decreased to -197 MCM/yr, which indicates that increased pumping to compensate for the drought will result in depletion of storage. Increased pumping by 30% during the ten year drought period would need to be managed carefully as the pumping is likely to exceed the recommended sustainable yield limit, and the risk of salinity impacts are higher.
6. Overall salinity trends in the top two layers are either stable or decreasing slightly in some bores, suggesting that for the tubewells selected the salinity concentrations are not increasing. Another reason why salinities may not be rising despite increased pumping is due to seepage of freshwater from canals and irrigation recharge in layer 1, as the layers are highly connected there is fresh water from layer 1 being drawn into layer 2.
7. Reduced surface supplies coupled with reduced rainfall recharge during the drought year's results in decreased total inflows which will impact on increased levels of salinity in the Rechna Doab. In particular, tail enders are likely to experience greater water stress as they will be affected by both lower surface water deliveries and increased risk of salinity as tail enders will tend to make up the shortfall by pumping greater volumes of groundwater which is likely to be of higher salinity. Additionally, decline in storage for the tail enders and for those in the lower mid portions of the doab would result in particular areas suffering rapidly declining water levels and increased salinity impacts as upward gradients from the lower layers will mobilize higher salinity groundwater. Where salinities in the deepest layer are high the vertical transport of salts is enhanced. A combination of increased pumping rates and high underlying salinity increases the risk of salinity concentrations increasing as shown by tubewells s182 and s627. The areas most at risk are portions of the mid and lower doabs in the district of Bhagat, Aminpur, Tandlianwala and Tarkhani with underlying salinities increasing rapidly with depth.
8. Moreover, given the data uncertainties and unknowns (e.g. Groundwater usage from 200,000 tubewells; and the relatively short period for calibration of 6 years) it would be prudent to manage pumping within the guidance provided for sustainable yield, at least until this estimate is revised in the future when the model is extended and improved.

12.1.2 Rakh Branch sub-model

9. A sub-model for the Rakh Branch was undertaken to gain a better insight into a specific region of the larger regional model. The basic premise for developing a detailed sub-model is to gain improved insight of system behaviour at a finer spatial scale with additional features such as modelling distributaries and minors. In this study the first step was taken to build capacity of participants in developing sub-regional models to gain a better insight for managing groundwater.
10. The Rakh Branch sub-model indicated drawdowns in layer 1 were in excess of 5 m, whereas in layer 2 water levels are either stable or show rising trends which is also in general agreement with measured values. This is interesting as the Rakh Branch is lined which means seepage losses are much lower which may be resulting in increased drawdowns in layer 1. Pumping intensity in the vicinity of large drawdowns needs to be evaluated. For instance WASA wells are not incorporated in this study and if significant pumping is occurring from WASA wells these may be contributing to greater drawdowns in layer 1.
11. Freshwater zones along the Chenab river, Jhang Branch and Rakh Branch canals are prominent In layer 1. There is a small zone of high salinity along the middle reach of Rakh Branch and on the right bank. Generally salinities are low in layer1. In layer 2

freshwater zones are prominent along the Chenab and along Jhang Branch only. The area along Rakh branch and to the southeast shows higher salinity concentrations in layer 2 towards the tail end of Rakh Branch

12.1.3 GW Status report

12. A framework for a groundwater status report is provided so that PID groundwater management team can be provided with up to date information for planning and decision making on groundwater issues. The aim of the groundwater status report is to provide stakeholders with a brief, factual statement of the status of groundwater conditions in Rechna Doab. Stakeholders include PID, PIDA, FO's and farmers and other government stakeholders. The report can also be used to highlight the current status of water levels and salinity in the aquifer and to recommend a course of action. At present PID does not have a policy or regulatory framework for managing groundwater. However, the groundwater status report can provide a means for helping policy makers to make informed decisions and also strengthen institutional knowledge of groundwater conditions.

12.1.4 Remote Sensing and GIS

13. Remote sensing techniques for estimation of potential and actual evapotranspiration offer new approaches for improved spatial and temporal estimation or evapotranspiration. The use of improved spatial and temporal assessment of rainfall and evapotranspiration has greatly assisted in providing accurate inputs for the groundwater model
14. Remote sensing and GIS technologies were used to estimate spatial and temporal crop water requirements and provide input data for ground water modelling. Increasing demand for water resources combined with limited availability is a crucial problem that requires sustainable water resources management. Reference evapotranspiration was calculated using Penman Monteith method using meteorological data such temperature data, humidity data, wind speed data and sunshine hours. Calculated ET0 was then interpolated for unknown values. Hyper temporal Modis satellite data used for crop mapping and Geographical information system data bases are used to processing the remote sensing data. Validation was performed using ground data to validate above mentioned outputs as shown in the following figure.
15. Reference evapotranspiration was very high in Jhang and Toba Tek Singh (southern) region of Rechna doab during May and July as compared to Sargodha, Lahore and Jhelum regions of Rechna doab (northern part). ET0 is high in south west region of Rechna Doab. Effect of crop characteristics on crop water requirement is accounted by crop coefficient (Kc), which is used to relate ET0 value with a specific crop. Temporal distribution of crop coefficients was used to estimate ETA. Kc values are lowest during initial weeks of the growing season and are increased with crop stages, and decrease by 50 to 60% at the time of crop maturity. Kc and spatial distribution of ET were analysed for wheat, rice, maize, sugarcane and cotton for Rechna doab. Remote sensing and GIS have the potential for estimating crop areas, crop monitoring, and crop evapotranspiration with reasonably high accuracy which has been very useful in providing inputs for the groundwater model.
16. The tools provided in this project include:

    Multi-location ET0 calculator: This tool is used to estimate potential evapotranspiration for multiple locations and for multiple years as compared to the existing CROPWAT tool by FAO which provides potential evapotranspiration using meteorological parameters.

Crop Water Needs Assessment: A web based tool was developed and handed over to PID staff to estimate crop water requirements for any location in the Punjab.

12.1.5 Socioeconomics

17. The SRA activities provided training sessions on groundwater modelling, remote sensing and socioeconomics analysis of irrigation water use. The training sessions were provided in two occasions in Pakistan during August 2015 and April 2016. The objectives of the SRA training sessions on the socioeconomics analysis were designed to improve the capacity of PIDA staff and postgraduate students at UAF and UAAR.
18. The socioeconomic training sessions and the exercises utilised a set of sample data from a recently completed ACIAR project in Pakistan (LWR/2005/144). Training sessions included methodologies for designing and conducting farms surveys, setting up water use scenarios and modelling water redistribution to enhance crop yield and farmers' income. The training sessions provided opportunities for the participants to rethink of groundwater use and irrigation practices.
19. A socio-economic study was also undertaken for LCC East (Lower Chenab Canal Command). The results of the water user scenario analyses, resulting from econometric as well as hydrological modelling approaches, will assist PIDA and Farmer Organisations for implementing more equitable, economically efficient and improved water quality options in the study areas.
20. The socioeconomic activities also included an additional water use scenario analysis for evaluating the technical, allocative and economic efficiency of the famers in three distributaries. This analysis provided further evidence on how to redistribute water in relation to water use efficiency and the equity in water use between the distributaries.

12.2 Recommendations

11. The PID staff participating in groundwater modelling, remote sensing and GIS training were civil engineering or Physics with good knowledge of surface water and varying skills levels and understanding of groundwater modelling. Some had been exposed to simple groundwater models during their studies. We recommend that PID invest in continuing training and development of key professionals in order to build groundwater expertise within the Department.
12. The feedback from this training course by senior officers of PID was that the participants would benefit from additional training in using Modflow and setting up a simpler model to help mid-career professional's to improve knowledge and skills in model development and calibration. This would assist participants to better grasp the complexities of the Rechna Doab model and the LCC East TMR sub-model.
13. The current professionals need additional training in hydrogeology, flow modelling and solute transport modelling with responsibility for developing models for actual case study sites in order to gain confidence in modelling. The lack of software is hampering the development of groundwater modelling expertise within the Department. It is recommended that PID make the necessary investment in modelling software. Moreover, PID needs to ensure its personnel can use the model to continue learning and developing groundwater models.

14. The development of expertise in remote sensing, GIS based Analysis for Mapping Crop Areas and their Performance needs further training to fully develop these capabilities. The PID team was keen to learn the use of web enabled tools for estimation and mapping of potential and actual ET. This is an area where further development would be useful as it will also help in estimating ET for groundwater models that PID will eventually develop in-house.
15. Continuous monitoring of water level and salinity using loggers would improve understanding of the salinity dynamics. The monitoring strategy needs to be devised strategically as it is not possible to monitor every bore in Rechna Doab.
16. To improve salinity predictions improved data on salinity concentrations in the deeper parts of the doab is vital. A program of monitoring deeper parts of the doab should be instituted by PID so that a better understanding of pumping risk can be ascertained.
17. A shift from manual measurements taken biannually to the use of automatic loggers would improve accuracy, reduce errors in recorded measurements, and more importantly allow the groundwater managers to improve their understanding of water level trends in the region.
18. The calibration of the solute model needs to be revisited when additional data becomes available as a 4 year period for calibration with only 2 measurement points per year is inadequate for robust calibration. Our recommendation is for PID to extend the calibration of the model over at least a 10 year period and also institute strategic monitoring of water levels and salinity.
19. Boundary conditions along the Ravi River could be improved by analysing monitoring data in the adjacent Bari Doab where there is considerably more pumping occurring.
20. We further recommend that water balances based on selected zones be conducted by PID where declining groundwater levels are a concern to ascertain the vulnerability of each zone to groundwater level decline as well as salinity. This would allow PID to exercise more flexible management of the Rechna Doab taking into account local area conditions.
21. We recommend that PID enhance the Rakh Branch sub-model to work on a finer grid scale (eg. 400 or 500 m grid) and to add in the distributaries and important minors (sub-regional scale). This would entail refining the river package to include a network of main canals, branch canals, distributaries and minors. Similarly, pumping, recharge and evapotranspiration processes would need to be reassessed at the finer spatial scale.
22. The available data from climate simulations for scenarios to 2050 and 2100 should be used to determine future water needs in order to evaluate the impact of climate change on irrigation water supplies. As shown by the scenario modelling a confluence of lower surface water supplies, and increased groundwater pumping during drought situations would lead to unsustainable extraction from the groundwater system and increased salinity risk for smallholder farmers at the tail end and lower portions of the doab..
23. PID at present does not have the institutional structure or the regulatory framework to manage groundwater in Punjab. Nor does PID have the policy and regulatory framework to enforce the recommended sustainable yield. Community engagement is needed to ensure that there is improved understanding of cumulative groundwater pumping impacts on the resource and on the aquifer due to increased salinisation.
24. We recommend that the Punjab Irrigation Departments, Groundwater Division produce a Groundwater Status Report annually to apprise PID’s management team on the status of groundwater in each doab. The framework for the groundwater status report is provided as a starting point for consideration. The report can be tailored to meet the needs of a particular region, the aim being to propose a framework for a

Groundwater Status Report that needs to be provided to management annually to enhance planning and decision making within the Department.

25. Capacity of Punjab Irrigation Department in remote sensing & GIS capabilities needs to be enhanced so that timely information can be made available for management. A state of the art GIS lab is needed with fully trained staff capable to perform tasks such as, agricultural land use mapping, evapotranspiration mapping, and generation of data needed by the stakeholders. Efficient management of land and water resources in irrigated agriculture requires comprehensive knowledge on many variables including climate, soil, land use, crops, water availability, water distribution networks, management practices. Most of these data are spatially distributed and their integration and use in irrigation planning and management demands to enhance such capabilities.
26. It is recommended to increase the number of weather stations capable of providing all the meteorological parameters to calculate evapotranspiration which ultimately helps in estimating crop water needs and balance.
27. The tools developed during the present study (web based crop water needs and spatial ET0 calculator) should to be tested in field for further improvement and implementation. We recommend that PID make use of these tools for estimating irrigation water requirements and to contribute suggestions for improving and enhancing these tools to suit their requirements.
28. Enhance capacity of the PIDA staff and postgraduates at UAF and UAAR to develop practicable guidelines on the applicability and use of the econometric models at farm level.
29. Conduct awareness workshops among the farmers on the implications of their current water use patterns and the need for a redistribution of water use between the distributaries.
30. Enhance knowledge base of stakeholders on socioeconomic and institutional drivers, as well as agronomic and irrigation practices, which influence tubewell installation and extent of ground water extraction, in order to guide an integrated hydrological and econometric modelling approach for deciding optimal water use scenarios at farm and distributary level.
31. Assist the irrigation management institutions and farmer organisations in implementing policies and mechanisms for more equitable and economically efficient water supply options in the canal system.

13 References

13.1 References cited in report

Coelli, T., S. Rahman and C. Thirtle (2002). Technical, Allocative, Cost and Scale Efficiencies in Bangladesh Rice Cultivation: A Nonparametric Approach. *Journal of Agricultural Economics*, 53: 607-626.

Culas, R. J., Baig, I. A., Ahmad, R. N., Blackwell, J., Punthakey, J. F and M. Riaz (2015): Socioeconomic Impacts of Water User Allocations in Crop Production: The Lower Chenab Canal Irrigation System in Pakistan, Report to ACIAR (LWR/2005/144). p. 72.

Farrell, M. J (1957): The Measurement of Productive Efficiency, Journal of the Royal Statistical Society, Series A (120): 351-381.

Haji, J (2006). Production Efficiency of Smallholder's Vegetable Dominated Mixed Farming System in Eastern Ethiopia: A Nonparametric Approach. *Journal of African Economies*. 16:1-27.

Javed, M. I (2009). Efficiency Analysis of Cotton-Wheat and Rice-Wheat Systems in Punjab, Pakistan, Unpublished PhD thesis, University of Agriculture Faisalabad, Pakistan.

13.2 List of draft publications produced by project

Sustainability of intensive surface and groundwater use on current and future water resources and salinity management options for Rechna Doab in Pakistan (draft manuscript in production)

Impacts of Irrigation Water User Allocations on Water Quality and Crop Productivity: The LCC Irrigation System in Pakistan (draft manuscript in production)

Factors Influencing Famer's Adaptation to Water User Allocations: The LCC Irrigation System in Pakistan (draft manuscript)

14 Appendixes

14.1 Appendix 1: Training Program for Groundwater, Remote Sensing and Socioeconomics

Date: 21 April 2016 – Travel Lahore to Faisalabad (8:00 am)

Venue: UAF, Faisalabad

No.	**Groundwater, Remote Sensing & Socioeconomic Training** **Thursday 21 April 2016**	**Time**	**Persons**
1.1	Travel to Faisalabad 8-10:30 am	10:30	All
1.2	Morning tea at UAF	10:45	
1.3	Opening and Welcome	11:00	Prof Ashfaq/Dr Riaz
1.4	Group introductions	11:15	All
1.5	Introduction to SRA - Goals	11:45	Dr Jehangir
1.4	Overview of Groundwater Section in PID and needs	12:15	Dr Javed/Dr Zakir
1.5	Overview of Rechna Doab groundwater model + Q&A • Model development, calibration, and water balance • Scenario Analysis	12:30	Dr Jehangir
1.6	Overview of Rechna Doab ET and Remote sensing + Q&A • ET calculator • Spatial analysis	13:00	Dr Mobushir
1.7	Overview of Socioeconomic modelling for Rechna Doab + Q&A Framework for socioeconomic analysis. Should cover the following (based on the previous workshop presentation with Q&A): • GW use issues and need for improving crop productivity • Water use scenarios for equitable distribution of water • Addressing salinity for improving crop productivity • Enhancing farmers income through better GW use • How to improve farmer's adaptation for the changes (policy issues/on-ground issues/implementation issues)?	14:00	Dr Richard
1.8	Overview of useful output for Rechna Doab farmers + Q&A Summarize the previous workshop presentation on survey design and data collection and their use (cover the following with Q&A): • Developing survey questionnaire and survey method • Sample (Household/area) selection and the criteria used • Data collection matrix and schedules with time frame • Codding the data and data entry in Excel as modules • Converting data for modelling and analysis in SPSS	15:30	Dr Irfan

Date: 22 April 2016 – Faisalabad
Venue: UAF, Faisalabad

No.	Groundwater & Remote Sensing Training - Friday 22 April 2016	Time	Persons
2.1	Introduction to Remote Sensing image analysis and linking with crop calendar and crop statistics for mapping crop areas (to estimate crop coefficients)	9:00	Dr Mobushir
	Morning Tea Break	10:15	
2.2	Introduction to MODFLOW + Q&A • Modflow basics • Modflow Packages • Solvers and Output	10:45	Dr Jay
2.3	Designing a conceptual model	11:45	Dr Jay
2.4	Using Spatial ET0 calculator and RS results to estimate ETA-1	12:15	Dr Mobushir
	Lunch Break	13:15	
2.5	Using Spatial ET0 calculator and RS results to estimate ETA-2	14:30	Dr Mobushir
2.6	Designing a simple MODFLOW model • Problem definition - understanding the problem • Grid Design and layers • Boundary conditions • Hands on exercise and assignment	15:30	Dr Jay
2.7	Wrap up of days activities – briefing for next day	16:30	All

No.	Socioeconomics Training – Friday 22 April 2016	Time	Persons
2.1	Introduction to data collection, types of data and tools to collect data,	9:00	Dr. Irfan
2.2	Data collection exercise (can use the following aspects for presentation): • ACIAR Household Survey Questionnaire Document • Codding and modules (data) build in Excel spreadsheets • Examples of data collected as ranking (order) by famers • Examples of data collected as quantitative variables (with their units) • Examples of data collected as qualitative variables (as dummy variables with responses as yes or no)	10:30	Dr Irfan/Richard
2.3	Arranging data and descriptive using different tools,	11:30	Dr. Irfan
2.4	GW management for enhancing crop productivity (should cover the following): • Economics of private and social costs of GW use (its relevance to “user cost”) and salinity as an “externality” • Model for analysing crop productivity with water use and other inputs • Model for analysing crop productivity with a	14:00	Dr. Richard

	variable for GW salinity • Developing water use scenarios (basic + 4 others) • Extending the models for differentiating the crop productivity between distributaries, head/middle/tail locations and Head/middle/tail ends within distributaries.		
2.5	Socio-economic variables: evidence from rural areas,	15: 30	Dr. Irfan

Date: 23 April 2016 – Fieldtrip near Faisalabad
Venue: Pubberwala Disty near Faisalabad and travel to Lahore

No.	Field Trip – Saturday 23 April 2016	Time	Persons
4.1	Depart Faisalabad for field visit (Pubberwala Distributary)	8:00	All
4.2	Lunch Break	13:30	
4.3	Depart Field Site (Faisalabad) for Lahore (Avari)	16:00	All

Date: 24 April 2016 – Sunday – Free Day

Date: 25 April 2016 – Lahore
Venue: Avari, Lahore

No.	Groundwater & Remote Sensing Training – Monday 25 April 2016	Time	Persons
3.1	Designing a groundwater model – adding stress packages • Adding stress packages (river, wells, recharge, evapotranspiration, GHB and constant head boundaries) • Hands on exercise and assignment	9:00	Dr Jay
	Morning Tea Break	10:15	
3.2	Using Google API, Web-GIS and spatial ET0 calculator for decision support system to calculate crop water requirements -1	10:45	Dr Mobushir
3.3	Using Google API, Web-GIS and spatial ET0 calculator for decision support system to calculate crop water requirements - 2	12:15	Dr Mobushir
	Lunch Break	12:45	
3.4	Example Rechna Doab Groundwater Model • Extracting a sub-model from Rechna Doab using TMR • Example of Rakh Branch TMR model	14:00	Dr Jay
	Afternoon Tea Break	15:15	
3.5	Example Rechna Doab Groundwater Model and Remote sensing	15: 30	Dr Jay/Dr Mobushir
3.6	Wrap up of days activities – briefing for field trip next day	16:00	All

No.	Socioeconomics Training – Monday 25 April 2016	Time	Persons
3.1	GW management for enhancing crop productivity (continues) - Present results of the models analysed for crop productivity under different water use scenarios and the differences between distributaries and locations	9:00	Dr. Richard

	Morning Tea Break	10:00	
3.2	Production function analysis for agricultural inputs use and methods - Present results of the production function analysis for wheat and cotton.	10:30	Dr. Irfan
	Lunch Break	12:45	
3.3	Bi-variate Analysis for GW management options - Present the socioeconomic framework for the relevance of PROBIT models and the results of those models in relation to the institutional/ management/agronomic/water use technology variables that can influence the famers adaptation/decision for improved water use scenarios.	14:00	Dr. Richard
3.4	Examples - Use data from the Excel files for building simple models for analysing crop productivity and estimating Gross-Margins for farmer's income (in relation to desired water use scenario and at a particular distributary or location)	15: 15	Dr. Richard

Date: 26 April 2016 – Lahore
Venue: Avari, Lahore

No.	Groundwater & Remote Sensing Training - Tuesday 26 April 2016	Time	Persons
5.1	Remote Sensing applications for crop monitoring and crop water management	9:00	Dr Mobushir
	Morning Tea Break	10:15	
5.2	Australian case study of a groundwater model developed for water planning.	10:45	Dr Jay
5.3	Utilising Remote Sensing and online weather for calculating next crop water needs.	11:45	Dr Mobushir
	Lunch Break	12:45	
5.4	Using groundwater models to assess impacts and support policy Using information in Rechna Doab to develop detailed sub-models Compare crop water needs with surface water supply and ground water quality of Rechna DOAB	14:00	Dr Jay and Dr Mobushir
	Afternoon Tea Break	15:15	
5.9	Training Questionnaire	15:45	All

No.	Socioeconomics Training – Tuesday 26 April 2016	Time	Persons
5.1	Designing a field survey (exercise)	9:00	Dr. Irfan
5.2	Drawing inferences from the numbers (econometric estimates) • Elucidating from what the analyses of crop productivity models under different water use scenarios, production functions, and the PROBIT	10:30	Dr. Richard

	models shows. • Demonstrating on what the implications are for, if the variables in the above models and their estimated parameters change, in relation to differing cropping, locational, groundwater use, seasonal, soil/salinity and economic and policy conditions.		
5.3	Policy Implications How this approach can be used to support policy • Drawing on the findings from crop productivity models, production function estimates and the PROBIT analysis for discussing how GW can be better used; what policy/institutional/ management/on-ground factors are relevant to achieve these objectives; and how farmers can be influenced/supported/adapted for the possible changes. • Discuss examples of approaches from informal water market (water-trading); water pricing and pricing structures; and non-market based approaches	14:00	Dr. Richard and Dr Irfan

Date: 27 April 2016 – Lahore
Venue: Avari, Lahore

No.	Groundwater, Remote Sensing & Socioeconomic Training Wednesday 27 April 2016	Time	Persons
6.1	Evaluation of training and feedback from training questionnaire	9:00	All and lead by Richard
6.2	Discussion on field trip – lessons learnt – How can be better design models to address issues affecting farmers	9:30	All and lead by Richard
	Morning Tea	10:30	
6.3	SRA report preparation	11:00	Jay, Richard, Mobushir, Irfan, Dr Riaz, Dr Javed
6.4	Wrap up and thanks	12:00	Dr Riaz/Dr Jehangir

14.2 Appendix 1: List of Participants

Trainers and Participants for SRA Capacity Development and Training Workshops

Name - Trainers	Training in:	Organization
Dr Mobushir Riaz Khan	GIS/Remote Sensing	UAAR
Dr Irfan Ahmed Baig	Socioeconomics	UAAR
Dr Jehangir F Punthakey	Groundwater Modelling	Ecoseal
Dr Richard Culas	Socioeconomics	CSU

List of participants for training – Groundwater Modelling, Remote Sensing & Socioeconomics - Lahore - Aug 2015

Name	Designation	Department
Dr Muhammad Riaz	Director (PMIU)	PID
Dr Muhammad Javed	Director (SEMU)	PID
Ghulam Zakir Hassan	Director (IRI)	PID
Nauman Kashif	Assistant Director (IRI)	PID
Haroon Rafique	Assistant Director (IRI)	PID
Ghulam Shabir	IRI, PID, Lahore	DD/SRO
Faiz Raza Hassan	Assistant Director (IRI)	PID
Saleem Akhtar	Assistant Director	PID
Zohaib Shahid	Data Analyst (PMIU)	PID
Rizwan Aslam	Manager	PIDA
Umair Sadaqat	Assistant Manager (Tech)	PIDA
Saeed Ahmad	Manager LCC West	PIDA
Zulifqar Ali	Manager LCC East	PIDA

List of participants for training – Groundwater Modelling, Remote Sensing & Socioeconomics - UAF, Faisalabad and Lahore - April 2015

Name	Designation	Department
Dr. Muhammad Riaz	Irrigation Department	PID
Dr Muhammad Javed	Director (SEMU)	PID
Ghulam Zakir Hussain	Director	PID
Nauman Kashif	Assistant Director (IRI)	PID
Haroon Rafique	Assistant Director (IRI)	PID
Ghulam Shabir	IRI, PID, Lahore	DD/SRO
Faiz Raza Hassan	Assistant Director (IRI)	PID
Saleem Akhtar	IRI, PID, Lahore	PID
Dr. Asghar Ali	IARE, UAF	UAF
Muhammad Awais	UAF	PhD Scholar
M. Ali Imran	IARE, UAF	PhD Scholar
Muhammad Usman	PMAS-UAAR	Lecturer

Muhammad Amin	PMAS-UAAR	Lecturer
Zulfiqar Ali	PIDA, Fsd.	Manager(IS)
Saeed Ahmad	PIDA	Manager(IS)
Imran Aslam	PIDA	Manager
Manzur Ahmad Siddique	PIDA	Manager(SM)
Asad Naseer	IARE-UAF	PhD Scholar

14.3 Appendix 2: Evaluation Form for training

Evaluation Form for training – SRA program April 2016

This form is intend to receive your feedback and evaluate the effectiveness of this training program.

Please provide a rating for each item by ticking the column your rating of each item corresponds to.

Key:

1 = Unsatisfactory

2 = Satisfactory

3 = Good

4 = Exceeds expectations

5 = Excellent

Participant name (optional):
……………………………………………………………………………………………………

Participant institution (optional):
………………………………………………………………………………………………………

Rate your overall satisfaction with the workshop and the training provided:	**1**	**2**	**3**	**4**	**5**
Were the training objectives met?					
Did the training enhance your knowledge of the issues?					
Would you recommend this training to others?					
Will you be able to apply the information to your job?					
Rate your satisfaction with the presentations (deliveries and demonstrations/examples applied).					
How do you consider the knowledge/skills that you gain from the field trip as useful?					
Are you satisfied with the catering and other facilities provided during the workshop?					
What was the most valuable part of the training in your own perspective and its practical implications in relation to the ground water management:					
Please provide any suggestions for how the objectives of the training could be improved/ made as beneficial in relation to helping farmers and ground water management issues:					

14.4 Appendix 3: Workshops conducted by PID

Title: Awareness Raising and Capacity Building of FOS/Farmers Regarding Groundwater Issues and Management in Punjab:
Held at Kamalia Distributary on November 28, 2015

Note: Separate Report attached

Title: Awareness Raising and Capacity Building of FOS/Farmers Regarding Groundwater Issues and Management in Punjab:
Held at Khikhi Distributary on February 20, 2016

Note: Separate Report attached

14.5 Appendix 3: Draft paper for flow and transport model for Rechna Doab

Draft paper 1 (Draft publication under preparation): (

Title: Sustainability of intensive surface and groundwater use on current and future water resources and salinity management options for Rechna Doab in Pakistan

Abstract: The Rechna Doab covers 2.98 million hectares of intensively irrigated land in Punjab, Pakistan. A dense network of canals supplies water from the Chenab River. Over the past three decades groundwater use has increased from a few hundred tubewells to over 200,000. The increase in farmer owned tubewells was largely driven by inequity in the surface supply system and the drive for increased cropping intensity. Farmers in the mid regions of Rechna Doab have to cope with scarcity of irrigation water as these areas are underlain by saline groundwater resulting in increased salinity and sodicity of soils. Thus management of surface and groundwater in Rechna Doab is an important instrument for increasing crop productivity and improving livelihoods of smallholder farmers. A regional flow and solute transport model was developed to assess availability of groundwater resources and interaction of surface and groundwater in Rechna Doab. Spatial and temporal assessment of groundwater use, availability of surface water supplies, and climatic variability were modelled to assess risks to existing groundwater supplies. Spatial variability of actual evapotranspiration was estimated at pixel scale for the entire Rechna Doab. The approach involved using MODIS NDVI data from 2008-14 to prepare monthly crop maps and to derive crop coefficients for various crops in Rechna Doab. Spatial and temporal estimates of recharge and actual ET were used to assess groundwater use on a monthly basis, as there are no recorded usage data for the vast majority of farmer-owned and operated tubewells in Rechna Doab. The modelled scenarios showed that if groundwater pumping was reduced by 10 percent and surface water availability was increased by 10 percent then an estimated total water savings of 900 Mm^3/yr is possible. Climate scenarios showed that the system can cope with short duration droughts up to 3 years, however, a longer duration drought of 10 years would increase the risk of salinity in the lower regions of the doab. Thus greater effort needs to focus on significantly enhancing the level of groundwater management. The project outcomes will support monitoring and planning for improved groundwater management and assist policy makers to make informed decisions on equitable, economically efficient and hydrologically sustainable canal and groundwater management options in the study areas.

Keywords: groundwater management, canal irrigation, salinity, NDVI, Pakistan

14.6 Appendix 4: Draft paper on GIS/Remote Sensing for Rechna Doab

Draft paper 2 (Journal publication): (under completion by Dr Mobushir)

14.7 Appendix 5: Draft paper for socioeconomic modelling in Rechna Doab

Draft paper 3 (Journal publication): (Attached)

Title: Impacts of Irrigation Water User Allocations on Water Quality and Crop Productivity: The LCC Irrigation System in Pakistan

Abstract: The irrigated agriculture sector in Pakistan is facing the challenge to cope with low crop yields, an increasing gap in the supply and demand of agriculture products, and a decreasing trend in agriculture productivity. This is exacerbated by the inequity of water distribution, among the water users located at head, middle and tail reaches of the irrigation systems. The aim of this paper is to identify opportunities for equitable distribution of canal and groundwater to improve famer livelihoods through maximizing crop production and managing the salinisation in irrigated landscapes in the systems. Based on the data from farm surveys conducted in 2009 and 2012 at the Lower Chenab Canal (LCC) Irrigation System in Pakistan, this study employs econometric models for crop productivity under different water user scenarios. The results reveal evidences that, compared to the current water use situation (base scenario), the distributary at the head location of the system can extract more of the groundwater while the distributary at the tail end of the system should utilize more of the canal (surface) water in relation to the proportion of total water uses. A redistribution of the water use (optimal scenario) in the system can improve the groundwater quality (minimize salinity) and improve the crop productivity (farm income). The outcome of this study provides better environmental and socioeconomic conditions for the farmers and will assist the irrigation management institutions and farmer organisations in implementing policies and mechanisms for more equitable and economically efficient water supply options in the canal system.

Keywords: groundwater, irrigation, econometric modelling, crop productivity, Pakistan

Draft paper 4 (Journal publication): (to be developed)

Title: Factors Influencing Famers Adaptation to Water Use Allocations: The LCC Irrigation System in Pakistan