CONJUNCTIVE WATER MANAGEMENT MODEL FOR A MULTI CROP IRRIGATION COMMAND

by

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KERALA, INDIA

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E.B. GILSHA BAI
(2016-28-003)

THESIS

Submitted in partial fulfillment of the requirement for the degree of

DOCTOR OF PHILOSOPHY

IN

AGRICULTURAL ENGINEERING

(Soil and Water Engineering)

Faculty of Agricultural Engineering and Technology

Kerala Agricultural University

Department of Irrigation and Drainage Engineering
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ABSTRACT OF THESIS

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2020

DECLARATION

I, hereby declare that this thesis entitled **“CONJUNCTIVE WATER MANAGEMENT MODEL FOR A MULTI CROP IRRIGATION COMMAND”** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Place: Tavanur	**E.B. Gilsha Bai**
Date:	**(2016-28-003)**

CERTIFICATE

Certified that this thesis entitled **"CONJUNCTIVE WATER MANAGEMENT MODEL FOR A MULTI CROP IRRIGATION COMMAND"** is a record of research work done independently by **Smt. E.B. Gilsha Bai (2016-28-003)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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Date:

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(Major Advisor, Advisory Committee)
Professor, Dept. of IDE
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CERTIFICATE

We, the undersigned members of the advisory committee of Mrs.E.B. GIilsha Bai, a candidate for the degree of Doctor of Philosophy in Agricultural Engineering, with major in Soil and Water Engineering, agree that the thesis entitled **"CONJUNCTIVE WATER MANAGEMENT MODEL FOR A MULTI CROP IRRIGATION COMMAND"** may be submitted by Mrs. E.B. Gilsha Bai**,** in partial fulfillment of the requirement for the degree.

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E.B. Gilsha Bai

Dedicated to

The memories of my beloved father

ABBREVIATIONS USED

AET : Actual Evapotranspiration
AEU : Agro-Ecological Units
ANN : Artificial Neural Network
BCM : Billion Cubic Meter
BMP : Bitmap
CCA : Cultivable Command Area
CGWB : Central Ground Water Board
CRDS : Chalakudy River Diversion Scheme
DEM : Digital Elevation Model
DN : Digital Number
DP : Dynamic Programming
DPR : Distributed Pumping and Recharge
Eng. : Engineering
ENSO : EL Nino Southern Oscillation
et al. : and others
FAO : Food and Agricultural Organisation
Fig. : Figure
FLP : Fuzzy Linear Programming
GA : Genetic Algorithm
GAMS : General Algebraic Modelling System
GDP : Gross Domestic Product
GIS : Geographical Information System
GMS : Groundwater Modelling Software
GWM : Ganges Water Machine
ha : Hectare
ISODATA : Iterative Self-Organizing Data Analysis Technique
IMD : Indian Meteorological Department
Int. : International
IR : Irrigation Ratio
ISM : Irrigation Scheduling Model
J. : Journal
km : Kilometer
km^2 : Square kilometer

KML	:	Keyhole Markup Language
LBC	:	Left Bank Canal
LP	:	Linear Programming
LPM	:	Linear Programming optimization Model
m	:	Metre
m/s	:	Metre per second
m^3/s	:	Cubic metre per second
m^2/day	:	Square metre per day
mm	:	Millimetre
Mm3	:	Million cubic metre
MSL	:	Mean Sea Level
NBSS&LUP	:	National Bureau of Soil Survey and Land Use Planning
NCP	:	North China Plain
NDVI	:	normalized difference vegetation index
NIR	:	Net Irrigation Requirement
NSGA	:	Non-dominated Sorting Genetic Algorithm
PAC	:	Pumping Along Canals
PERC	:	Probability of Exceedance of Rainfall and Canal water availability
PET	:	Potential Evapotranspiration
Proc.	:	Proceedings
RBC	:	Right Bank Canal
RMSE	:	Root Mean Square Error
RVM	:	Relevance Vector Machine
RWS	:	Relative Water Supply
SA	:	Simulated Annealing
Sci.	:	Science
SEBAL	:	Surface Energy Balance Algorithm for Land
SO	:	Simulation-Optimization
Soc.	:	Society
STP	:	Sewage Treatment Plant
SVM	:	Support Vector Machine
SWAP	:	Soil–Water–Atmosphere–Plant
TDS	:	Total Dissolved Solids
USDA	:	United States Department of Agriculture
USGS	:	United States Geological Survey

Viz.	:	Namely
WUA	:	Water Users Association
WUR	:	Water Use Ratio
YCRT		Yung Conflict Resolution Theory
o		Degree
%		Per cent
/		Per
’		Minute
”		Second

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ABSTRACT

Water is an important input to agriculture and its judicious use is necessary to attain food security of the nation. Irrigation compensates the lack of soil moisture for crops due to spatial and temporal variability in rainfall. The use of surface water in conjunction with groundwater during summer months reduces the crop stress as well as stress on water resources and creates underground storage space for the upcoming rainy season. Conjunctive water use should be adopted in a planned manner to ensure sustainability of water resources. Mathematical models are good tools for planning conjunctive water use. Optimization, simulation, and simulation-optimization models are used for the planning process. Linear programming is a simple optimization technique used for conjunctive water use planning. Command area of Chalakudy River Diversion Scheme faces acute water scarcity during summer due to the irregularities in canal water supply. The use of groundwater for irrigation is relatively nil in the area. Hence, a conjunctive water management model was developed using linear programming optimization technique and a stable conjunctive water use policy for the area was derived by simulation runs of the optimization model.

The conjunctive water management system has three distinct and interlinked components – surface water, irrigated area, and groundwater. These three components were modelled and analyzed separately and linked together by an optimization model for sustainable use of both surface and groundwater resources. Surface water availability and adequacy of canal water supply were studied using the water withdrawal data obtained from irrigation department and field measurements of canal water discharge rate and seepage loss. The irrigation requirement of the command area was computed using the FAO CROPWAT 8.0 software. Land use map of the area was prepared with ERDAS Imagine 2015 software. Data on cropping patterns and its areal extent in the CCA of the CRDS was extracted using the ArcGIS 10.3.1 software. Groundwater status of the command area was studied using Visual MODFLOW 2.8.1 software. Water level observation data from the Central Groundwater Board (CGWB) and pumping data

from Kerala Water Authority were used for calibration of the model in Visual MODFLOW. The calibrated and validated model was used to estimate the net groundwater inflow/outflow of the command area. An optimization model was developed using the linear programming technique with an objective function to maximize the relative yield of all the crops in the command area. Canal water availability was the major constraint to achieve maximum objective value. The potential irrigation demand of each crop was fixed as the upper limit of water allocation from both sources. The proportion of canal water and groundwater in the total water allocation to each crop forms another constraint in the model. The model was solved using the software LINGO 18.0. For developing a stable conjunctive use policy for the command area, the optimization model was run for different combinations of surface water-groundwater proportions for a normal year. The groundwater balance of the study area was computed from the results and the proportion which produces only negligible change in the groundwater storage was identified as the stable policy. Temporal allocation of this stable policy over a normal year was done by simulation runs of the model for monthly time periods. Using the identified stable policy, the LP optimization model was run for past years to get the impact of the policy on aquifer storage response over the years.

From the prepared land use map, it was observed that 80% of the command area is covered by the crops that require irrigation. The average irrigation requirement of each branch canal was computed and summed up to get the total irrigation requirement of the command area. It was found that the CRDS command area required 46.90 Mm^3 of net irrigation water annually. Field measurements of canal water discharge rate and seepage loss showed that the discharge rate decreases from head to tail end in the main canal as well as the branches. The seepage loss rate per km increases towards the tail end in the main canals. The high seepage loss caused by damaged lining, waste dumping and vegetation growth in canals reduced the conveyance efficiency of the canal system to 51 per cent. Performance indicators like Relative Water Supply and Adequacy Iindicator showed that the performance of the CRDS canal system falls in the class of ‘fair’.

Predictions using calibrated and validated Visual MODFLOW model revealed that the groundwater status of the area is sufficient for conjunctive management of water for irrigation. Net groundwater inflow/outflow from the aquifer obtained from zone budget output of Visual MODFLOW was used to predict the change in groundwater storage due to conjunctive water use for the pre-determined surface water ratio.

The solution of the optimization model from LINGO 18.0 software gives the maximum relative crop yield as objective value and the quantity of water to be allotted from both sources to attain this value. From the results obtained by running the linear programming optimization model for a normal year, a stable policy of 76:24 (surface water: groundwater) was identified as best for the command area. With the developed stable policy, a temporal allocation pattern of canal water and groundwater within a year was identified.

The impact of the application of the developed stable conjunctive use policy was checked by running the model with this policy for past years from 2005 to 2012. An increase of 74.72 mm in groundwater storage would occur by the application of this stable policy over a period of 8 years. This implies a groundwater storage change of 9.34 mm/year. This change in storage would result in a groundwater level rise of 24.6 mm/year which was considered negligible. Thus, it could be recommended that, the use of a stable policy, 76:24 for conjunctive management of canal water and groundwater in the CRDS command area is capable of maximizing the relative yield of all crops in the command area without affecting the groundwater storage in the area.

CHAPTER1

INTRODUCTION

Agriculture is one of the most prominent sectors of Indian economy. Its contribution to Gross Domestic Product (GDP) crosses 17 per cent as per India's economic survey 2018-19. Water is an important input to agriculture as that of seed and fertilizer. India has 4 percent of the worlds available freshwater and needs to feed seventeen percent of the world population. As the population is growing up and freshwater availability remains constant, the nation is moving through a water-stressed condition with 1544 m^3 of per capita water availability, towards the water-scarce situation (Dhawan, 2017). Productivity should be enhanced to a higher level to feed the growing population, for which irrigated agriculture is a necessity. In India, 56% of food grain production is achieved through irrigated agriculture. Ultimate irrigation potential of the country is 140 million hectares and the potential acquired so far is only 85 million hectares. The under-utilized potential should be acquired to achieve the goal of food security for the nation. The Central Water Commission (2017) has assessed the water resource availability of the nation as 1869000 Million cubic meter (Mm^3) and utilizable water as 1123000Mm^3. Out of the 1123000Mm^3 of utilisable water, 433000 Mm3is replenishable groundwater.

All over the world, rainfall varies both spatially and temporally and in India also, the scene is not different. Spatial variability ranges from 100 mm annual rainfall in Rajasthan to 11000 mm at Cherrapunji in Meghalaya. Around 75 percent of annual rainfall is received in monsoon months. Temporal variability of rainfall and surface water induces water scarcity during summer months, especially for irrigation. Integrated use of available water resources is a possible solution to face the situation. Water stored on above-ground storage structures like dams and below-ground aquifers are the two major resources of water available for irrigation. Better integration of these major water resources through conjunctive use may give enough water to meet growing irrigation demands.

Conjunctive use is actually the combined use of surface water and groundwater. Integrated use of surface and subsurface water becomes possible with conjunctive water use and it is suitable for tropics as well as arid regions. The risk due to the stochastic nature of surface water supply is not there in conjunctive water use. It ensuresa reliable water supply for irrigation.An increase in agricultural productivity, improved use of water sources, reduced fluctuation of groundwater level and reduced environmental impact are the other major advantages of conjunctive use of water.

Farmers usually combine the surface water and groundwater use in an unscientific manner. The sustainability of water resources is not considered here. All the resources may not be optimally utilized. Conflicts between stakeholders' interests may occur. A systematic approach of integrated use of surface and groundwater that requires coordinating mechanisms grounded in hydraulic and hydrological knowledge is called conjunctive water management (Wrachien andFasso, 2007).Water management through conjunctive use is thus a good tool to optimize productivity, equity in water distribution and sustainability of the environment through the coordinated management of surface and subsurface water resources. Groundwater withdrawal reduces waterlogging problems, soil salinity and thereby leaching requirement in a conjunctive water management system. Water quality and groundwater sustainability issues are generally solved through conjunctive water use. Here comes the importance of proper planning when water is used conjunctively.

Burt is the first researcher who introduced the idea of conjunctive use of water in 1964. He considered surface water and groundwater as two independent components of a combined water system. Surface water and groundwater, the major water resources have inter-connections known as a hydrologic connection. Conjunctive water use utilizes this hydrologic connection existing between surface water and groundwater. The use of surface water for irrigation needs huge storage structures like dams. However, the storage capacity of aquifers could be exploited in planned conjunctive water use systems. Utilization of aquifer storage space to store rainwater reduces the flood possibility and flood peak. Groundwater is a more reliable source compared to surface water. Over-extraction leads to a decline of groundwater table level and this, in turn, affects the base flow contribution to rivers.

Due to the interaction of surface water and subsurface water during critical periods, it is possible to store the surplus of one to reduce the deficit of the other. Usually, surface water is stored in costly dams and reservoirs and losses due to evaporation is more from this storage. If water has been pumped out from aquifer during the dry season it could absorb more water in the succeeding monsoon season and thus avoid flooding or waterlogging that may occur in low lying areas. This aquifer storage could be pumped out to compensate surface water scarcity in the upcoming summer season, which creates a cycle of storage and discharge with dynamic equilibrium. That is, extraction and recharge of groundwater will reach equilibrium.

Planned conjunctive water management maximizes the use of surface water when it is available in surplus and saves groundwater for lean periods. Mathematical modelling techniques are being used to aid the planning process. Optimization models, simulation models and simulation –optimization models are there to solve water management issues. Optimization models are used to try different permutations and combinations of surface water and groundwater percentages to get an optimum one which meets the water required to achieve maximum production or economic benefit. The conjunctive water management system can be approached in different ways to develop optimization models. Models are actually simplified representation of a real system. Linear programming is a simple optimization technique in which a real system is represented by linear equations.

Linear programming models consider the linearity of the system. Butmost of the conjunctive management systems are nonlinear in nature.To account for the nonlinear nature of real systems, researchers often go for nonlinear programming for optimization. Any real system in nature is dynamic, especially the irrigation systems. Using dynamic programming, optimization could be done to get sequential decisions according to the dynamic nature of the system.

Simulation models imitate the processes going in a real situation and give an answer to the question ‘what if’. These models will give near optimum solutions. Simulation- optimization models will give optimum solutions after analysing various situations by a number of simulations.Some researchers arrived at optimum cropping pattern suitable for the selected area, to maximize the benefits by utilizing surface and groundwater conjunctively, using modelling approach. Several researchers developed economic optimization models for solving conjunctive water management problems. Multi-objective models are also common. Simulation-optimization methods usually have lengthy and iterative computations. To reduce this computational burden, evolutionary optimization techniques like Genetic Algorithm, Artificial Neural Network etc. are used nowadays. Even though several conjunctive water management models are available, each command area is different from others and hasits own peculiar characteristics or constraints. Problems vary in situations and areas.

As in India and all over the world, rainfall varies both spatially and temporally in Kerala also. Being a small state having a land area of 38,863 km^{2}temporal variations are more significant than spatial variation. Out of the total 3000 mm annual average rainfall, almost 70 per cent is received in monsoon months. During the summer months, there is an acute shortage of water in many areas. Industrial and domestic demands are always conflicting with agricultural needs.

Kerala is blessed with 44 medium and small rivers. Surface water flowing through these rivers is used for power generation and irrigation apart from maintaining ecological flow. Chalakudy River is one among them having 145 km length and fifth position in the list of longest rivers of Kerala. The river originates from Anamalai hills, Parambikulam Plateau and Nelliampathy hills of Southern Western Ghats and flows westwards through three districts,viz. Palakkad, Thrissur and Ernakulam, of Kerala. There are four tributaries for this river, viz. Sholayar, Parambikulam, Kuriarkutty and Karapara. The total drainage area of the river is 1704 km^2 including 300 km^2 of Tamil Nadu state. The basin of the river lies between 10^{o}05' to 10^{o} 35' North latitude and 76^{o} 15' to 76^{o} 55' East longitude. The estimated utilizable yield of the river is 2033 Mm^3 including 494 Mm^3 from Tamil Nadu. There are six large dams in the Chalakudyriver and its tributaries out of which five are operated according to the ParambikulamAliyar Project agreement. The sixth one is Poringalkuthu dam located at the downstream side of the other five dams. Poringalkuthu hydroelectric project is operated using the water stored in this dam and after power generation water is released to the river. Chalakudyriver is one of the most utilized rivers in the state. Around ten lakh people in the command area depend on this river directly or indirectly.

Chalakudy river basin was originally known for biodiversity and riparian vegetation, which includes some endemic species of flowering plants. The upstream side of the river basin is covered with grasslands, lush evergreen forests and semi-evergreen forests. Dams cause inundation of large forest area. Tribes living in forests towards the upper reach of the river depend on the river for almost all of their living needs. Diversified fish population was observed in the river in past years. It declined drastically after the construction of dams (George*et al.,* 2001; Latha *et al*, 2012; Padikkal *et al*, 2018).

Chalakudy River Diversion Scheme (CRDS), a major irrigation project in the state, is located in the river. A diversion weir of height 3.96m constructed across the river raised the water level sufficient for diversion through the right and left bank canals of CRDS. The stage I of the scheme was commissioned in 1957 and stage II in 1966. The irrigation scheme has a total command area of 39,685 ha and cultivable command area of 13895ha. The whole command area is comprised of 15 Panchayaths and one Municipality (George*et al*., 2001).

Chalakudy River Diversion Scheme only diverts the river flow through canals as there is no storage facility at the weir site. In recent years summer flow in the river reduced due to various reasons. In peak summer, CRDS depends only on the tail water release of Poringalkuthu dam. Hence, water release through canal and water availability to the tail end of main canals and all branch canals reduced. Maintenance problems, lack of lining which causes seepage loss, waste dumping in the canal, over use by the head end farmers etc. badly affected the situation (Latha *et al*, 2012).

Due to these reasons, both head end farmers and tail end farmers started drawing groundwater from the unconfined aquifer for irrigation and domestic purposes. On the other hand, groundwater is getting recharged from canal seepage as well as deep percolation from irrigated area. In order to cater their needs for drinking water the people in the area mainly depend on the seepage loss from canal water that contributesto groundwater.Several lift irrigation schemes that draw water from river or ponds are also operating in the command area.

The command area of CRDS is cultivatedmainly by water demanding crops like paddy, nutmeg, banana and vegetables. The use of surface water alone cannot meet the demand in summer and conflicts between head and tail end farmers are common in the command area.The use of groundwater is meagre for irrigation purpose and it is not donein a planned manner.The groundwater level on an annual basis is continually declining in this area.There is immense scope for conjunctive use of surface and groundwater for irrigation in the area.But this can be implemented only in a well-planned and systematic manner. Hence, a planned conjunctive water management model is necessary for this multi-crop irrigation command area in order to arrive at a stable conjunctive use policy.

Moreover, the command area of CRDS is peculiar due to various other reasons also. The area represents a typical cross-section of the undulating topographic feature ofthe state of Kerala. The command area includes high land, midland and some alluvial patches. Hence, the agro ecology of the command area varies considerably. Agro-ecological units included in the command area varies from AEU 5 (Pokkali land) to AEU 15 (Northern high hills). Hence, the surface and ground water dynamics will be specific to the terrain characteristics. The nature of conjunctive water management needed for the area might be different from the command areas of other irrigation projects in the state. Already developed conjunctive water management models for other areas cannot be applied to the study area, because of variation in agro-ecology from location to location.

Most of the research in conjunctive water management addresses only the water deficiency problem. Only a few studies come up with a stable policy that balances the effect of deficit and excess rainfall on irrigation requirements as well as on groundwater. Such a stable policy is highly site-specific that depends on cropping pattern, topographic characters, soil characters etc. Therefore, a specific study is necessary for the development of a stable conjunctive water use policy and its temporal allocation pattern for the command area of CRDS.

In this context, the present study was initiatedwith the following specific objectives.

1. To analyse the adequacy of irrigation water and the current trends in conjunctive use in the selected command area.
2. To study the dynamic response of the aquifer to groundwater extraction and recharge.
3. To develop an optimization model to arrive at a stable conjunctive use policy for the command area.
4. Simulation studies to derive an optimal temporal allocation pattern and aquifer storage response over the years.

CHAPTER2

REVIEW OF LITERATURE

Conjunctive use of surface and groundwater is the use of both surface water and groundwater to meet the water needs by developing the co-existence of these water resources and supplementing the shortage of one by another. Thus the largest water storage of nature, the groundwater storage in the aquifer, is used to buffer the surface supply during the lean period. In turn, the same surface supply is used to refill aquifer storage. This becomes practical due to the interconnections of both surface water and groundwater resources (Foster *et al.*, 2010). Adequacy of irrigation in a command area determines the necessity of groundwater pumping. The dynamic nature of groundwater in an unconfined aquifer is exploited in conjunctive water use.But proper planning is required to maintain the sustainability of major water resources. Mathematical models are very good tools to support decision-makers in planning conjunctive water use. Some of the research works conducted in this field to estimate the adequacy of irrigation water, the interaction between surface water and groundwater, conjunctive water management, and mathematical models and software are discussed in this chapter.

2.1 ADEQUACY OF CANAL IRRIGATION WATER

Canal irrigation schemes are intended to meet the irrigation requirement of the command area. Adequacy of irrigation water and equity in distribution are the two major performance indicators of surface water irrigation schemes. A lot of studies have been conducted to evaluate the performance of canal irrigation schemes and thereby to check the adequacy of surface water for irrigation.

Gorantiwar and Smout developed a framework for the performance evaluation of heterogeneous irrigation schemes in 2005. In this study, the authors suggested two types of allocation measures viz. productivity and equity and five types of scheduling measures viz. adequacy, reliability, efficiency, flexibility and sustainability for the evaluation of irrigation water management within irrigation schemes. Methodologies for estimating these measures based on various indicators were also given. For example, adequacy implies the supply of water to crop compared to its original demand. Relative water supply, which is the ratio of water supply from effective rainfall and irrigation to the demand due to evapotranspiration and other needs, is a good indicator to measure the adequacy of water. Like this, equations for indicators were given for other performance measures also.

Akkuzu *et al*. (2007) used remote sensing techniques to assess the performance of water delivery of some water users associations (WUA) in a canal irrigation system.Adequacy of irrigation was measured using indicators *viz.* irrigation ratio (IR) which is the ratio of actual irrigated area to the projected irrigation area, water use ratio (WUR) which is the ratio of actual water use to the target water use and the average of normalized difference vegetation index (NDVI) which is the ratio of the difference between the reflection of near infra-red band and red band to the sum of reflection of near infra-red band and red band from the vegetation surface. Equity in water distribution was determined according to the coefficient of variation of NDVI values. The study revealed that the IR of WUAs depends on their position along the main canal. With regard to the adequacy, indicators showed that WUAs located at the tail end of the main canal were facing acute shortage of water for irrigation.

Kuscu *et al*. conducted a study in 2009 for the performance assessment of irrigation water management in the Karacabey irrigation scheme in Turkey. They used the average irrigation ratio and relative water supply as the physical performance indicators for the evaluation of the irrigation scheme along with other financial and social performance indicators. The study showed a negative result with regard to physical performance indicators. There was a scarcity in irrigation water supply through the canal system.

Kharrou *et al.* (2013) used remote sensing based indicators such as NDVI to assess equity and adequacy in water delivery of an irrigation scheme located in Morocco. Remote sensing techniques were used to estimate NDVI from a command area. There exists a relationship between NDVI and biophysical characteristics and this was used to prepare an evapotranspiration map of the area using the FAO-56 dual crop coefficient method. Equity of irrigation was measured from the coefficient of variation of crop evapotranspiration. Relative irrigation supply, depleted fraction and relative evapotranspiration were used to indicate the adequacy of irrigation. From the study, the authors concluded that equity and adequacy were not satisfied in the irrigation scheme.

Elnmer *et al*. (2018) developed a framework with two components, external and internal, for the irrigation water performance assessment using remote sensing data and it was tested in the Nile Delta. The external component of the framework was used to assess water supply, agricultural and economic performance and internal component to assess spatial and temporal variation in the distribution in terms of equity, adequacy, and dependability. Landsat images and Surface Energy Balance Algorithm for Land (SEBAL) model were used for the estimation of crop water requirement. From the results external component classified the performance as poor. The internal component showed a non-uniform distribution of water between the head and tail branches.

In a study conducted in China, Fan *et al*. (2018) evaluated the water allocation and delivery performance of the Jiamakou irrigation scheme. Adequacy, equity, dependability, and efficiency were the indicators used for the evaluation. They found that the overall performance of the irrigation scheme was poor due to inadequate, inefficient, and unequal allocation and distribution of water.

2.1.1 Irrigation demand using CROPWAT model

To assess the adequacy of irrigation, calculation of net irrigation requirement is necessary. Software CROPWAT developed by the Food and Agricultural Organization (FAO) is widely used to find out irrigation requirement and scheduling. Several researchers used this CROPWAT model for determination of actual evapotranspiration, crop water requirement and scheduling irrigation (Kuo *et al.,* 2001; Bana, *et al*., 2013; Abdulla *et al*., 2015; Trivedi *et al.,* 2018)

Knežević*et al.* (2013) used two software, CROPWAT, and ISAREG, to calculate net irrigation requirement (NIR) for conducting a water balance study related to winter wheat production. Results obtained from the models were compared and it was found that NIR to get maximum yield calculated by CROPWAT was higher than that done by ISAREG. From the results obtained the authors concluded that both models are good tools for determining water balance of wheat crop.

Gangwar*et al.* (2017) conducted a study to estimate the net irrigation requirement of rabi crops in the Bina command area of Madhya Pradesh using CROPWAT 8.0 software. The average daily reference crop evapotranspiration was estimated as 4.62 mm/day. Wheat, gram –pulses, and mustard were the rabi crops considered and 349.8, 304.1, and 316.9 mm respectively were the water requirement of the crops determined using the software. The authors estimated the net irrigation demand of the Bina command as 212.27 Mm^3.

Surendran *et al.* (2017) assessed crop water need and availability of water resources to meet the requirement of the Kollam district in Kerala using the CROPWAT model. The total water balance of the district based on agro-ecological units was determined, considering domestic, industrial and agricultural demands. Present as well as future needs were estimated. Projected future water demand was 1550 mm^3 more than the existing utilizable resources. Even though irrigation is required to attain maximum crop production, under a water deficit scenario it is difficult to sustain agriculture without reducing the irrigated area. Otherwise possible water conservation strategies like deficit irrigation, micro-irrigation techniques and adjustment of planting periods must be followed.

2.2 STUDIES ON SURFACE AND GROUNDWATER INTERACTIONS

Groundwater is one of the major sources of irrigation water in India. Even though rainfall and rivers are plenty in Kerala, groundwater contributes a marked share of water for agricultural purposes in the state. In earlier days surface water and groundwater were considered as two separate water sources. Later scientists were interested in the interactions of surface water and groundwater sources (Kalbus*et al.,* 2006). The interaction between surface water and groundwater contributes recharge to the groundwater. Several studies were conducted in India and abroad about the inter-relationship between surface water and groundwater.

Ahmad *et al.* (2005) developed a new technique to estimate net groundwater usage over a large irrigated area using remote sensing and water balance approaches. The study was conducted at Rechna Doab in Pakistan. In the new methodology, groundwater recharge was not computed explicitly, but it was taken as a component of water balance study. The spatial variation of recharge was quantified using remote sensing techniques. Climate data, canal water releases, phreatic water surface fluctuations, soil textural properties etc. were the input data to the new remote sensing tool. The result obtained from this study was compared to the conventional specific yield method and showed 65% variation.

Sharda *et al.* (2006) studied the impact of water storage structures on groundwater recharge by estimating the recharge using two methods, water table fluctuation method and chloride mass balance method, in a semi-arid region in India. Both methods gave almost the same quantity of recharge. From the study, the authors inferred that the storage structures have only a limited effect on groundwater recharge irrespective of annual rainfall. The study revealed that a minimum of 104.3 mm cumulative rainfall is required for a 1mm increase in the water table. Recharge- Rainfall ratio was found to be higher for low rainfall year than average rainfall year. The authors claimed that this finding is very useful in the design of water harvesting structures.

Anuraga *et al.* (2006) conducted a study for estimating groundwater recharge using land use and soil data in Bethamangala sub-watershed and reported that the average groundwater recharge is more sensitive to soil type compared to agricultural practices. The authors used the agro-hydrological model soil–water–atmosphere–plant (SWAP) for testing this as an alternative to water table rise method suggested by Groundwater Evaluation Committee in India. Estimation of actual withdrawal of groundwater is a challenging process than recharge estimation. The study was conducted by generating different simulation units that have almost homogeneous land use and soil type. The simulated water balance was in line with that obtained from the water table rise method. The results showed that an increase in the irrigated area reduced the groundwater recharge.

In 2006, Scanlon *et al*. reported that average groundwater recharge from large areas varies from 0.1 to 5% of average annual rainfall, after conducting a study over 140 sites in arid and semi-arid regions globally. The chloride mass balance method was used for the study. EL Nino Southern Oscillation (ENSO) increased the recharge in the United States continent and Australia. Land use /land cover changes affect the recharge very much. Recharge could be controlled very well by managing land use. The authors also reported that groundwater recharge from the irrigated area can go as high as 25% of rainfall plus irrigation. Even then, the groundwater level declines in irrigated areas due to over pumping for irrigation.

Scibek *et al.* (2007) used a three-dimensional transient groundwater model to evaluate the effect of climate scenarios on surface water-groundwater interactions. The study was conducted in Canada. The study revealed that there is a strong hydraulic link between unconfined aquifer and river in the study area, Kettle River and Grand Fork valley aquifer. The interaction between the river and the aquifer has a high flow rate during the spring. About 15% of river flow contributed to aquifer during this period and most of this water returned to the river within 60days as base-flow. If pumping is there for irrigation considerable reduction in return flow occurs. The effect of future climate scenarios indicated that differences in aquifer water levels may occur when comparing the same date of the year. This change in the water level is more near the river than away from the floodplain. River peak flow may be shifted to an earlier day without affecting the shape of the hydrograph.

Korus and Burbach (2009) conducted a study to analyze aquifer depletion criteria for groundwater management on the Great Plains. Generic models in three hypothetical systems with four depletion limits, 5%, 10%, 15% and 25% were used for the calculation of transient water budgets with simulation studies. The study revealed that management operations of groundwater should be planned according to the safe yield of aquifer and corresponding groundwater level predictions. The authors suggested that the management strategy should also depend on the hydrologic relation between stream and aquifer. And an aquifer depletion limit may be considered as one of the criteria to limit groundwater withdrawal. The authors suggested that the identification of groundwater depletion criteria should be a part of the dynamic groundwater management process.

Martinez *et al.* (2009) conducted an experiment with the root-zone modelling approach to get the recharge to groundwater from the irrigated area. Knowledge about recharge, evaporation and transpiration from the irrigated area is necessary for the sustainable management of water resources like groundwater. HYDRUS-1D softwarewas used for the study after calibration. Evapotranspiration, irrigation and soil moisture dynamics were simulated using the software. The results showed that the software is good for recharge estimation. The recharge was more during the periods of low evapotranspiration. The authors reported that even though the root-zone modelling approach is more data-intensive it gives fine estimation compared to other techniques.

Hassan *et al.* (2014) conducted a study to evaluate the use of an integrated transient hydrologic model, GSFLOW, in simulating surface and groundwater interactions in hard rock terrains characterised by shallow water table, dense drainage network, and low aquifer storage. In such regions, the water table rises suddenly in response to recharge and this leads to groundwater exfiltration and preferential flow towards streams. From the study, the authors came to know that GSFLOW is an efficient model for converting precipitation into the recharge considering groundwater exfiltration to shallow soils, compared to MODFLOW model.

In 2015, Ruiz used a number of methods to evaluate the spatial and temporal variability in vertical recharge of groundwater. He conducted the study in Mexico City. Water table fluctuation method, groundwater flow modelling etc. were the methods used. The author observed that the temporal variation in recharge was more than the variation in precipitation that causes the recharge. Spatial variations were also noticed, at the rate of more than 20% of precipitation in the high lands and less than 3% of rainfall in the level areas.

Fernald and Guldan (2016) studied the surface water- groundwater interaction effects on hydrologic budget and water quality in New Mexico. From the study, it was found that almost 5% of the flow in deep irrigation ditches seeps out in a season. Water levels from observation wells showed the rise of groundwater level within one month after the commencement of irrigation. Baseflow from the aquifer to stream also developed by this one month time. This was the evidence for the strong interaction of surface water and groundwater in an alluvial aquifer system.

Russo and Lall (2017) observed groundwater levels in deep aquifers and correlated these to climate variability and annual rainfall in a study conducted in the United States of America. The authors realized that depletion in groundwater storage has been occurred corresponding to climate change. The response of water levels in deep wells reflects the variation between annual precipitation and climate-induced pumping, in irrigated areas. Even if it is expected that natural recharge to deep aquifer takes multi-year time lags, the authors experienced the response of deep water levels to climate variation over timescales of less than one year. The study concluded that groundwater pumping, a natural response of the human to drought, may reduce the groundwater storage to critical levels that affect the sustainability of this valuable resource.

Yihdego and Khalil (2017) assessed the long-term impact of groundwater extraction and recharge using a conceptual water balance model and time-series data analysis. The authors realized from the study that the undeveloped groundwater resources are in a state of equilibrium with equal recharge and discharge. Only groundwater extraction can break this equilibrium. Usually, researchers focussed more on recharge for estimating the yield of an aquifer. The study revealed that instead of recharge, the discharge estimation gives a reliable estimation of yield from an aquifer. The size of the aquifer/ groundwater resource that could be developed sustainably depends on the discharge that could be taken from the aquifer during the development which depends on the dynamic nature of the aquifer, not on recharge.

2.2.1 Studies on dynamic responses of aquifer using MODFLOW

To study the dynamic response of the aquifer to recharge and discharge, models are very good tools. Various modelling software is available for simulating groundwater flow. MODFLOW, MIKE SHE etc. are some of them. MODFLOW is the widely used software for research purpose.

Wang *et al.* (2008) developed an integrated groundwater model using the MODFLOW code and GIS system for groundwater flow simulation in the North China Plain (NCP). A database for water resource evaluation was created and Geographic Information System (GIS) based modelling data were stored in this database. Input files to the numeric model were created from this database with the help of GIS technology. After doing simulation the results were displayed. This integrated system was applied to NCP. When a water budget analysed during the development of the groundwater model, it showed a negative budget in the NCP. Groundwater pumping, the major discharge from the resource was the reason for the water crisis.

Kushvaha *et al.* (2009) conducted a study in north-eastern Rajasthan by developing a groundwater model using the conceptual model approach. Groundwater Modelling Software (GMS) that supports the MODFLOW 2000 code was used for this purpose. The developed model was calibrated and validated using historical water level data. The model was used to predict the groundwater situation from 2006 to 2020 in the study area. A decrease in groundwater storage from 349.50 to 222.90 Mm^3 and an increase in groundwater draft from 258.69 to 358.74 Mm^3 per annum were predicted. The authors predicted the widening of the groundwater deficit zone due to the reduction in groundwater storage. From the study, it was suggested that artificial recharge and diversification of crops should be followed as remedial measures.

Akram*et al.* (2012) compared two important software used for groundwater study, MODFLOW and MIKE SHE, by simulating groundwater levels in

Bangladesh. Both the software used the finite difference method. MIKE SHE considers the flow through the unsaturated zone also, whereas MODFLOW accounts only flow through the saturated zone and this is the major difference between the two models. Because of this difference MIKE SHE doesn't need separate software for recharge estimation. In the study, the first model was developed using MIKE SHE and the recharge component taken from this model was used as an input in the second model developed with MODFLOW. Simulated groundwater level hydrographs obtained from both the models were almost similar and on par with the observed groundwater level hydrograph. From the study, the authors found that MODFLOW has several advantages over MIKE SHE. Auto calibration facilities, less data requirement for the development of the model, less time requirement etc. are some of them. Moreover, MODFLOW is more user-friendly than MIKE SHE. Hence, the authors concluded that MODFLOW is more suitable for research purposes.

Chitsazan and Movahedian (2015) evaluated the effect of artificial recharge on groundwater in Iran using the MODFLOW model. The aquifer was simulated using MODFLOW code of GMS software. For the assessment of the recharge project, the area was discretized in the GMS software and the initial, as well as boundary conditions, were quantified. Historical data were used for calibration and validation. The results of the study revealed that artificial recharge has a positive effect on the western part of the project area even though it is not sufficient.

Khadri and Pande (2016) developed a groundwater flow model using MODFLOW software for calibrating steady-state flow in the Mahesh river basin in Maharashtra. Simulated the hydraulic head was compared with observed values and it was found that they matched well and the developed model was reliable. The model should be used to predict groundwater levels under various hypothetic conditions. It could also be used to study the impact of human activities like the encroachment of river banks, conversion of wetlands, on groundwater flow and to formulate good management practice scenarios for sustainability of this vital resource. From the results, the researchers got some reasonable and some unsatisfying simulations which showed the necessity of coupling of surface water model and groundwater model to perform accurate analysis of more complex hydrologic systems.

In 2019,Sajeena and Kurien conducted a study using MODFLOW to model groundwater resources of Kadalundy river basin. The analysis was done to find out hydraulic continuity existing in the study area and the results revealed that there is an interaction between surface and groundwater in the major area of the river basin. Resistivity analysis was carried out to obtain layer properties of the aquifer. Groundwater flow modelling was done by Visual MODFLOW. A conceptual model for the study area was developed with the help of the base map, well logs, and observed geophysical data. Monthly pumping rates and water level data were used as inputs to the model along with other hydrologic parameters. The model was calibrated and validated using historical data. After that, it was used for predicting flow head for fifteen future years. These predictions showed that for the first five future years, the groundwater resources of the river basin will remain in a safe condition. Artificial groundwater recharge is required to continue the sustainable nature of this vital water resource.

2.3 CONJUNCTIVE WATER MANAGEMENT

The main purpose of conjunctive water management is to address the issues of unequal water distribution in canal commands and to ensure an uninterrupted supply of the stipulated quantity of water to the tail end users. Researchers, as well as decision-makers, tried a number of strategies to solve this issue. Conjunctive water management is one of the best strategies to alleviate water deficiency issue to a good extent. This strategy utilizes the storage space available beneath the earth's surface effectively. Thus recharge and discharge of groundwater are the major phases of conjunctive water management (Fig 2.1).

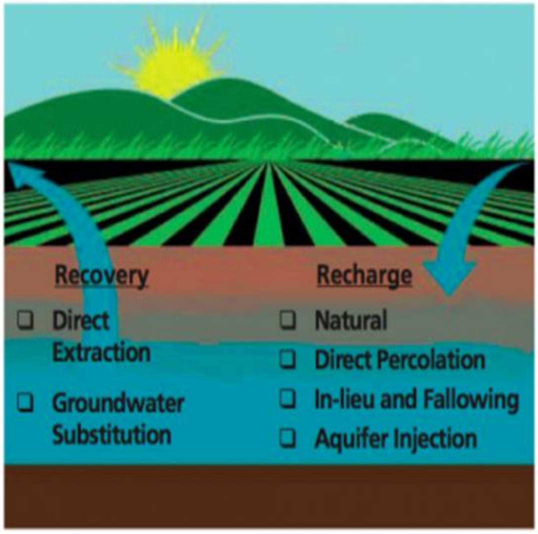


Fig.2.1 Major phases of conjunctive water use – Recharge and Discharge of groundwater

(Source:https://www.sswm.info/sswm-university-course/module-4-sustainable-water-supply/further-resources-water-sources-hardware/conjunctive-use.)

Tyagi *et al.* (2005) investigated the possibility of improving farmers' decisions in mitigating canal water deficiency towards the tail end of watercourses with a view to improving water productivity. The study was conducted in Haryana. From the study, it was revealed that the farmers have very little chance to make decisions related to canal water management due to the rigid supply schedule and inadequacy of water. Their decisions were limited to the operation of tube wells to compensate canal water deficit to some extent. During summer farmers find it difficult to choose the proper crops that tolerate water scarcity as well as salinity due to poor quality groundwater. Even though higher utilization of groundwater increases the crop yields to some extent towards the tail end of watercourses, the reduced water quality affected the yield adversely. The study suggested that by choosing salt tolerant high yielding verities of crops water productivity can be increased to some extent. Aquaculture using both fresh and brackish water was another suggestion for improving water productivity and farmer's income.

Awan *et al.* (2016) reported that head-end farmers of distributaries and watercourses of the canal irrigation systems use a higher percentage of both canal water and groundwater, after conducting a study on equity of water distribution in the Indus basin irrigation system. The study analyzes water distribution in spatial and temporal scales using geospatial techniques. The results showed that 42% of the evapotranspiration needs of the command area were met from groundwater resources making groundwater as an essential part of the irrigation system. The use of water resources varies temporally. Groundwater has been used at the maximum rate in the month of May whereas the canal has been used at the maximum rate in the month of August.

2.3.1 Modelling conjunctive water management

To enable optimum allocation of water in canal commands and to ensure uniform distribution, conjunctive use of water in a planned manner is important. Mathematical modelling techniques are being used to aid the planning process. Researchers have developed several types of mathematical models for planning conjunctive water use suiting to their situation. Optimization models, simulation models and simulation –optimization models are the major types of models used for conjunctive water management.

2.3.1.1Optimization models

An optimization approach for conjunctive water management began since 1960’s itself. An optimal solution/strategy is mathematically the best that can be developed from the formulated mathematical problem of the system/situation. In a conjunctive management system, a groundwater pumping strategy that is optimal for one situation is often sub-optimal for a different situation. Various optimization techniques like linear programming, non- linear programming, dynamic programming, etc. are used to find out optimal solution corresponding to each situation (Safavi*et al*., 2010; Peralta and Shulstad, 2004).

Linear programming techniques for planning conjunctive water use

Linear programming may be considered as the most popular and simple optimization technique used in conjunctive water management. A number of software *viz.* LINGO, LINDO, Solver etc. are available for doing optimization with linear programming. Linear Programming (LP) depicts complex relationships between decision variables into linear functions. Both objective functions and constraints are linear functions of decision variables. Constraints may be equality constraints or inequality constraints (Vedula and Mujumdar, 2005). Many studies have been reported on the modelling of conjunctive water management with optimization techniques using linear programming.

A linear programming model was developed by Kumar and Pathak in 1989. The model was used to work out the optimum cropping pattern suited for the region situated in between the Yamuna river and Eastern Yamuna canal. They also determined the optimum share of the canal as well as groundwater supply on a monthly basis. A sensitivity analysis conducted by them showed that the total net annual benefit was more influenced by the supply of canal and groundwater rather than the total area under cultivation.

Barlow *et al.* (2003) combined numerical simulation and linear optimization techniques to develop a conjunctive water management model for a stream-aquifer system. The model gave a way to evaluate the control over the sustained yield of the aquifer. The relation between groundwater withdrawal and depletion in stream flow obtained from the model could be utilized for taking decisions on groundwater withdrawal strategies. Results from the model application study showed that groundwater withdrawal could be increased up to 18% over the present use without increasing depletion in stream flow. It may be increased up to 50% over the present use by allowing more reduction in the rate of stream flow.

A mathematical model using linear programming was developed by Vedula *et al.* in 2005 to arrive at an optimum policy for allocation of the canal as well as groundwater in a reservoir-canal–aquifer system with multiple crops in its command area. The main objective of the study was the maximization of the sum of relative yields of multiple crops by integrating irrigation using canal water and pumping groundwater.Thus the crop water allocations during different crop periods were attained through the conjunctive use of canal water and groundwater by satisfying the three major constraints. The constraints were a mass balance of water in the reservoir, soil moisture balance for individual crops and the limits of groundwater level fluctuation. The authors validated the applicability of the model by carrying out a study in the command area of a reservoir in Chitradurga district, Karnataka State.

Khare*et al.* (2006) investigated the possibility of conjunctive management of surface and groundwater in a canal command area in Indonesia and suggested an optimum cropping pattern for the area considering the future requirements also. Linear programming package LINDO 6.1 was used for solving the optimization model. The authors found that conjunctive water management is possible with the proposed cropping pattern without adversely affecting groundwater resources.

Raul *et al.* (2012) developed an irrigation scheduling model (ISM) and alinear-programming optimization model (LPM) to plan conjunctive use of surface water and groundwater for the irrigation command area of Hirakud multipurpose project. The model was able to manage the available natural resources, land and water, effectively under uncertain hydrologic conditions in the canal command area. The ISM predicted the actual crop yield under full and deficit irrigation policies. The yield of the crops obtained from ISM was fed to the LPM to optimize the allotted cropped area and surface water based on the net irrigation requirement. Results showed that net annual return was maximum under full irrigation strategy and it decreased as water deficiency increases.

Linear programming is useful in solving multi-objective optimization problems also. Nikam and Regulwar (2015) developed an optimization model with linear programming for the conjunctive use of surface water and groundwater in the command area of a multipurpose single reservoir. The developed model was suitable to find out the best operative strategy for a reservoir and the model was tested in a case study at Jayakwadi reservoir, Maharashtra to obtain the ideal cropping pattern and ideal water release policies. The model was solved by considering two cases 1) by using surface water only and 2) by using both resources, surface water, and groundwater. Optimum discharges for the power generation and irrigation were obtained from the model after giving the first water supply priority for drinking and industrial use. Model allotted more area to most of the crops in the second case considered, that is, conjunctive use of surface water and groundwater.

Non-linear programming techniques for conjunctive water use planning

Even though linear programming is easy to formulate and apply it is unable to solve problems related to non-linear situations (Singh, 2014). Most of the conjunctive water management situations are non-linear in nature. So, non-linear programming is used for optimization, in such a situation where it is difficult to express the objective function and constraints as linear functions (Vedula and Mujumdar, 2005).

A non-linear optimization model was developed by Montazar *et al*. in 2010 for deriving an optimum cropping pattern that maximizes the net benefits due to the planned conjunctive use of surface and groundwater. The model was evaluated by applying in a semi-arid region of Iran. Several conjunctive use scenarios along with existing as well as four proposed cropping patterns were tested.The scenario with deficit irrigation practices was also analyzed. Results showed that the proposed cropping pattern with 78% surface water and 22% groundwater allocation will save a significant quantity of water which can be used for extending the irrigation facilities to more areas in dry conditions. Investigations showed that deficit irrigation could be practiced to increase the conjunctive use of both water resources, surface water, and groundwater, for maximizing the overall benefits, if, groundwater draft has to be compensated through an allowable annual recharge. The authors recommended a 20% deficit irrigation as the ideal conjunctive use plan among the different scenarios studied.

Dynamic programming

To solve sequential decision problems in conjunctive management of water resources, dynamic programming (DP) is used. An example of the sequential decision problem is the release of canal water. The release of canal water depends on reservoir storage and this, in turn, varies temporally.So decisions need to be taken at different time periods according to the storage. Unlike linear programming, problems cannot be formulated by single standard algebraic functions. Specific features of the problems need to be considered while formulating dynamic programming problems. Variables used in water resource allocation problems are considered as discrete variables when dynamic programming is used for optimization. DP problems may be single-stage problems or multi-stage problems (Vedula and Mujumdar, 2005).

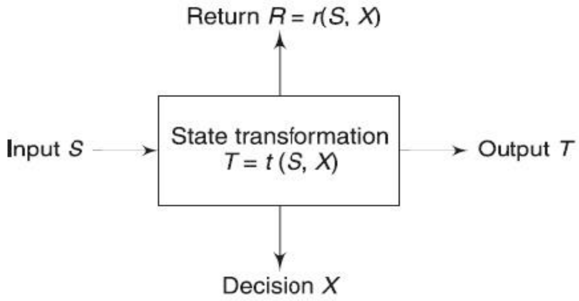


Fig. 2.2 Representation of a single stage dynamic problem (Source: Vedula and Mujumdar, 2005).

Figure 2.2 shows the representation of a single-stage problem. S is the input, X is the decision and T is the output. Due to the effect of decision X on input S return R takes place, which is a function of S and X. Output T is also a function of S and X. In a multi-stage decision problem (fig.2.3) the output T of one stage forms the input S of the next stage. A decision X is added in each stage. Sn is the input to stage n, xn is the decision taken at this stage n, and Rn is the return at this stage, corresponding to the decision xn for the input Sn. As a result of this decision, the input Sn gets transformed into output Sn-1 that forms the input to the next stage n–1.

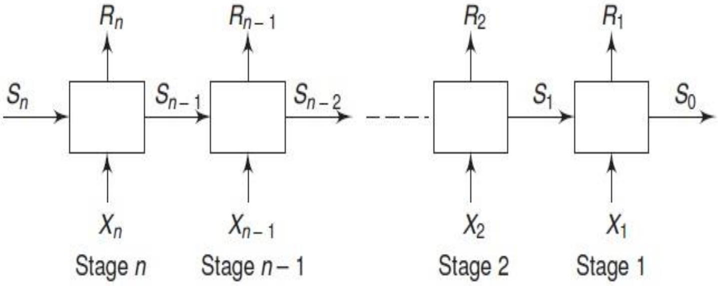


Fig.2.3. Representation of a multi-stage dynamic problem (Source: Vedula and Mujumdar, 2005).

The objective of a multistage decision problem like this is to find the values of decisions x_1, x_2, x_3, …,x_n to maximize the return function (e.g. to maximize the sum of returns overall stages) while satisfying the state transformation equation (Vedula and Mujumdar, 2005).

A dynamic optimization model was developed by Karamouz *et al.* in 2004 for planning conjunctive use of surface water and groundwater in complex water use and recharge system in Tehran, where, sewage effluent was the main source of groundwater recharge. They developed a multi-objective model in which, the supply of water to meet agricultural demands, reduction in pumping cost, reduced fluctuation of groundwater levels etc. were the major objectives. A number of scenarios were tested to find out the long-term impact of conjunctive use planning and it was found that the developed model was effective for planning conjunctive water use.

In 2011, Safavi and Alijanian *developed* a simulation-optimization model using fuzzy dynamic programming to plan optimum crop pattern to overcome uncertainties due to climate changes with conjunctive use of surface water and groundwater for the Najafabad Plain in Iran. Interactions of surface water and groundwater were accounted for in the simulation model and optimum crop plan and conjunctive allocation of surface water and groundwater were decided by the optimization model. The results obtained from the optimization model were used to run a simulation model. To reduce the computational burden and to include uncertainty in the data due to climatic changes a dynamic fuzzy regression was usedin the model. The results of the study indicated that the model is successful in optimum crop planning based on predicted climatic conditions with the conjunctive use of surface water and groundwater in arid and semiarid regions.

Zayandehrood river basin in Iran is an area where the available surface water is insufficient to meet various water demands like domestic, industrial, agricultural and environmental demands. This water scarcity induces high pressure on groundwater resources. In this area, Safavi *et al.* (2013) conducted a study to develop an optimal model for reservoir operation with the conjunctive use of surface water and groundwater resources. Dynamic programming algorithm was selected for optimization, with initial reservoir storage volume as the state variable and optimal canal water release as the decision variable. Minimum and maximum storage capacity of the dam and minimum environmental water demand were the constraints for developing the model. They developed fuzzy models, as a simulator to reduce the computational burden of the DP model and to form operating rules for the reservoir. Another model known as ANFIS was also developed and compared with other models. The authors found that ANFIS and fuzzy models performed better in terms of their dependability as in these models the number of failure months were less compared to other models investigated.

2.3.1.2Simulation models

Simulation is a modelling technique, which is used to imitate the performance of complex water resources systems. It is particularly useful where optimization techniques cannot be used because of their limitations. Simulation, alone, is not an optimization technique but can be used to get near optimum results. In water resources modelling, these near-optimum solutions are as useful as the optimum solutions itself.

Simulation is an important method used for assessing alternate water resources systems and plans. It is an ideal tool for performance evaluation by tracing the behaviour of a complex system (Mohan and Jyothiprakash, 2003). The simulation could give an expected performance of the system with the help of computer programmes written for a specific problem. Under various operating policies or decisions, it is possible to analyze the performance or output of the system by running simulation models. Characteristics of the system should be given as input variables. Also, inputs/inflows to the system like rainfall and other hydrologic parameters should be given as inputs to the simulation model. For the given aquifer parameters and climatic data, a simulation model is able to give groundwater levels corresponding to different pumping rates. Operating policy (pumping rates) may be the result of another optimization model.

Inputs, outputs, physical relationships between variables and constraints, and operating rules are the components of a simulation model. The model transforms inputs into outputs according to physical relationships, constraints and operating rules. For doing simulation, first, a complex system must be divided into sub-systems and proper linkages between them. Computer programmes are formulated for each sub-system and to convey information from one sub-system to another. Verification of the model is necessary with known inputs and outputs. After verification, the model is ready for running with alternate sets of inputs to get corresponding outputs. Simulation runs gave a set of outputs for each set of inputs. Results from a number of simulations are referred to as response surfaces. The slope of the response surface determines the sensitivity of the system to input variables. Near optimum solutions will give a flat response surface. If the system is very sensitive, a large number of simulation runs are necessary to attain this flat response surface. Even then there is a chance that attained optimum may be a local optimum. Hence, the judgement of an experienced systems analyst is important in interpreting the usefulness of the solution obtained from these techniques (Vedula and Mujumdar, 2005).

Bejranonda *et al*. (2011) conducted a simulation study to address the problem of increased water requirement for farming in Thailand, where rice is a major crop. They investigated and mimicked the surface water-groundwater interaction using a mathematical model for groundwater flow and found that there is strong evidence for seasonal surface-groundwater interaction in the study area.The groundwater potential of the area was estimated by running simulations with the maximum possible drawdown of hydraulic head. The authors concluded that by utilizing the unused surface water during the transition period from wet to dry season for groundwater recharge and by doing proper apportioning of this groundwater for conjunctive water use could solve the water scarcity problem in the study area.

Mahjoub *et al.* (2011) developed a simulation model to investigate the conjunctive use option of surface and groundwater in the Maraghe area of Iran. Maximization of total relative yields of all crops in the command area was the objective function used for the conjunctive use model. The maximum level to which the decline of groundwater level could be permitted was selected as the major constraint. GMS software was used to simulate groundwater aquifer. The model was calibrated using four years of data, beginning from a dry year to a normal year. Conjunctive use program was developed in Visual Basic. Two types of scenarios, annual and seasonal, were tested based on the allocation ratio of surface water to that of groundwater. Among annual scenarios, 75 per cent surface water and 25 per cent groundwater was found as the best scenario. The best seasonal scenario selected by the model was 100 - 40 - 60, the percentage of surface water use during spring, summer and winter respectively.

Distribution of canal water may not be fair in most of the command areas. Usually, head-end farmers over-utilize the surface water which in turn forces the tail-end farmers to withdraw groundwater from the unconfined aquifer to meet their irrigation demand. An appropriate scientific tool for evaluating various scenarios is necessary before making decisions on water distribution. With this objective, an integrated numerical simulation model was developed by Biswas *et al.* (2017) considering various processes involved in a basin irrigated canal command area. From this study, they found that even distribution of surface water through a dense network of canals will reduce withdrawal of groundwater by the tail end farmers and waterlogging issues in the head reaches

2.3.1.3 Simulation Optimization models

Most of the conjunctive water management systems are large and quite complex systems to be modelled by either an optimization model or a simulation model. Combination models are necessary in this case. Simulation-optimization model (SO model) is a suitable combination. Within this combination simulation model predicts the consequences of management, and optimization model computes the mathematically best management strategy. Simulation model produces near-optimal solutions and optimization model refines these solutions to get an optimal solution. Thus, the simulation model reduces the size and complexity of the optimization model. Simulation-optimization models are nowadays common in dealing with conjunctive water management problems. Most of the SO models are now handling multi-objective, sometimes conflicting objectives, in conjunctive water management issues. (Vedula and Mujumdar, 2005; Peralta and Shulstad, 2004; Mohan and Jyothiprakash, 2003).

Mohan and Jyothiprakash (2003) combined a simulation-optimization approach for developing an alternate priority-based policy for the conjunctive use of surface and groundwater systems. An optimum cropping pattern for the area that utilizes conjunctive use and without utilizing conjunctive use has been derived from a linear programming based optimization model. Simulation model evaluated the best policies derived from the optimization model. From the results of this optimization-simulation approach, the authors concluded that the conjunctive use of two major water resources, surface water and groundwater, is a must in the command area of Sri Ram Sagar Project in Andhra Pradesh.

Irrigation demand, canal water supply and groundwater balance were the components of an integrated modelling framework developed by Kumar *et al.* (2013) to study the characteristics of interactions between surface and groundwater in a canal-irrigated area to assess the influences of various levels of conjunctive use. Three alternative scenarios, design supplies with current cropping pattern, design supplies with an increase in cropped area, and optimum supplies with an increase in cropped area were tested using simulation modelling. In the scenario analysis, the third scenario- that is, optimum supplies with an increase in cropped area was found optimal. The model has been applied in a case study conducted at Srisailam RBC project in the state of Andhra Pradesh and the results showed that by regulating canal water supply, sustainable use of groundwater could be maintained and canal water could be saved up to 48%. This water savings could be diverted to other areas to achieve equity in water distribution.

A simulation-optimization model was developed by Raul and Panda (2013) to predict the maximum permissible groundwater pumping from the Hirakud canal command area for conjunctive use management of surface and groundwater. Simulation analysis was done by developing a conceptual three-dimensional groundwater flow model which uses Visual MODFLOW for calibration and validation. They also developed an optimization model for determining the optimal cropping pattern that maximizes net annual benefits. Lingo software was used for solving the model. Various possible conjunctive use scenarios were tested. Results indicated that groundwater that can be pumped from the aquifer were 2.0 and 2.3 million m^3 during monsoon and non-monsoon seasons, respectively if rainfall exceeds 90% of normal value. Optimal cropping pattern can increase the net benefits from the command area around 51.3–12.5 % for 10–90 % PERC (probability of exceedance of rainfall and canal water availability), compared to the existing cropping pattern.

Management of different water resources in Ganges basin has been studied by Khan *et al.* (2014) by comparing three strategies for conjunctive use of surface and groundwater. Ganges Water Machine (GWM), Pumping Along Canals (PAC) and Distributed Pumping and Recharge (DPR) were the three strategies involving the use of subsurface water storage. The efficacy of these strategies was determined using numerical models based on MODFLOW. Results showed that using the first strategy GWM, a quantity between 17 and 46 BCM water from the river would be stored as groundwater during monsoon. In the case of PAC this storage would be between 20 and 40 BCM and for DPR this would be 14 and 90BCM. That is around 6–37 % of water exiting Uttar Pradesh through the Ganges during an average monsoon could be stored as groundwater in aquifers. In spite of this advantage, the cost involved in infrastructure and maintenance could be very high. Among the three strategies tested GWM was the most costly one, followed by PAC and DPR. These strategies have been tested for a wide range of scenarios, and they concluded that the actual efficacy of the management of different water resources in the basin conjunctively would vary depending on aquifer characteristics, river characteristics, the topography of the region, and other hydrologic and anthropogenic factors. Hence, before the implementation of conjunctive use policies testing in limited areas is required as pilot projects.

Chen *et al.* (2016) integrated a simulation and optimization model for scheduling irrigation in a multi-crop command area, to alleviate the effect of seasonal drought, using the combined operation of reservoirs and ponds. The objective is to maximize the annual net benefits. There are two components in the integrated model; an operating policy model and an allocation model. The operating policy model optimizes the releases from reservoirs and ponds considering the regulatory role of ponds. Irrigation allocations from reservoirs and ponds were done by the allocation model so as to get an optimum allocation to each crop by considering water production function. To solve this complex integrated problem artificial bee colony algorithm incorporated with differential evolution algorithm and particle swarm optimization algorithm was used. The integrated model is applied at Zhanghe Irrigation District, in China, and compared with the other three simulation models. The results indicated that the integrated model is efficient in reducing the impact of drought and increased the average annual return by 7.9, 7.0 and 3.1% compared to the other three simulation models, respectively.

Chang *et al.* (2017) developed a simulation-optimization model for minimizing the shortage of water for irrigation in a reservoir-pond irrigation system in China, using conjunctive management of these resources. The developed integrated model has two components; an optimal model, which optimizes the reservoir release, and a simulation model that simulates the water supply from ponds and reservoirs. The model is applied in Yarkant River Basin, China. Results showed that due to the combined operation of reservoirs and ponds in the Yarkant River Basin, 51.21% decrease in average annual water shortage will occur after the construction of all the three reservoirs in the Yarkant river sub-irrigation regions. Another advantage of the conjunctive operation of reservoirs is that ecological flow to the river could be maintained.

2.3.1.4Economic optimization model

The use of groundwater in conjunction with surface water leads to an increase in crop production and income compared to the use of a single source. Groundwater acts as a secured source against uncertain surface water during drought periods. However, groundwater use increases production cost due to the cost involved in pumping (Montazar *et al*., 2010). Sometimes the poor quality of groundwater may affect the crop yield. Many studies have been carried out to analyze the economics involved in planned conjunctive water use with the help of a modelling approach. Both optimization models and simulation-optimization models are available for planning conjunctive water management to get maximum economic benefits.

Water resources allocation options were assessed by Khare *et al.* (2007) for planning the combined operation of surface and groundwater resources in the command area of a link canal with an economic optimization model. Linear programming technique was used for optimization to work out a suitable cropping pattern that maximizes net benefits considering various hydrological and management constraints. The objective function was formulated by considering the benefits from different cropping activity and cost for providing a unit quantity of water for irrigation. The model has been run for both the existing and proposed cropping pattern under different scenarios of surface and groundwater use and the proposed cropping pattern has been found suitable for the link canal command. They concluded that by implementing conjunctive use to meet agricultural demands a considerable amount of surface water can be saved for other purposes.

Bharati *et al.* (2008) developed an economic hydrologic simulation-optimization model to help in decisions for the successful management of land and water resources in a small reservoir based irrigation system. WaSiM-ETH, a physical hydrology model that combines surface, subsurface and groundwater hydrology and developed by the Swiss Federal Institute of Technology was used for simulation in this study. The economic optimization model was written in GAMS (General Algebraic Modelling System) with the objective function to maximize the net profit. Time series of surface runoff, groundwater levels and other hydrologic parameters were the major outputs of the WaSiM-ETH model. The outputs from this model provide the boundary conditions for the economic optimization model. After obtaining an optimum solution, values of decision variables are conveyed to the WaSiM-ETH model to re-examine boundary conditions. If boundary conditions have been violated, by restricting groundwater extractions, the optimization model will be re-executed. Results showed that WaSiM-ETH is a successful hydrologic simulation model. Using the data from the hydrologic model, GAMS determined the optimum cropping pattern using nonlinear optimization.

2.3.1.5 Models to handle Water Quality Issues

Conjunctive water management often faces water quality issues along with water scarcity problems. Poor quality water, which is otherwise not suitable for irrigation, could be used for irrigation with conjunctive use of surface and groundwater resources (Singh, 2014c). Many scientists tried to find a solution to the water quality problem using the modelling approach.

Ejaz and Peralta (1995) developed a simulation-optimization model to address the common conflicts between water quantity and quality objectives. The water quantity objective is to maximize water used conjunctively to minimize water shortage. The water quality objective is to maximize waste loading from a Sewage Treatment Plant (STP) to the river without affecting downstream water quality. An increase in conjunctive use of water reduces water for dilution. Hence, a simulation-optimization model to compute optimal conjunctive water use strategies for a stream-aquifer system was developed. The developed model was applied to a hypothetical study area and found that the model could efficiently do the optimization.

Sethi *et al*. (2002) developed a conjunctive water use model to get optimum cropping patterns suited to the coastal river basin. The developed model has two major components, the groundwater balance model and the optimum cropping and groundwater management model. The groundwater balance model was based on a mass balance approach for regulating the groundwater flow to avoid the water table fluctuations and make the system sustainable. The second component of the model maximizes the economic benefits by selecting the optimum cropping pattern and providing proper groundwater management. The optimization model yielded a cropping pattern for three situations. The developed model was applied in a coastal river basin in Orissa and provided an optimum cropping pattern suited for the region under various scenarios. The authors advised the state agencies and farmers to practice conjunctive use of surface and subsurface water to control further depletion of the groundwater level.

In coastal and deltaic regions, irrigation with surface water faces two major issues- uneven distribution, both temporal and spatial and seawater intrusion. Excessive irrigation may lead to waterlogging condition and excess withdrawal of groundwater may lead to intrusion of seawater. Rao *et al.* (2004) developed a conjunctive use model to solve irrigation issues of a coastal deltaic region using a simulated annealing method. Flow simulation is achieved using the Sharp interface model. As we know the availability of both surface water and groundwater varies spatially and temporally. This Spatial and temporal variations of major water resources form constraints for the management model. Quality of water can be maintained by placing well screens above the interface of freshwater and seawater. The management model had to achieve two conflicting objectives, that is, minimizing operational cost and maximizing groundwater reserve. The methodology adopted was combined simulation- optimization with Simulated Annealing (SA) algorithm (optimizer) and Sharp model (simulator). To reduce the computational burden, the Sharp model was replaced later by the Artificial Neural Network (ANN) model.

Lari *et al* (2009) developed a conflict resolution model considering water quality issues in conjunctive water use. In complex surface water and groundwater systems, different stakeholders have multiple conflicting interests. Improving groundwater quality is conflicting with reducing the cost of wastewater collection and purification system. In such a region, the authors developed a model using Non-dominated Sorting Genetic Algorithm II (NSGA II) and Yung Conflict Resolution Theory (YCRT). The groundwater quantity and quality were simulated by using MODFLOW and MT3D. These simulation models were interconnected with the NSGA-II optimization model to get a set of good solutions. Among these solutions best were selected using YCRT. Results showed that, based on the optimal solution, both the objectives were satisfied. That is, the demand for irrigation water is completely delivered and the allocated water satisfies the quality standards.

Heydari *et al.* (2016) developed a multi-objective simulation-optimization model to handle quantity-quality issues in water allocation. Two evolutionary models, an Artificial Neural Network model for simulating groundwater levels and a Genetic Programming model for predicting Total Dissolved Solids (TDS) concentration were combined with NSGA-II. Minimizing water shortage, the drawdown of the groundwater level, and groundwater quality changes were the multi-objectives of the model. MODFLOW was used to simulate groundwater flow. The model was applied to Najaf Abad plain in Iran. The application of the simulation-optimization model showed that the model could generate satisfactory solutions to increase the quality and quantity situations of the aquifer. The results showed that the optimum pattern reduced the water scarcity, near to zero for seven months in a year. Increased groundwater level and the decreased TDS concentration in the groundwater relative to the existing condition were other major results. The authors concluded that the developed model was capable to support in decision making so as to allocate optimum water in a conjunctive management system.

2.3.1.6 Use of Evolutionary Algorithms

For planning conjunctive water management optimization, simulation and simulation –optimization models are widely used. Classical optimization methods have a disadvantage that it needs a large number of numerical computations to get an optimal solution. Sometimes that optimal solution may be a local optimum. Evolutionary techniques like a Genetic Algorithm (GA) are efficient in solving the optimum conjunctive management models and identifying global optimal solutions.

The use of simulation –optimization models is common in recent years for planning conjunctive water management. The simulation model represents the physical nature of the system and the optimization model represents the conjunctive water use characteristics of the system. Linking between simulation and optimization models often faced difficulty due to computational load, because the simulation model has to be called several hundred or thousands of times to fulfill the constraints. Researchers often overwhelmed this problem, by using an approximate simulator of the physical processes. Artificial neural networks, Support Vector Machines (SVMs), Relevance Vector Machines (RVMs) etc. are some examples.These type of estimation models are based on machine-learning theory (Safavi and Esmikhani 2013).

Genetic Algorithms

Genetic Algorithms (GA) are used to solve complex optimization problems. It is a search technique based on the theory of biological evolution, i.e. survival of the fittest. The evolution starts from a random population and optimization occurs in generations. A fitness function formulated in the model evaluates all the individuals in the population, in each generation, for their fitness. Several individuals are selected from one population and modified to form a new population (Singh, 2014). Genetic Algorithms are nowadays used in various conjunctive water management models.

Chowdhary *et al.* (2012) developed an optimization model for conjunctive use of surface water and groundwater using both Genetic algorithm and Linear

Programming and applied for multipurpose Mahanadi Reservoir Project in Chhattisgarh. Optimum canal release, pumping quantity from groundwater and water allocation for each crop etc. were the outputs obtained from the model with the objective function of maximizing the total relative yields of all individual crops. In this study optimization model (both GA based and LP) was formulated for optimal allocation of both the surface and groundwater available for each season among different crops. The authors compared the results obtained from GA and LP and found that both are reasonably close. The study proved that GA can be used for modelling integrated use of surface and groundwater.

A multi-objective optimization model based on inter-basin water resources and restoration of outer-basin water resources was developed by Tabari and Yazdi in 2014. The objectives of this plan included reducing the water scarcity for agricultural purposes, reducing the water leaving out of the boundary of Iran and increasing the water transferred to an unused lake for remediation. A planning period of 10 years and 26 decision variables for each month were considered. Since the decision variables were plenty and nonlinear relations were existing between water resources, NSGA-II was used for optimization. The results indicated that the implementation of the optimal policies that were obtained from the model could reduce the volume of water flowing off the border and increase the inter-basin transfer to the adjacent basin.

Artificial Neural Network

Artificial Neural Network (ANN) resembles the biological neural network mainly in two aspects. It can acquire knowledge through a learning process and is able to store it and recollect it through interconnections known as synaptic weights. ANN is able to perform a number of tasks like classification, data clustering, optimization and pattern-matching, an approximation that is challenging for ordinary computers.

ANN has a large number of processing elements known as nodes or neurons. Neurons are inter-connected through connection links. Weight is given to these links that carry information about the input. Artificial neurons are also connected by some weighted links in a specific network pattern and that is ANN. Natural neural network transforms inputs into meaningful outputs. To achieve this ANN is trained to learn the relationship between the input and the output. A number of sets of inputs and outputs are needed for this. ANN achieves the training with the help of a training algorithm by determining the optimal values for synaptic weights. Thus, using a supervised learning process a trained ANN could act as a good simulator. It is possible to use ANN successfully in conjunctive water management models (Vedula and Mujumdar, 2005).

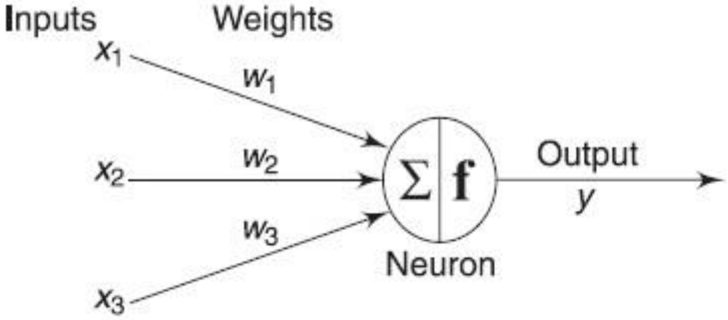


Fig. 2.4. Representation of Artificial neuron. (Source: Vedula and Mujumdar, 2005)

Karamouz*et al.*, (2007) developed a multi-objective simulation-optimization model using Artificial Neural Network (ANN) and Genetic Algorithm (GA) which effectively reduces the computational time, for the combined use of surface and groundwater resources. Sufficient water to meet irrigation demands, minimizing the pumping charges and fluctuations in the groundwater table was the objective functions. MODFLOW- PMWIN model, by Chiang and Kinzelbach (2001), was used as a simulator that simulates the aquifer characteristics. The results obtained from the groundwater model were utilized to train an ANN. The results of this ANN-based groundwater simulation model were then combined with a GA- based optimization model for getting a monthly allocation of canal water and groundwater in a conjunctive management system.

Fuzzy optimization

While developing conjunctive water management models, various natural parameters are involved like rainfall, surface water availability and groundwater recharge. Most of these parameters are uncertain in nature. By including the uncertainty of such parameters perfection of the model could be improved. The application of fuzzy logic is a method for this. Fuzziness indicates vagueness in events. Usually, it is expressed as qualitative terms in objective function or constraints. Vagueness is represented as a membership function. For example, heavy rainfall to cause runoff is a vague term. The quantity at which rain becomes heavy depends on various factors. This uncertainty could be included in the model using some functions known as membership functions and some operating rules. Several models are developed for conjunctive water management in which fuzzy logic is used for optimization (Louks and van Beek, 2005; Vedula and Mujumdar, 2005).

An irrigation planning model was formulated by Regulwar and Pradhan (2013) for the conjunctive use of surface and groundwater. While planning irrigation management, decision-makers deal with uncertain resources like rainfall, surface water, groundwater etc. Hence, in this study, the uncertain nature of water available for agricultural purposes was used to get an optimum cropping pattern. Major resources considered, surface water, groundwater and crop area were represented in a fuzzy set. A Fuzzy Linear Programming (FLP) model was formulated with an objective function of maximizing the net profits and it was applied in a case study of Jayakwadi Project in Maharashtra. Optimization resulted in a satisfaction level up to 0.546, when the uncertainty involved in the availability of water resources has been taken into consideration.

CHAPTER 3

MATERIALS AND METHODS

Irrigated agriculture is necessary to produce enough food for the growing population. Surface water alone is not sufficient to meet the irrigation requirement in almost all places due to the temporal variation of rainfall. Integrated use of available water resources, surface and groundwater, is a possible solution to overcome the situation. Optimum utilization of these vital resources is necessary for sustainability. Hence, the present study aims to develop an optimization model for conjunctive use of surface and groundwater for a multi-crop irrigation command. The development of the model comprises of various components like determination of irrigation demand of the command area, assessment of the adequacy of surface water availability, evaluation of groundwater potential, formulation of the optimization problem and its solution. This chapter describes various details pertaining to the study area, various software and tools used for the study, the sources of data, and the methodology followed for the development of the model.

3.1 DESCRIPTION OF THE STUDY AREA

The study was conducted in the command area of Chalakudy River Diversion Scheme located in the Thrissur and Ernakulam districts of Kerala. The command area is lying between the north latitudes10^{o} 8’45” and 10^{o}24’ 28” and the east longitudes 76^{o} 12’ 37” and 76^{o} 22’ 17” (Fig.3.1). Chalakudy River Diversion Scheme is a major irrigation project in central Kerala, which was commissioned during 1957 after the construction of a diversion weir at Thumburmuzhi and stage II was commissioned in 1966. The weir having a height of 3.96 m diverted water to both the banks of the river. The canal system supplies water to a cultivable command area of 13,895 hectares out of a total area of 39685 hectares (Madhusoodhanan and Eldho, 2012).

3.1.1 Climate

The Chalakudy river basin and its river diversion scheme command area lies in the humid tropical region. The average temperature varies from 25.77°C to 35.12°C. The data on weather parameters for 27 years (1990- 2016) were collected from Agronomic Research Station, Chalakudy, located at the centre of the command area.Additionally rainfall data from two more nearby Indian Meteorological Department (IMD) rainfall stations were also collected. The average monthly meteorological parameters during the period 1990 to 2016 of the command area are shown in Table 3.1.

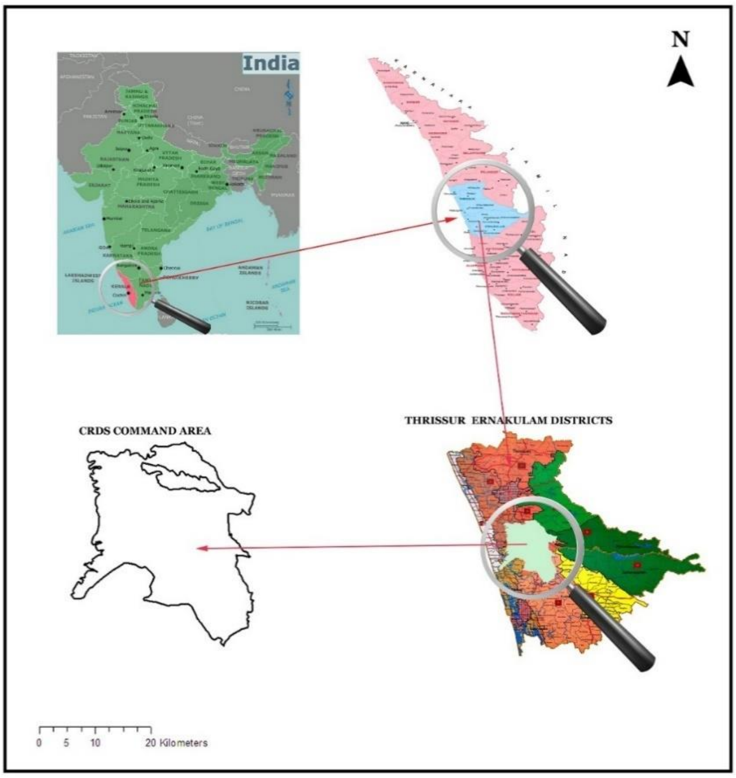


Fig.3.1. Location map of the study area

3.1.2 Soil

Laterite is the predominant type of soil in this region. It is highly porous and drainable. Alluvial soil is also found in some low lying patches in the area (CGWB, 2013; Varma, 2017). For the computation of the irrigation requirement of the area, soilcharacteristics of the Agro-Ecological Units (AEU) through which the canal passes were taken from the agro-ecological zone map of Kerala prepared by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). Out of the 23 AEU's of Kerala, seven units lie in the command area (Fig 3.2). Table 3.2 shows the agro-ecological units of the command area.

Table 3.1 Mean daily meteorological parameters of CRDS command area (1990 – 2016)

Month	Mini Temp (°C)	Max Temp (°C)	Humidity (%)	Sun shine hours (h)	Radiation (MJm-^{2}day^{-1})
January	20.2	33.4	73	8.4	19.7
February	21.4	34.5	73	8.5	21.1
March	23.5	35.4	75	8.0	21.5
April	24.5	34.8	78	7.2	20.6
May	24.4	33.6	79	6.6	19.4
June	23.3	30.3	83	5.0	16.6
July	22.8	29.4	84	4.7	16.3
August	23.0	29.7	84	4.7	16.5
September	23.0	30.7	82	5.3	17.4
October	22.6	31.3	80	5.9	17.4
November	22.0	32.0	78	6.7	17.4
December	21.4	32.7	76	7.3	17.7

3.1.3 Rainfall

The precipitation was found adequate in the study area with an average annual rainfall of 3193.5 mm. The spatial and temporal variations in rainfall were experienced in the region. About seventy percentage of rainfall is obtained during the southwest monsoon and eighteen percentage during the northeast monsoon. The remaining twelve percentage is obtained as summer rains.

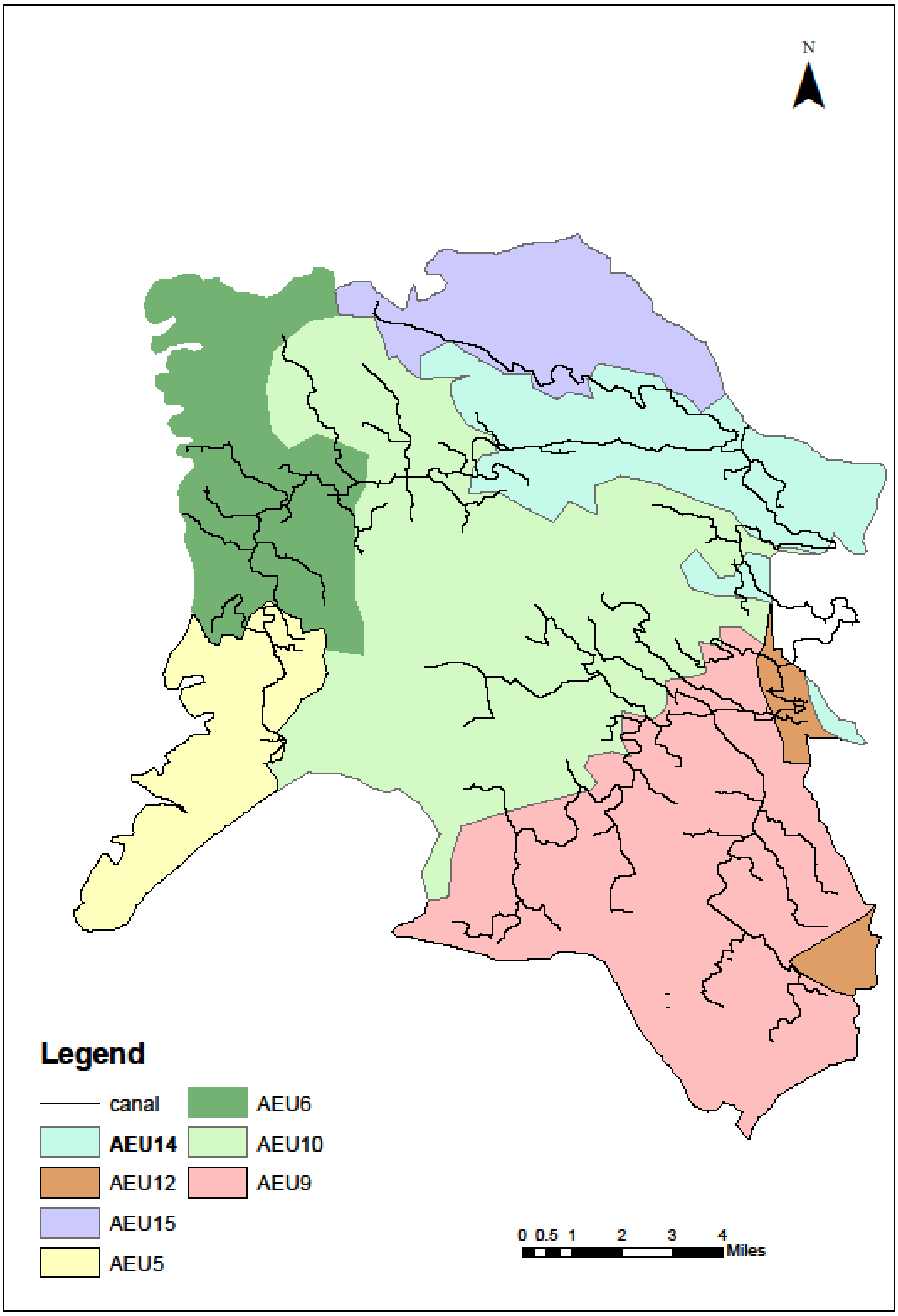


Fig.3.2. Agro-ecological units in the CRDS command area

The average annual rainfall varies from 2135 mm to 4087 mm from 1991 to 2014. Rainfall data were collected (1991-2014) from Agronomic Research Station, Chalakudy and two nearby IMD rain gauge stations, Kodungallur and Perumbavoor. Since the rainfall data of the two IMD stations were available for the period from 1991 to 2014 only, the data for the same period was collected from Agronomic Research Station, Chalakudy and used in the analysis.

Table 3.2 Agro-Ecological Units in the CRDS command area

Agro-Ecological Unit	Description
AEU 5	Pokkali Lands
AEU 6	Kole lands
AEU 9	South Central Laterites
AEU 10	North Central Laterites
AEU 12	Southern and Central Foothills
AEU 14	Southern High Hills
AEU 15	Northern High Hills

(Source: http://www.keralasoilfertility.net/en/agroecology.jsp)

3.1.4 Cropping Pattern

Generally, multiple cropping pattern isfollowed in the command area, except in paddy fields. The major crops in the multiple crop pattern are coconut, nutmeg, banana and vegetables which are highly water demanding. Paddy is cultivated in two seasons, ‘Virippu’ or Kharif and ‘Mundakan’or Rabi, between May and January. In the third season, paddy cultivation is less and summer fallow is cultivated by vegetable crops.

3.1.4.1 *Crop Water Requirement*

Paddy, the most water-demanding crop, covered one tenth of the command area. Average irrigation water requirement of paddy in the command area varies with season, around 250 mm for *Virippu,* 800 mm for *Puncha*and in between for *Mundakan*. Around 70 per cent of the command area is occupied by multiple cropsand coconut based cropping system. The average irrigation requirement of banana, a high water demanding cropis around 650 mm per year. Nutmeg and coconut, the other two major crops of these two cropping patterns,followed banana in the case of yearly irrigation requirement.

3.1.4.2 *Water Use Efficiency*

The canal system of CRDS has high amount of seepage losses due to the damaged lining and poor water management issues. Moreover, the water delivered to the fields from the canals is applied through inefficient surface irrigation methods. Due to these reasons, the field water use efficiency of the crops in the command area are relatively low.

3.1.5 Hydrogeological parameters

The study area lies in the midland region of Kerala. The average elevation of midland is around 20 m above the mean sea level (MSL). Some patches of low lands/ paddy fields are also found in between the lateritic areas (CGWB, 2013). Below the lateritic layer weathered rock and hard rock formations exist. The lithology data of the study area were collected from the State Government Groundwater Department and shown in Appendix I. Lithological data showed that the thickness of the lateritic zone in the area ranges from 3 m to 15 m. Lateritic aquifer covers most of the study area. The transmissivity of the aquifer in the area varies from 22 to 288 m^2/day (Varma, 2017).

3.1.6 Groundwater Scenario

The groundwater from the aquifer is extracted through dug wells and shallow depth bore wells. Water level data of 17 observation wells from 1996 to 2016 were collected from the website of the Central Groundwater Board (CGWB) and are shown in Appendix II. Location of these wells are shown in figure 3.6. The average depth to the water table in the study area ranges from 0.59 to 14 m below the ground level. (CGWB, 2013; Varma, 2017). Groundwater level data of dug wells recorded by the State Government Groundwater Department also indicated similar variation in depth of water level in Thrissur and Ernakulam districts. In

Thrissur district, minimum depth is 1.53 mbgl and maximum depth is 12.72 mbgl during May 2020. In Ernakulam district depth to groundwater level varies from 0.25 mbgl to 10.12 mbgl during this period. During 2019, CGWB reports the depth to water level varies from 0.31mbgl to 15.55 mbgl in Ernakulam district and from 1.28 mbgl to 14.82 mbgl in Thrissur district in the pre-monsoon period. This indicates similarity in the average depth to water level observed by both CGWB and State Groundwater Departments. District wise depth to water level observed by the State Groundwater Departmentduring the pre-monsoon for the year 2020 and that observed by the Central Groundwater Board during the pre-monsoon for the year 2019 are shown in Appendix III.

3.1.7 Irrigation system in the command area

The average annual rainfall over the command area is 3193.5 mm and temporal variation was found even within a single year. Irrigation is needed during ‘Mundakan’ or Rabi and ‘Puncha’ or Summer season. The cultivable command area mainly depends on CRDS canal water for irrigation. The canal water supply is from Thumburmuzhi weir and the distribution is controlled by the Irrigation Department. Some lift irrigation schemes are also operating in the nearby area which is not coming under the CultivableCommand Area (CCA) of the canal system. The view of the Thumburmuzhi weir is shown in plate 3.1.

3.1.7.1 *Canal Network*

The CRDS canal system has two main canals, Right Bank Canal (RBC) and Left Bank Canal (LBC). The RBC which is 52.7 km long distributes water to the command area through 24 branch canals and their distributaries. The LBC having a length of 33.2 km covers its command area with 14 branches and their distributaries. Almost 90 percent of the canal length including the main canal and branches has been lined. But the present situation of lining is pathetic. It is worn out at many places in almost all branch canals. Scouring of the channel bottom is observed in many canal branches and in main canals towards the tail end. The poor condition of the canal lining is shown in plates 3.2 (a) and (b). The schematic diagram of the CRDS canal system is shown in Fig.3.3.

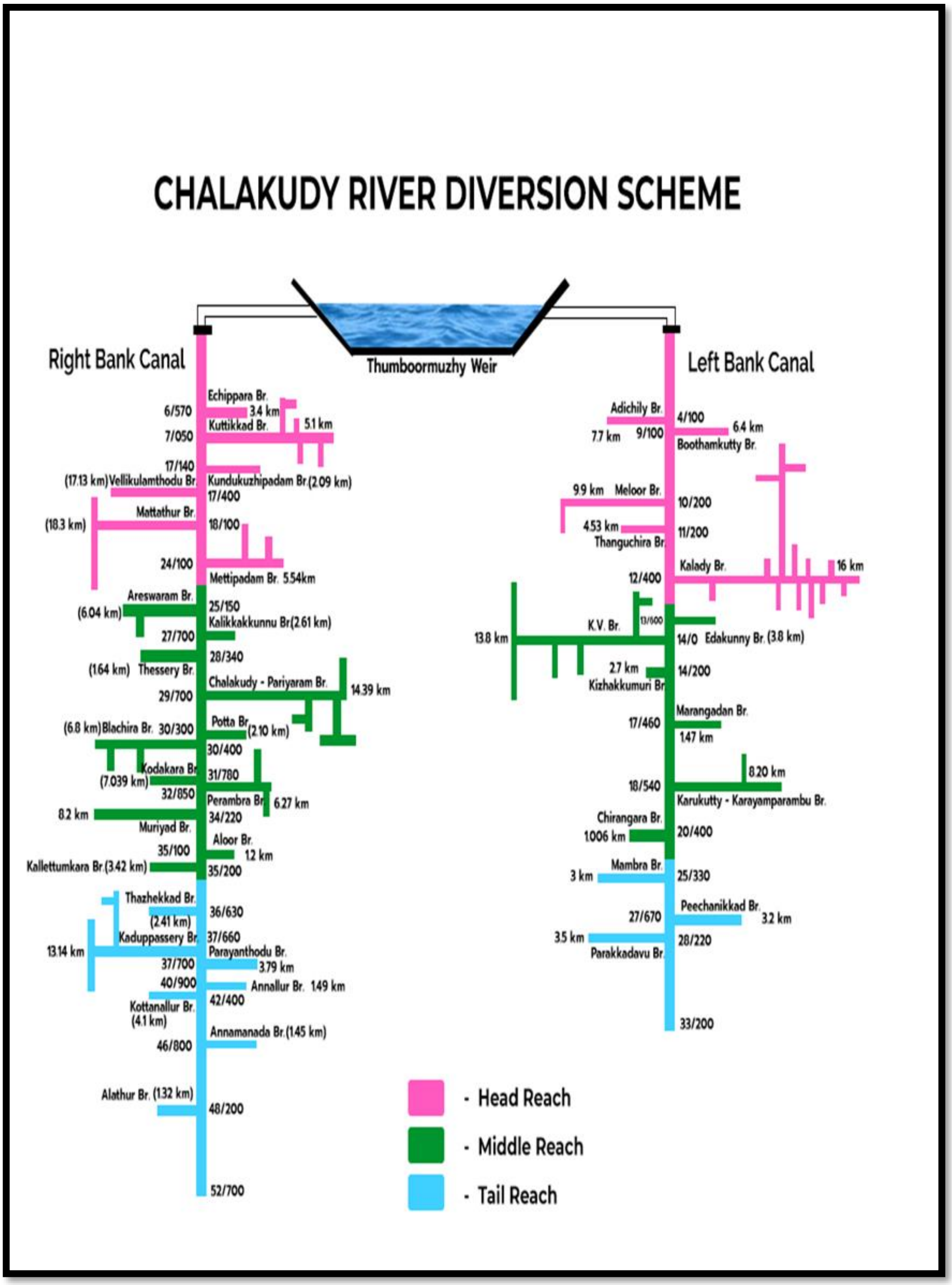


Fig.3.3 Schematic diagram of the CRDS canal system

3.2 SOFTWARE AND TOOLS USED

The following different software, tools and the corresponding methodology were used for the analysis of various data for the development of conjunctive water management model.

3.2.1 ArcGIS software

The geographical information system software ArcGIS 10.3.1 developed by Environmental System Research Institute was used for the preparation and analysis of maps. The work was done using the facilities available at the geospatial laboratory at KCAET, Tavanur. The software offers capabilities for creation of maps, spatial analysis of geographic data, manipulation and editing of geodatabase.

The extraction tools of the software clip and buffer were used for the study. Conversion tools convert the layer into shape and Keyhole Markup Language (KML) files and vice versa. The data management tools were used for exporting data. The surface tools were used to prepare contour map from Digital Elevation Model (DEM). The proximity analysis tool was used for deriving Thiessen polygons to compute the average rainfall of the command area.

3.2.2 ERDAS IMAGINE

ERDAS Imagine 2015 developed by Intergraph, USA is the software used for image processing and is capable of editing raster graphics. It can perform geospatial analysis of vector as well as raster images. Analysis of hyper spectral images is also possible with this software. The land use/land cover classification was done using the software. The processed imageries from ERDAS IMAGINE are suitable for working with ArcGIS and other GIS software. The work was done at the geospatial laboratory at KCAET, Tavanur.

Digital image processing based on the reflectance of materials on the earth surface was used for land use classification. Satellite imagery, Sentinel 2 level 1C of the study area was downloaded from United States Geographical Survey, USGS Earth Explorer website. Cloud free image, captured during the month of March was used for the study. The multispectral image has 13 bands with resolutions ranging from 10 m to 60 m. Six bands of spatial resolution 20 m which can be effectively used for land use classification were taken for the study. They were joined and converted into a single layer by stacking of the imageries in ERDAS IMAGINE. The imagery of the study area was separated by sub setting the stacked imagery with the geo-referenced boundary of the study area.

3.2.3 CROPWAT 8.0

The **w**ater requirement of crops in the command area was computed using CROPWAT 8.0 software developed by FAO. From this, the irrigation requirement of major cropping patterns in the command area was obtained using the scheme schedule module of CROPWAT 8.0. The total irrigation requirement of the crops was multiplied with cultivated area to get the requirement in volume units.

3.2.4 Visual MODFLOW

Visual MODFLOW 2.8.1 is a software developed by Waterloo Hydrogeologic with a graphical interface. The software uses finite difference method for describing the movement of groundwater beneath the surface of the earth. Groundwater models can be developed graphically on-screen by uploading data existing in common formats like BMP, Excel and other databases. Input data to the model *viz.* aquifer properties, boundary conditions and well data can be assigned graphically in row, column and layer into the model.

Visual MODFLOW translates this information into text files so that the model could run by USGS MODFLOW to generate a groundwater flow solution. The user interface of Visual MODFLOW helps for easy analysis and interpretation of the model results by producing colour/contour maps and charts. Water table contour map and water level hydrographs of wells obtained after calibration and validation were used to analyse the groundwater status of the study area. It is easy to check the calibration using this visual interface. Groundwater balance of the aquifer known as zone budget could also be obtained as a bar chart from Visual MODFLOW. This output was used for the development of stable conjunctive use policy for the command area.

3.2.5. LINGO

LINGO is the software developed by LINDO Systems Inc. for solving optimization problems that have linear, nonlinear or integer relationships. The version LINGO 18.0 was used for the study to solve the optimization model for conjunctive water management planning. The software is easy to operate with its powerful language. Models can be built, edited and solved in a quicker way with the help of its built-in solver.

Use of sets is possible in LINGO 18.0 to group related objects. Lengthy programmes could be reduced to shorter ones with the use of sets and related modelling language. A number of similar constraints can be reduced to a single statement by the use of sets.

3.2.6. Overview of the methodology

A conjunctive water management model was developed using all the above models and the collected site-specific data. A general flowchart of the methodology followed is shown schematically in Figure 3.4.

3.3 ADEQUACY OF IRRIGATION WATER

Conjunctive water use is the judicious use of both surface and groundwater so as to get maximum yield /benefit. The rational and scientific use of these resources in a planned manner is essential for ensuring water use efficiency in canal commands**.** The computation of irrigation requirements of the command area is essential for proper planning of the use of these water resources. Land use map of the area is a pre-requisite for estimating the area under each crop. Since surface water is the easily available water for irrigation, the availability of surface water and its distribution in the canal system also needs to be assessed before planning conjunctive water management.

3.3.1 Preparation of base map of the study area

Base map of the study area was prepared using ArcGIS software. The boundary of the command area and the canal network were obtained from the ‘India-WRIS’ website.

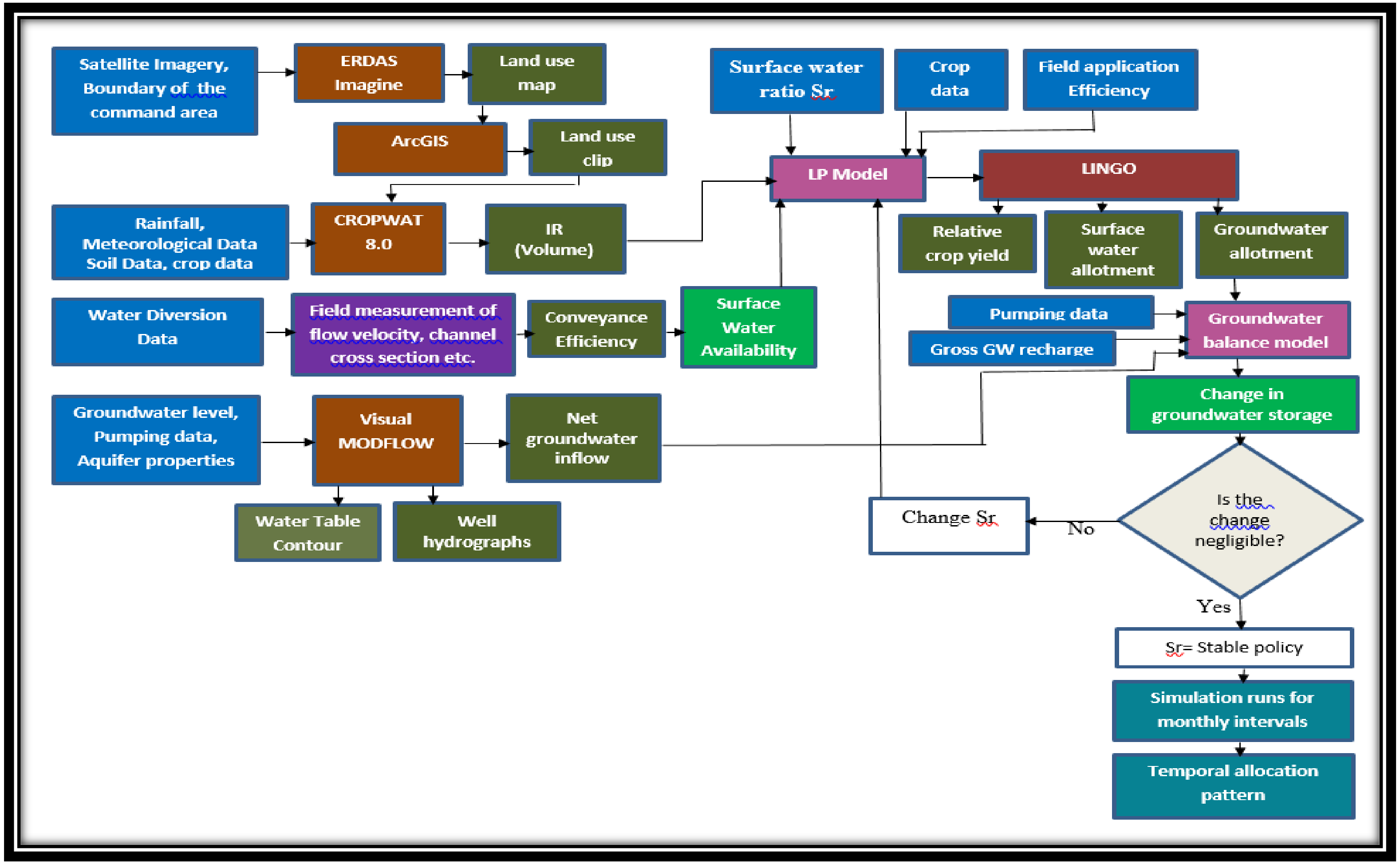


Fig. 3.4 Methodology flow chart

3.3.2 Preparation of Land use map

Land use map of the CRDS command area was prepared using ERDAS Imagine software. Unsupervised classification was done for the preparation of land use map. Training data sets are not required for this classification. The software algorithm itself grouped the image pixels into several clusters based on their properties. Iterative Self-Organizing Data Analysis Technique (ISODATA) is the algorithm used in ERDAS Imagine to execute unsupervised classification. The algorithm forms the clusters using the method of the minimum spectral distance formula. The number of groups to be generated should be given. Each group/cluster is then identified comparing it with the ground verified land use/cover.

All Digital Number (DN) values were divided into thirty classes. The classes were identified manually from the experience gained from the area during the field survey. Google earth imagery of the area was also used for identifying the classes. After identifying all the classes, the similar land cover classes were grouped together using attribute editor toolbar and named according to the ground truth land cover. The process was repeated and ten land use/land cover classes were identified in the area.

3.3.3 Land use data of branch canals

From the land use map of the command area of CRDS, land use in the cultivable command area of each branch canal was clipped using the buffer area of each branch. The clip tool in the ArcGIS software was used for this purpose. Thus the area under different crops/cropping pattern in the command area of each branch were identified from the attribute table of the land use clip. The data thus derived was used for the computation of water requirement of crops in the area.

3.3.4 Estimation of Irrigation requirement

Irrigation requirement of the CRDS command area was calculated using the software CROPWAT 8.0. For the estimation of reference crop evapotranspiration, CROPWAT 8.0 uses the Penman-Monteith equation (Allen *et al.,* 1998) which is as follows.

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma(900/(T+273))\, u_2\, (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\, u_2)} \qquad \text{(Eq. 3.1)}$$

where,

ETo -Reference crop evapotranspiration, mm day^{-1}

Rn - Net radiation at the crop surface, MJ m^{-2} day^{-1}

G - Soil heat flux density, MJ m^{-2} day^{-1}

T - Mean daily air temperature at 2 m height, °C

u_2 -Wind speed at 2 m height, m s^{-1}

e_s - Saturation vapour pressure, kPa

e_a - Actual vapour pressure, kPa

e_s-e_a - Saturation vapour pressure deficit, kPa

Δ - Slope vapour pressure curve, kPa $°C^{-1}$

Γ - Psychrometric constant, kPa $°C^{-1}$

ET $_{crop}$ was then calculated as follows,

$$ET_C = K_C \times ET_0 \qquad \text{---------} \qquad \text{(Eq. 3.2)}$$

Where, K_C is the crop coefficient.

Irrigation requirement was computed as follows

$$\text{Irrigation Requirement} = ET_C - P_{eff} \qquad \text{-----------} \qquad \text{(Eq. 3.3)}$$

United States Department of Agriculture(USDA) Soil Conservation Service method available in the model was selected to calculate the effective rainfall as follows:

$$P_{eff\,(dec)} = P_{dec} * (125 - 0.6 * P_{dec}) / 125 \qquad \text{-------------} \qquad \text{(Eq. 3.4)}$$

for $P_{dec} <= 250/3$ mm

$$P_{eff\,(dec)} = (125/3) + 0.1 * P_{dec} \qquad \text{-------------} \qquad \text{(Eq. 3.5)}$$

for $P_{dec} > 250/3$ mm

where,

P_{eff} - Effective rainfall, mm

P_{dec} – Rainfall for 10 days, mm

3.3.4.1 *Data input to CROPWAT8.0*

There are five input modules in this software. They are climate/ET$_0$, rain, soil, crop and crop pattern, the details of which are as follows.

Climate module

Twenty seven years' (1990 – 2016) average daily data of the maximum and minimum temperature was used as climate/ET$_0$ input (Appendix IV). Other parameters, relative humidity, sunshine hours and wind speed were estimated by the software according to the latitude, longitude and altitude of the area. Reference crop evapotranspiration is obtained as output from this module.

Rainfall module

The average dailyrainfall of 24 years (1991 to 2014) was used as input to this module (Appendix V). Since the command area of CRDS is of large areal extent, spatial variation of rainfall is experienced. In order to account for this variation, rainfall data from two more nearby IMD rain gauge stations *viz*, Kodungallur and Perumbavoor were also collected. Since these IMD rain gauge stations are outside the command area of CRDS, the area influenced by these rain gauge stations was estimated by preparing Thiessen polygons using ArcGIS software. After finding out the influential area of each rain gauge station, the weighted average of rainfall was calculated with influential area as weight of rainfall recorded at the respective station. This average daily rainfall was entered into the CROPWAT 8.0 software in the rainfall input module. The monthly total rainfall and the effective rainfall were obtained from this module.

Soil module

The command area of CRDS consists of seven agro-ecological units. Soil characteristics such as total available soil moisture, maximum rain infiltration rate and maximum rooting depth of these seven agro-ecological units were entered and saved in the software. While computing irrigation requirement of each branch canal command area, corresponding soil file of the respective agro-ecological unit, through which the branch canal passes was selected. Representative values of soil characteristics of one AEU are shown in Table 3.3. Soil characteristics of agro-ecological units within the command area are shown in Appendix VI

Crop module

The details of all crops cultivated in the command area were entered in the crop input module. Various inputs to this module are planting date, crop coefficient values corresponding to each growth stage, stage length, rooting depth, yield response factor, and critical depletion .etc. Among the different inputs crop coefficient values, and yield response factor were taken from the literature (Anjana *et al*., 2015; Surendran *et al*., 2017).

Table 3.3 Soil characteristics of AEU 10 (North central laterites)

General soil data	
Total available soil moisture (FC-WP)	86 mm/m
Maximum rain infiltration rate	107 mm/day
Maximum rooting depth	200 cm
Initial soil moisture depletion (as %TAM)	0 %
Initial available soil moisture	86 mm/m
Additional data for rice calculations	
Drainable porosity	22 %
Critical depletion for puddle cracking	0.8 (fraction)
Maximum percolation rate after puddling	4.7 mm/day
Water availability at planting	50 mm WD
Maximum water depth	50 mm

The crop coefficient values of seasonal crops vary according to the growth stages. While for perennial crops, crop coefficient values corresponding to the late stage of growth was used for the computation of crop water requirement. The planting dates of the crops in the command area were collected from Agronomic Research Station, Chalakudy. The details of data related to the crops are shownin Appendix VII.

Crop pattern

Crop pattern is another input module. The percentage of area occupied by each crop in a cropping pattern and its planting date are entered in this module. Major crops that are cultivated in the command area and the percentage coverage of various crops in a particular cropping pattern were collected from the State Agricultural Department. Details of the cropping pattern in the cultivable command area of CRDS are shownin Appendix VIII.

3.3.4.2 *CROPWAT 8.0 Output*

The variousoutputs of CROPWAT 8.0 are reference crop evapotranspiration, effective rainfall and water requirement of the crop. Irrigation requirement of cropping patterns of different branch canals were obtained from the 'Scheme' module of the software. These different outputs were used for the computation of the irrigation requirement of the command area.

3.3.4.3 *Net Irrigation requirement of the command area*

Irrigation requirement of paddy and other cropping patterns differ in different agro- ecological units. Hence, depending upon the agro-ecological unit through which a branch canal passes, the corresponding depth of irrigation was assigned to crop/cropping pattern existing in its command area. This depth of irrigation was multiplied by the area occupied by the corresponding crop/cropping pattern in the branch canal to get the irrigation requirement in volumetric units. The area was taken from the land-use clip of each branch canal command area. By adding the irrigation requirement of all such branch canals the total irrigation requirement of the entire cultural command area of CRDS was computed.

3.3.5 Performance of canal water distribution system

The performance of the canal system was evaluated by field measurement of seepage loss and estimation of adequacy indicators. The measured seepage loss was used for assessing the conveyance efficiency. The availability of canal water is a constraint in the optimization model.

3.3.5.1 *Flow measurement in canals*

The present status of canal water availability was evaluated by measuring the discharge rate through the main canal and the selected branches of CRDS canal system. Two branches were selected from each reach, at the head, middle and tail end, of the canal system. The velocity-area method was used for measuring the flow rate. The velocity of flow was measured with a pigmy current meter which can measure flow rate between 0.1 to 3.5 m/s. The canal cross sectional area was measured using a tape. Flow measurement using the instrument is shown in the plate 3.3. Then flow rate was estimated using the following formula,

$$Q = A \times V \qquad \text{----------- (Eq. 3.6)}$$

where,

Q = Flow rate in m^3/s

A = Cross- sectional area in m^2

V = Velocity of flow in m/s

3.3.5.2 *Seepage loss and conveyance efficiency*

Inflow- outflow method was used for the measurement of seepage loss. A section of canal that doesn’t have any spout to deliver water to the field was selected for seepage measurement. This inflow- outflow method involves measuring the amount of water flow into a canal at the inlet section and amount that flows out at the tail end of the section. The difference between inflow and outflow of a section gives the seepage loss. The rate of flow at the inlet and outlet of the section were obtained by multiplying velocity of flow and the cross sectional area. The difference in inflow and outflow is the seepage loss, evaporation being ignored

(Akkuzu*et al.*, 2007). Conveyance efficiency is obtained as the ratio of water delivered to the field to the water diverted to the canal (Michael, 1991). Different equations used for the calculation are as follows.

Seepage loss, m^3/s = Discharge at inlet of the section - Discharge at outlet of the section ------- (Eq. 3.7)

$$\text{Seepage loss } (m^3/s \text{ per km}) = \frac{\text{Seepage loss } (m^3/s)}{\text{Length of the section in km}} \quad \text{----- -- (Eq. 3.8)}$$

$$\text{Conveyance efficiency } = \frac{\text{Water delivered to the field}}{\text{Water diverted to the canal}} X\, 100 \text{----- (Eq. 3. 9)}$$

The seepage loss at the head, middle and tail reach of the main canal were estimated. The rate of seepage loss per km length was multiplied by the length of the corresponding section and the period of water flow occurring through the section on an annual basis. But in the case of branch canal, six branches were selected and their seepage loss was measured. The average of these was applied uniformly to estimate the seepage loss in branch canals. By adding the seepage loss from main canals and branch canals the total seepage loss of the canal system was estimated.

Data on the quantity of water diverted to the canal system was collected from the irrigation department. Water delivered to the field was estimated by deducting the annual seepage loss from water diverted to the canal system. Conveyance efficiency was calculated using equation 3.9.

3.3.5.3 *Adequacy indicators*

Adequacy of an irrigation system can be defined as its ability to deliver the intended quantity of water during the required time periods (Jahromi*et al.*, 2000). Scientists have suggested several indicators to measure this parameter. Relative Water Supply and Adequacy Indicator are the two performance indicators used in this study to quantify the adequacy of irrigation water applied.

Relative water supply

Relative Water Supply is the ratio of total water supply to total water demand. Total water supply includes both irrigation supply and effective rainfall. Total water demand comprises water needed to meet the evapotranspiration requirement of crops and losses through seepage and percolation (Sakthivadivel*et al.*, 1993). Hence, the relative water supply of an irrigation system was computed using the following formula.

$$\text{Relative Water Supply } = \frac{(\text{IW}+\text{Re})}{(\text{ET}+\text{S}\ \&\ P)} \qquad \text{---------- (Eq. 3. 10)}$$

where,

IW - Irrigation water delivery
Re - Effective rainfall
ET - Crop evapotranspiration
S&P - Seepage and percolation

Adequacy indicator

Adequacy indicator is the ratio of the quantity of water delivered to the quantity of water required for an area R for a period T (Elnmer*et al.*, 2018). The formula is,

$$PA = \frac{1}{T}\sum\nolimits_T \left\lfloor \frac{1}{R}\sum\nolimits_R \left(\frac{QD}{QR}\right)\right| \qquad \text{------- (Eq. 3.11)}$$

where,

$PA = \frac{QD}{QR}$ if QD < QR
$P_A = 1$, otherwise, where,

T is the time period and R is the area/region.
Q_D is the water delivered
Q_R is the water required

Molden and Gates (1990) suggested standards for the adequacy indicator to categorize the performance of an irrigation system as given in the Table 3.4.

Table 3.4 Performance standards of adequacy indicator

Indicator	Performance classes		
	Good	Fair	Poor
P_A	0.90-1.00	0.80- 0. 90	< 0.80

3.4 DYNAMIC RESPONSE OF THE AQUIFER TO GROUNDWATER EXTRACTION AND RECHARGE

Groundwater is the second major source of irrigation water. Aquifer response to groundwater extraction plays an important role in conjunctive water management. Visual MODFLOW software was used to study this dynamic response of the aquifer. MODFLOW solves groundwater flow equation for a porous medium. The law of conservation of mass (Grodzka-Łukaszewska *et al.*, 2017) governs the flow of groundwater.

Simulation of groundwater flow in the Visual MODFLOW software is governed by Darcy’s equation and partial differential equation for anisotropic and heterogeneous medium in a three-dimensional flow, (Lamsoge*et al.*, 2014) as shown below.

Darcy’s equation

$$Q = -k\ i\ A \qquad \text{---------------------- (Eq. 3.12)}$$

where,

Q – The discharge (L^3T^{-1})

k - Hydraulic conductivity(LT^{-1})

i – Hydraulic gradient

A – Area of flow (L^2)

Partial differential equation for anisotropic and heterogeneous medium in three-dimensional flow, used in MODFLOW is,

$$\frac{\delta y}{\delta x}\left[Kxx\ \frac{\delta h}{\delta x}\right] + \frac{\delta}{\delta y}\left[Kyy\ \frac{\delta h}{\delta y}\right] + \frac{\delta}{\delta z}\left[Kzz\frac{\delta h}{\delta z}\right] = Ss\ \frac{\delta h}{\delta t} \pm W \qquad \text{------- (Eq. 3.13)}$$

Where,

K_{xx}, K_{yy}, K_{zz} - Hydraulic conductivities along X,Y and Z directions (LT^{-1})

h - Potentiometric head (L)

$\underline{+}W$ - Volumetric flux per unit volume that represents sources and/or sinks of water (T^{-1})

S_s - The specific storage of the porous material (L^{-1})

T - Time (T)

3.4.1 Data input to Visual MODFLOW

Input data can be imported to Visual MODFLOW as excel files, surfer grid, GIS and AUTOCAD data (Hariharan and Sankar, 2017). There are three separate modules *viz*. input module, run module and output module in visual MODFLOW interface (Khadri and Pande, 2016). The input module is further divided into several units such as grid, well, property, boundaries, particles, Zbud, tools and help.

3.4.1.1 *Conceptual model of the study area and its discretization*

The base map of the study area in bitmap (BMP) format was imported to Visual MODFLOW to develop a conceptual groundwater model of the study area with two layers *viz.* upper lateritic layer and lower weathered rock layer. The area was then discretized into 60 rows and 60 columns of 0.5 km x 0.5 km finite difference grid (fig. 3.5). The elevation of the surface and the bottom layers were further added in text format. The surface topography was generated from DEM of the study area. The elevation of the sub-surface aquifer layer was calculated from the lithological data obtained from the State Government Groundwater Department.

Wells

Pumping well data and observation well data, are important inputs to the model. Figure 3.6 shows the position of water level observation wells and pumping wells in the CRDS command area.

Water level data of 17 observation wells for 15 years from 1996 to 2010 were used for calibration and four years of data from 2011to 2014 were used for validation. Quarterly water level data ie, Monsoon, Post-monsoon Kharif, Post-monsoon Rabi, and Pre-monsoon, were used. Figure 3.7 showed the edit screen of observation well.

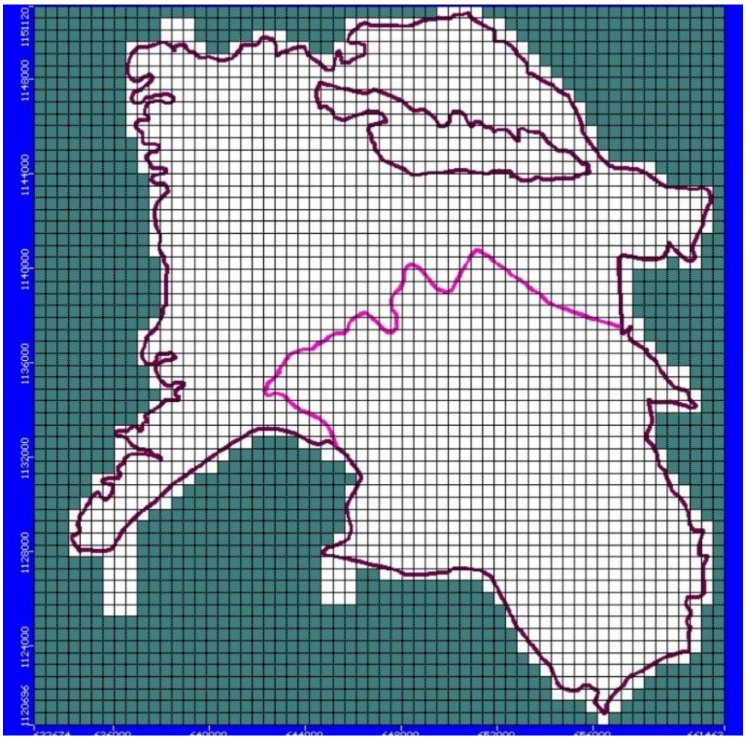


Fig. 3.5 Finite Difference grid formation of the study area

The pumping data of 14 wells in the command area, collected from Kerala Water Authority were used as input to the model (Appendix IX). Edit screen of pumping well is shown in fig. 3.8.

Hydrogeological properties

Hydrogeological properties of the layers, hydraulic conductivity, specific storage, specific yield and porosity are the other inputs to the model. The values of these properties for laterite and weathered rock were collected from literature. The values of hydraulic conductivity and storage properties are depicted in Tables 3.5 and 3.6.

Table 3.5 Initial values of hydraulic conductivity

Aquifer layers	Horizontal Hydraulic Conductivity (m/day)
Laterite	8.64
Weathered rock	0.864

(Source: CGWB, 2009)

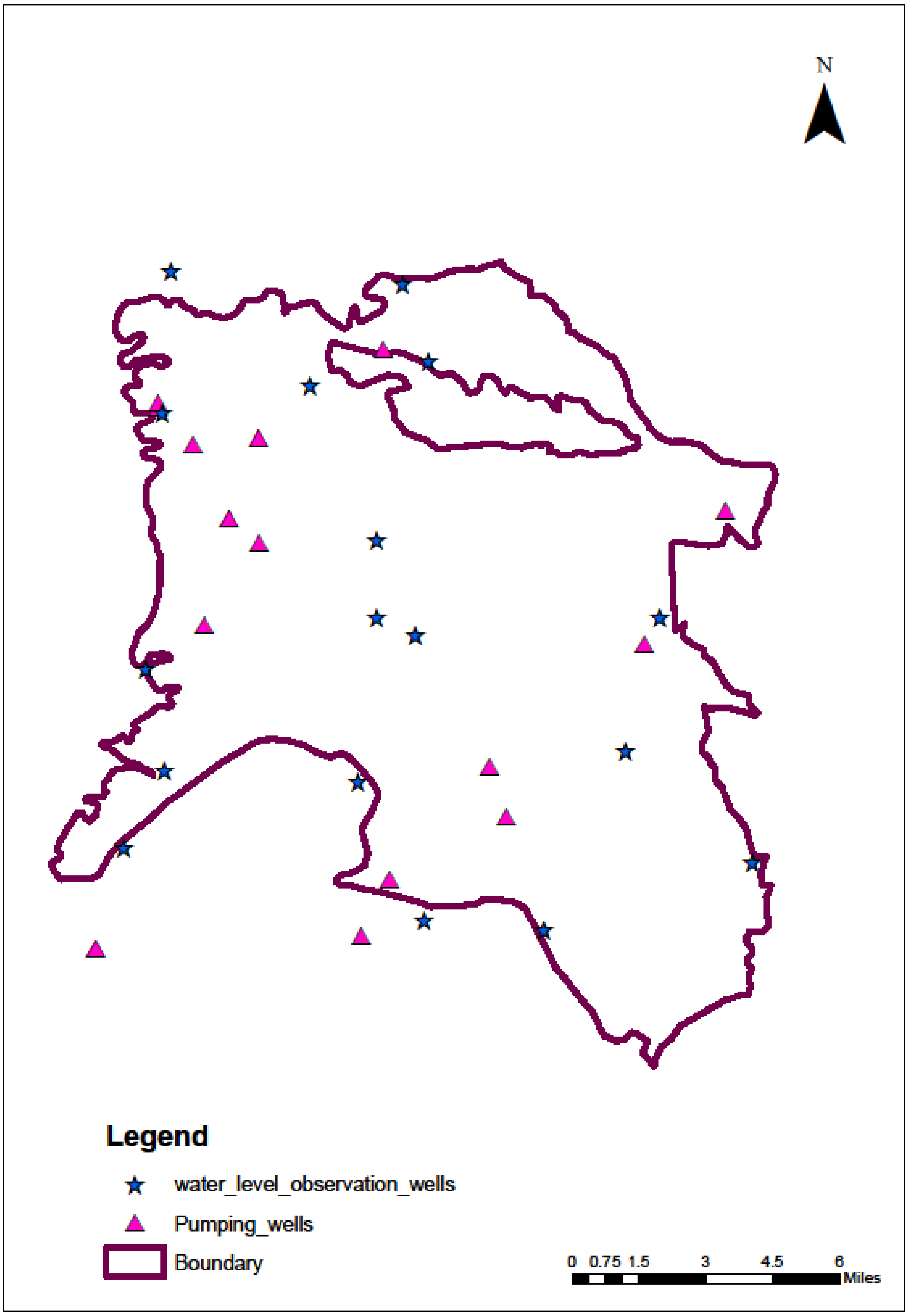


Fig.3.6 Position of observation wells and pumping wells in the CRDS command area

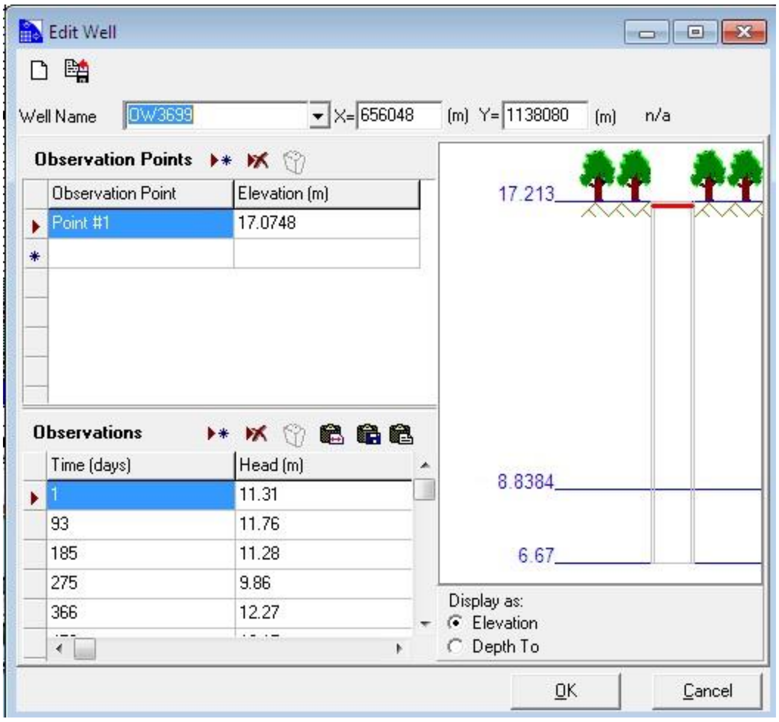
Initial head

An initial head value is required to assign water head distribution over the study area for simulation. Water level data collected from CGWB were used for this. The monsoon water level data during 1996 was assigned as initial head for the study.

Table 3.6 Initial values of storage properties at the start of calibration

Aquifer property	
Specific Storage (Ss) (m^{-1})	0.0003
Specific yield (Sy)	0.15
Effective porosity	0.38
Total porosity	0.45

(Source: Todd, 1980)



Well Name OW3699 X= 656048 (m) Y= 1138080 (m) n/a

Observation Points

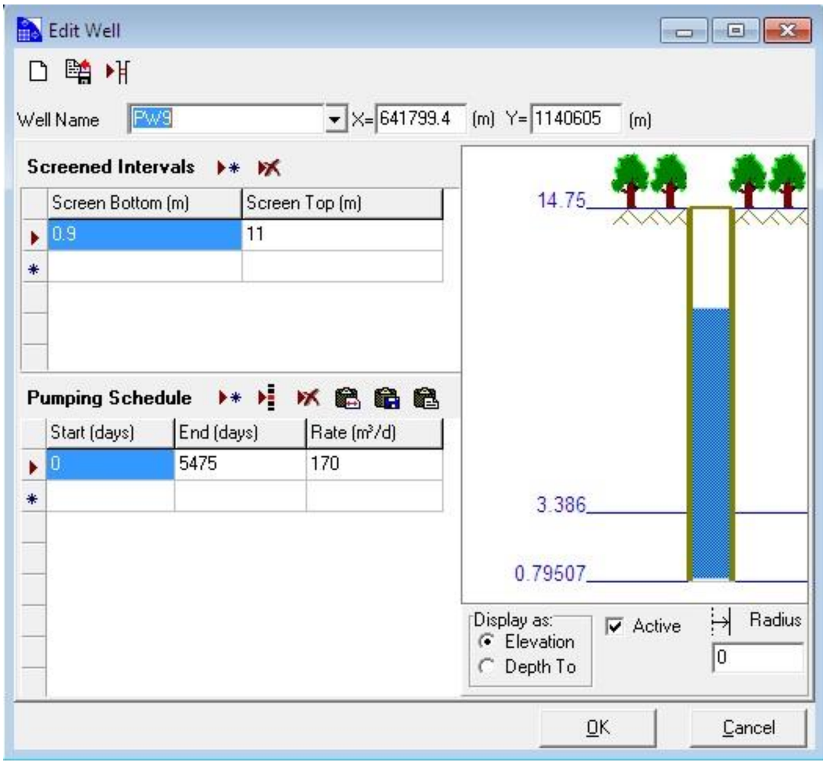
Observation Point	Elevation (m)
Point #1	17.0748

Observations

Time (days)	Head (m)
1	11.31
93	11.76
185	11.28
275	9.86
366	12.27

Display as:
● Elevation
○ Depth To

Fig. 3.7 Edit screen of observation well



Well Name PW9 X= 641799.4 (m) Y= 1140605 (m)

Screened Intervals

Screen Bottom (m)	Screen Top (m)
0.9	11

Pumping Schedule

Start (days)	End (days)	Rate (m³/d)
0	5475	170

Display as: ● Elevation ○ Depth To

☑ Active

Radius 0

Fig. 3.8 Edit screen of pumping well

3.4.1.2 *Boundaries*

Boundary conditions such as recharge to the area, rivers, drains and evapotranspiration are necessary for development of groundwater model in Visual MODFLOW. At least one boundary is necessary to run the model.

Recharge

The recharge to the area includes recharge from rainfall, canal seepage, and return flow from irrigated land. Recharge from rainfall was calculated using the formula developed by Irrigation Research Institute, Roorkee as follows. The formula is well suited for tropical regions and is widely used by many researchers (Saghravani *et al.*, 2013; Adeleke *et al.*, 2015). Rainfall data from1996 to 2014 was collected and used for computation of annual rainfall recharge.

$$R = 1.35\,(P-14)^{0.4} \text{ ------------------------- } \quad \text{(Eq. 3.14)}$$

where,

R= Recharge in inches

P = Precipitation in inches

For the computation of return flow from irrigated area, recommendations given by CGWB were taken. That is, 35% return flow from paddy cultivated area and 30% return from irrigated non-paddy area. Groundwater recharge due to seepage loss from canal water was estimated from field measurement of seepage loss. Recharge dataare given in Appendix X.

River head

Three rivers are there in and around the command area of CRDS. Chalakudy river, from which water is diverted through the canal system, passes through almost centre of the command area from east to west.Kurumaliriver passes a short distance along the northern boundary of the command area. River Periyar flows near to the southern boundary of the command area. Conductance of these rivers was calculated using the following formula and entered as input in the study (Waterloo Hydrogeologic Inc., 1999).

$$C = \frac{K \times L \times W}{M} \qquad \text{------} \quad \text{(Eq. 3.15)}$$

Where,

C = Conductance, $m^2d^{-1,}$

L= Length of river reach through a cell, m

K=Vertical hydraulic conductivity of riverbed, md^{-1},

W= Width of river in a cell, m

M= Thickness of riverbed, m.

Evapotranspiration which is a loss from groundwater through capillary rise is needed to be entered into the input module. It was computed as 32 per cent of the annual rainfall based on the crop water requirement calculations using CROPWAT 8.0 software and assumed to occur uniformly over the entire CRDS command area. Drain is another boundary condition to simulate the effect of agricultural drains on aquifer head. Drains are there some distance along the boundary of the study area.

3.4.2 Calibration and validation of the model

Model calibration is a trial and error process of changing the input parameters, mainly hydraulic conductivity, to attain the computed head almost equal to the field observed head. According to the data availability, 60 stress periods of 91 days (three months) were used for the calibration. The water level in July 1996 was taken as the initial condition. Calibration of the model was done for both steady and transient state. Root Mean Square Error (RMSE) was used for assessing the performance of the model.

Using the calibrated values of various input parameters, the model was validated. In the process of validation, the model was run for the data of four years (2011 to 2014) which was not used during calibration without changing the input parameters.

3.4.3 Prediction of future scenarios

To analyse the scope of conjunctive management in the study, Visual MODFLOW model developed for the CRDS command area was used to predict the groundwater conditions under two scenarios. They are as follows.

In Scenario I, it was assumed that recharge to the aquifer and pumping from the command area remains the same as at the end of the validation period, 2014.

In Scenario II, it was assumed that recharge to the aquifer decreases annually at the rate of 5% and pumping increases annually at the rate of 10% from the end of the validation period, 2014. These assumptions were made to take into account the expected climate change, urbanization, and change in irrigation demands of the area.

3.4.4 Output from Visual MODFLOW

Various outputsof Visual MODFLOW are water table contours**,** head vs time and zone budget (mass balance of the aquifer). It also gives a calibration chart between calculated and observed heads in the observation wells. This graph will help to check the level of calibration by assessing the RMSE. The RMSE value of less than five is considered as acceptable. The net recharge of the study area was assessed by the zone budget of the model.

3.5 CONJUNCTIVE WATER MANAGEMENT

The area commanded by the CRDS experiences water scarcity frequently due to low rainfall, inefficient water delivery and inequitable water distribution. Conjunctive water management would be an optimal solution to this problem, provided it will not cause depletion or decline of groundwater level over the years. Hence, for proper conjunctive water management planning it is necessary to develop an optimization model to arrive at a stable conjunctive use policy.

Figure 3.9 represents the different components of a conjunctive water management system. The main components of the system are water source, irrigated area, and aquifer. These three components are linked together by the dynamic relationship of inflows and outflows to them. Surface water source and the irrigated area are linked by the canal water release.

Seepage from the canal and the irrigated area forms the connection between these components and the aquifer. Base flow from the river is another input to the aquifer. Rainfall is an input to the irrigated area other than irrigation water. Water applied to the irrigated area comprises pumping from the aquifer also. Conjunctive water management takes into account the interconnections between the components through inflows and outflows. Outflow from one component forms the inflow to the other. Proper apportioning of the two major inflows to the irrigated area will keep all the components in a stable condition and results in the maximum relative production of the crops. This is the basis of conjunctive water management. For this purpose, the modelling of surface water and groundwater systems was done as detailed in the previous sections.

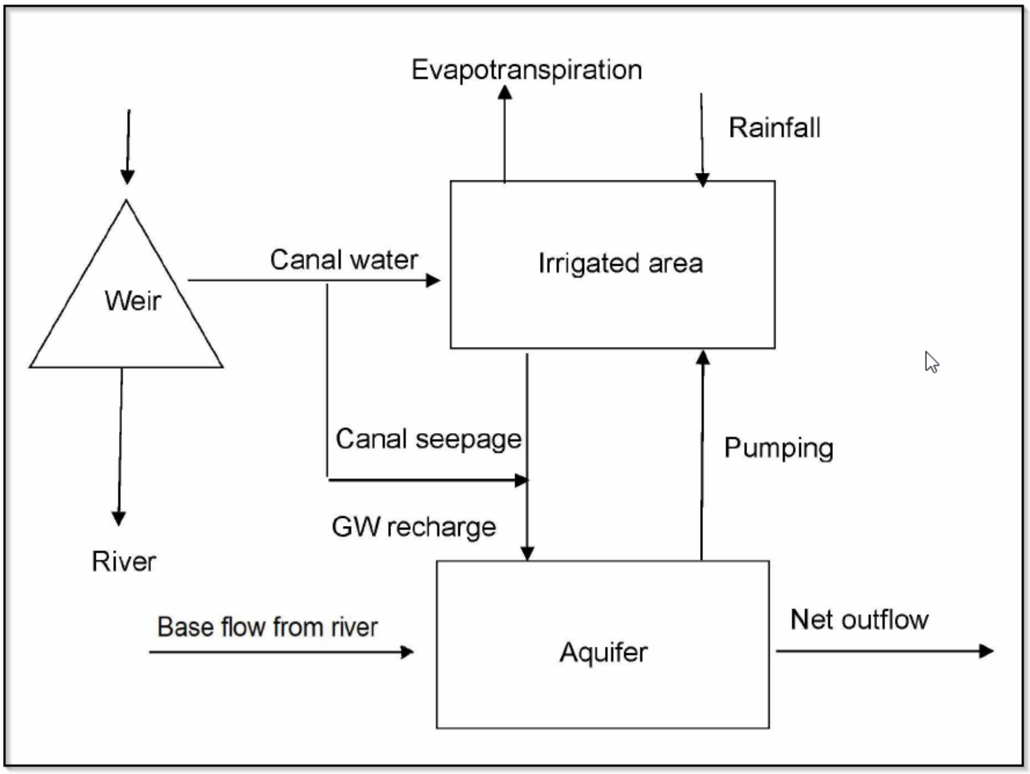


Fig. 3.9 Schematic representation of a conjunctive water management system

(Source: Vedula*et al.*, 2005)

3.5.1 Optimization model

The scarcity of canal water availability in the field could be compensated by pumping groundwater. Hence, a linear optimization model to allocate canal water and groundwater based on a pre-determined ratio was developed to maximize the relative crop yield.

3.5.1.1 Assumptions

Major assumptions involved in the development of the conjunctive water management model are the following.

- Yield of the crops is proportional to the evapotranspiration, which in turn is proportional to the water availability in the root-zone.
- Relative crop yield is proportional to the ratio of Actual Evapotranspiration (AET) and Potential Evapotranspiration (PET).
- The ratio of AET/PET for any crop is approximately equal to the ratio of water applied in the root-zone (IA) to potential water demand (ID) of the crop.
- Crops cannot utilize water more than their irrigation demand.

The developed model has the following objective function and constraints.

3.5.1.2 Objective function

The term relative crop yield, which is the ratio of actual yield to maximum yield, will be maximum when the ratio AET/PET is maximum. This occurs when AET equals PET. If available water in the root-zone is equal to the potential water requirement of the crop, AET will be equal to PET and the ratio AET/PET becomes one. So when available water in the root-zone is equal to the crop water requirement, then the relative crop yield becomes maximum. Hence, the objective function of this optimization model is to maximize the relative crop yield or indirectly minimize the difference between irrigation demand and water availability.

For a single crop, relative crop yield is given by the following equation (Vedula*et al*., 2005).

$$\frac{y}{y_{\max}} = 1 - \sum_{g=1}^{NGS} \mathrm{ky}_g \left(1 - \frac{\mathrm{AET}}{\mathrm{PET}}\right)_g$$

. ---------(Eq. 3.16)

Where, y is the actual yield of the crop; $y_{max}$is the maximum yield of the crop; g is the growth stage index; NGS is the number of growth stages within the growing season of the crop; $ky_g$is the yield response factor for the growth stage g; AET is the actual and PET is the potential evapotranspiration.

For a multi-cropped area, the right hand side of the equation becomes (Vedula*et al*., 2005),

$$\sum_{c=1}^{NC}\left[1-\sum_{g=1}^{NGS}ky_g^c\left(1-\sum_{t\in g}\frac{AET_t^c}{PET_t^c}\right)\right] \text{--- (Eq. 3.17)}$$

Evapotranspiration is proportional to water available in the root zone. Hence, the ratio AET/PET in the equation can be approximated as the ratio of water used (IA) to potential water demand (ID), that is, IA/ID (Montazar*et al*., 2010).

Hence, the objective function of the linear programming model to maximize the relative yield of various crops grown in the command area of CRDS is formulated as follows.

$$Z=\sum_{a=1}^{Na}\sum_{b=1}^{3}\sum_{c=1}^{NC}\left(1-ky(1-{}^{IA}/_{ID}\right) \text{------------ (Eq. 3.18)}$$

where,

a – branch canal

b – Crop season

c - Crop

IA – Irrigation water applied for the crop

ID - Irrigation water demand of the crop

3.5.1.3Constraints

The various constraints considered for obtaining maximum value for the objective function are the water allocation to crops from both the sources, water applied in the crop root zone, proportion of water allocation, availability of surface water and the non-negativity of water allocation.

Water allocation

Water is applied to meet the irrigation demand of crops. Hence the maximum level of water allocation should be based on their irrigation requirement. Total annual irrigation requirement of the command area should be met from surface and groundwater allocations (Das *et al*., 2015). Hence, the water allocation constraint of the command area was formulated as :-

$$\sum_{c=1}^{NC} ID_c - \alpha\,(\beta\, SW_c + GW_c) \geq 0 \qquad \text{-------- (Eq. 3.19)}$$

where,

ID- Net irrigation demand

α- Field water application efficiency

β- Conveyance efficiency

c – Crop

SWc – Surface water allocation for the crop

GWc –Groundwater allocation for the crop

Water applied in the root zone

Water applied in the crop root zone from both sources should be less than or equal to the net irrigation demand of the crop (Montazar*et al*., 2010) and hence, the constraint was formulated as,

$$IA_c \leq ID_c \qquad \text{------- (Eq. 3.20)}$$

where,

$IA_c = \alpha(\beta\, SWc + GWc)$

IAc = Water applied in the root zone of the crop

IDc = Net irrigation demand of the crop

Proportion of surface water and groundwater (Sr)

Proportion of the surface water with respect to total water allotment, denoted as Sr (surface water ratio) forms another constraint (Vedula*et al*., 2005). Hence, the canal water and groundwater in the study were allotted in pre-determined ratios as follows.

$$SWc = Sr\,(SWc+GWc) \quad \text{---------- (Eq. 3.21)}$$

$$GWc = (1- Sr)\,(SWc+GWc). \quad \text{---------- (Eq. 3.22)}$$

where,

$$S_r = \frac{SWc}{SWc + GWc} \quad \text{---------- (Eq. 3.23)}$$

SWc – Surface water allocation for the crop

GWc –Groundwater allocation for the crop

Water availability

The surface water used for all the crops in the command area should be less than or equal to total available surface water in a season or in a year. Groundwater allocation should be according to the predetermined ratio of surface water and total water allotment for the crop. Hence, the water availability constraint was formulated as,

$$\Sigma_c SW_c \leq TSW_{av} \quad \text{---------- (Eq. 3.24)}$$

where,

SWc – Surface water allocation for the crop

TSW_{av} – Total available surface water

Non-negativity constraint

Surface water and groundwater allotment for the crops is always positive. Hence, the non-negativity constraint was formulated as,

$$SW_c \geq 0,\ GWc \geq 0 \quad \text{-------- (Eq. 3.25)}$$

3.5.1.4 Input data for the optimization model

The input data for the developed optimization model are net irrigation demand of the crops, yield response factor of crops, surface water ratio, conveyance efficiency of the canal system and field water application efficiency.

The developed optimization model was solved using the software LINGO to get the quantity of surface water and groundwater to be used in the command area for maximizing the relative yield of crops. Programme was written in LINGO using sets. LINGO uses dual simplex method for solving linear programming optimization models.

3.5.2 Testing of groundwater balance of the aquifer.

In order to assess the changes in **g**roundwater storage of the aquifer by the implementation of conjunctive water use in the study area a separate equation was used (Vedula*et al.,* 2005). Groundwater allocation as per the LP model was also added along with the groundwater draft to get the proposed change in groundwater storage. Hence, the Groundwater storage is estimated as,

$$\Delta S = Rg \pm Qn - Qd \qquad \text{------(Eq. 3.26)}$$

where,

ΔS = Change in groundwater storage, mm

Rg = Gross groundwater recharge, (Rr+Ri+Rs), mm

Qn= Net groundwater inflow/outflow to the surroundings, mm

Qd=Groundwater draft through wells, mm

The gross groundwater recharge was estimated as the sum of, recharge from rainfall, seepage loss from canal water and return flow of irrigation. Hence, the gross groundwater recharge is

$$Rg = Rr + Ri + Rs \qquad \text{-------} \qquad \text{Eq.(3.27)}$$

where,

Rg = Gross groundwater recharge, mm

Rr = Recharge due to rainfall, mm

Ri = Return flow from irrigation, mm

Rs = Recharge due to seepage loss of canal water, mm

Net groundwater inflow/outflow to the aquifer existing in the area is available from the zone budget output of the Visual MODFLOW model. Groundwater draft through wells includes the existing pumping and the proposed pumping for irrigation obtained from the LP model. This groundwater balance model was used for the development of stable conjunctive use policy for the study area.

3.5.3 Development of stable conjunctive use policy

In the developed linear programming model no constraint is included for groundwater availability. It is always possible to obtain maximum relative yield by supplementing the deficiency in surface water availability by groundwater. But this may lead to a decline of groundwater level over the years. To avoid this, the LP optimization model was run for different combinations of surface water-groundwater proportions for a normal year. The results obtained from each run were used for the computation of groundwater balance of the study area. Comparing the change in groundwater storage corresponding to each surface water-groundwater proportions, one combination was identified as stable policy. This stable policy is the one that creates only negligible change in the groundwater storage of the area when the model is run for a normal year.

3.5.3.1 *Stable policy parameters*

The developed stable policy was characterized by two parameters which are surface water ratio, S_r and irrigation ratio, a^c_t. Surface water ratio is the ratio of surface water allotted to the total irrigation water and its mathematical representation is given in Eq. 3.23. Second parameter, a^c_t, the ratio of actual irrigation water allotted to potential irrigation demand of a given crop in a time period t, is known as irrigation ratio. The parameter can be expressed mathematically as follows:-

$$a^{c}_{t} = \frac{IA_t^c}{ID_t^c} \qquad \text{--------------(Eq. 3.28)}$$

Where,

IA_t^c =Water applied in the root zone of the crop during the time period t

ID_t^c = Irrigation water demand of the crop during the time period t

IA_t^c was obtained from the LP model. These parameters were used to find temporal allocation of surface and groundwater corresponding to the stable policy over a normal year.

3.6 TEMPORAL ALLOCATION PATTERN OF SURFACE AND GROUNDWATER BY SIMULATION RUNS

Simulation studies were conducted by running the LP model for different time periods over a normal year. The temporal allocation pattern of surface water and groundwater that should be maintained in the area was thus obtained. In this study, a normal year was divided into monthly intervals from June to May. A stable policy parameter, S_r was computed for each time period according to irrigation requirement of the command area and canal water availability. The parameter S_r for different time intervals was computed in such a way that the annual allotment of surface water and groundwater is in the proportion of stable policy.

For a specific time interval say one month, surface water – groundwater proportion was obtained from S_r as per equations 3.20 and 3.21. The LP model was run with this proportion to get the water allocation for each crop during the time period. S_r was adjusted to get the maximum value for the irrigation ratio $a^{c}_{t.}$ At the same time, it should be able to keep the stable policy on annual basis. Hence, temporal allocation was given as a trial and error procedure.

3.6.1 Impact of stable policy on aquifer storage response over the years

Using the identified stable policy LP optimization model was run for past years for which rainfall and water diversion data were available. The data from

2005 to 2012 was used for this analysis. Groundwater balance was computed for each year and summed up to obtain the cumulative change in groundwater storage while applying the stable policy over the years. This was done to ascertain that the developed policy was a stable one for the CRDS command area.

CHAPTER 4

RESULTS AND DISCUSSION

The study for the development of a conjunctive water management model for a multi crop irrigation command has been conducted in the command area of Chalakudy River Diversion Scheme. Surface water diverted through the canal system is the major source of irrigation water for the command area. The diverted water is not efficiently conveyed to all parts of the command area. High seepage loss due to damaged lining and obstructions to flow because of waste dumping creates water scarcity problems, mainly towards tail end. Groundwater is another source of water on which people mainly depend for their drinking and other domestic purposes. Seepage loss from canal as well as irrigated area enriches the groundwater storage in the area. There is ample scope to tap this groundwater to some extent to compensate the scarcity of surface water for irrigation. But this has to be done in a planned manner in order to ensure sustainable groundwater storage. For this purpose, a conjunctive water management model was developed. The various results obtained in the study are discussed under the following sub heads:-

4.1 PREPARATION OF DIGITAL DATABASE USING GIS

A digital database necessary for conducting the study was prepared using ArcGIS and ERDAS Imagine software. Images of CRDS command area boundary and canal system were taken from the ‘India-WRIS’ website and were used for the preparation of this database.

4.1.1 Base map and canal network

The base map with canal network is shown in Fig. 4.1. The estimated area of CRDS command from this base map is 40,127 ha, which is approximately equal to the reported area of 39,685 ha (Madhusoodhanan and Eldho, 2012).

4.1.2 Land use map of the command area

The land use map of CRDS command area was prepared using ERDAS IMAGINE software.

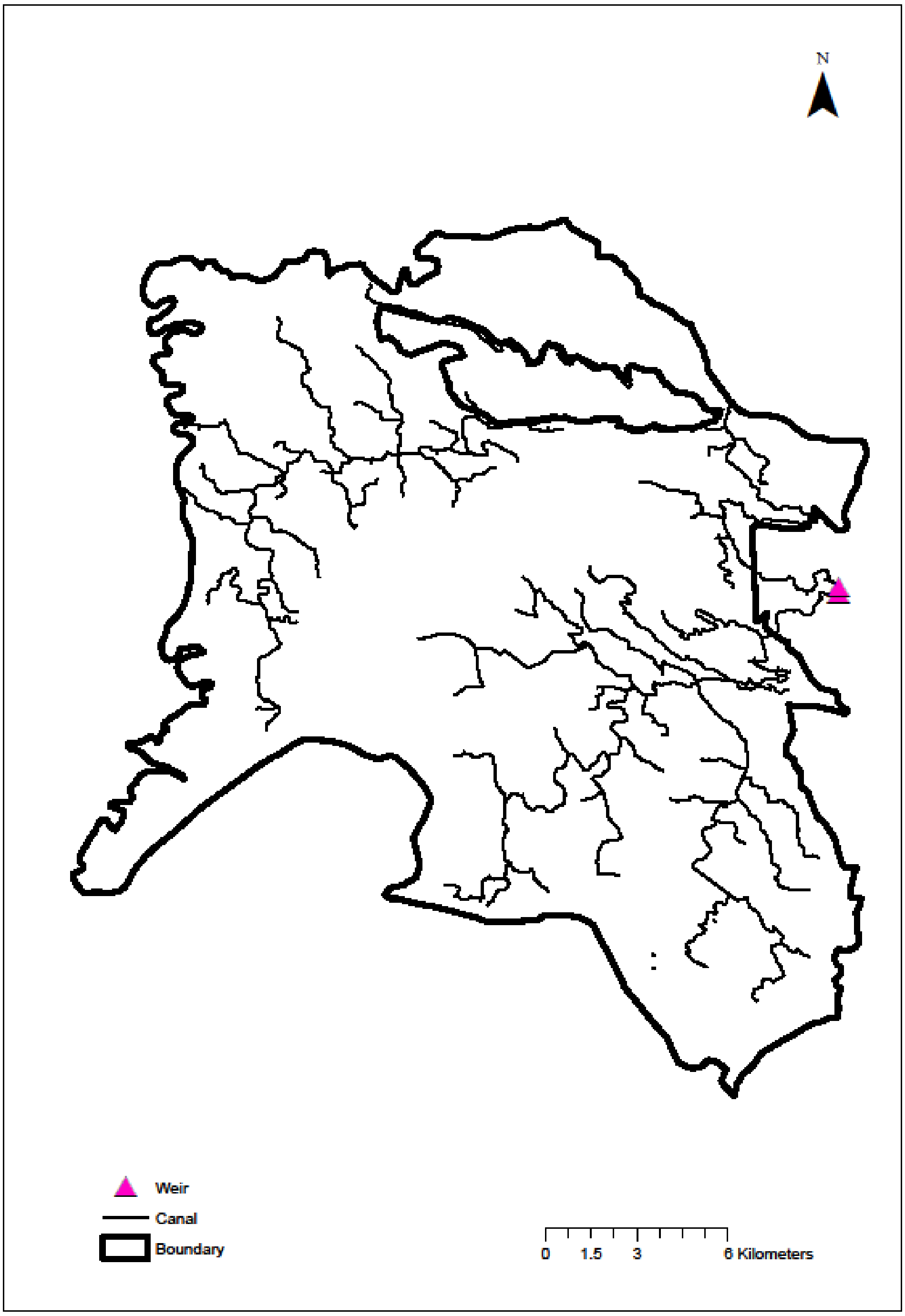


Fig. 4.1 CRDS Command area with canal network

The whole land use wasclassified into ten classes viz. Paddy, multiple crop, coconut based cropping system, and rubber. Among these, rubber is cultivated as a rain-fed crop. The vegetables cultivated in the paddy fields were considered as a summer crop. The built-up area, barren land and scrub are the other land use classes

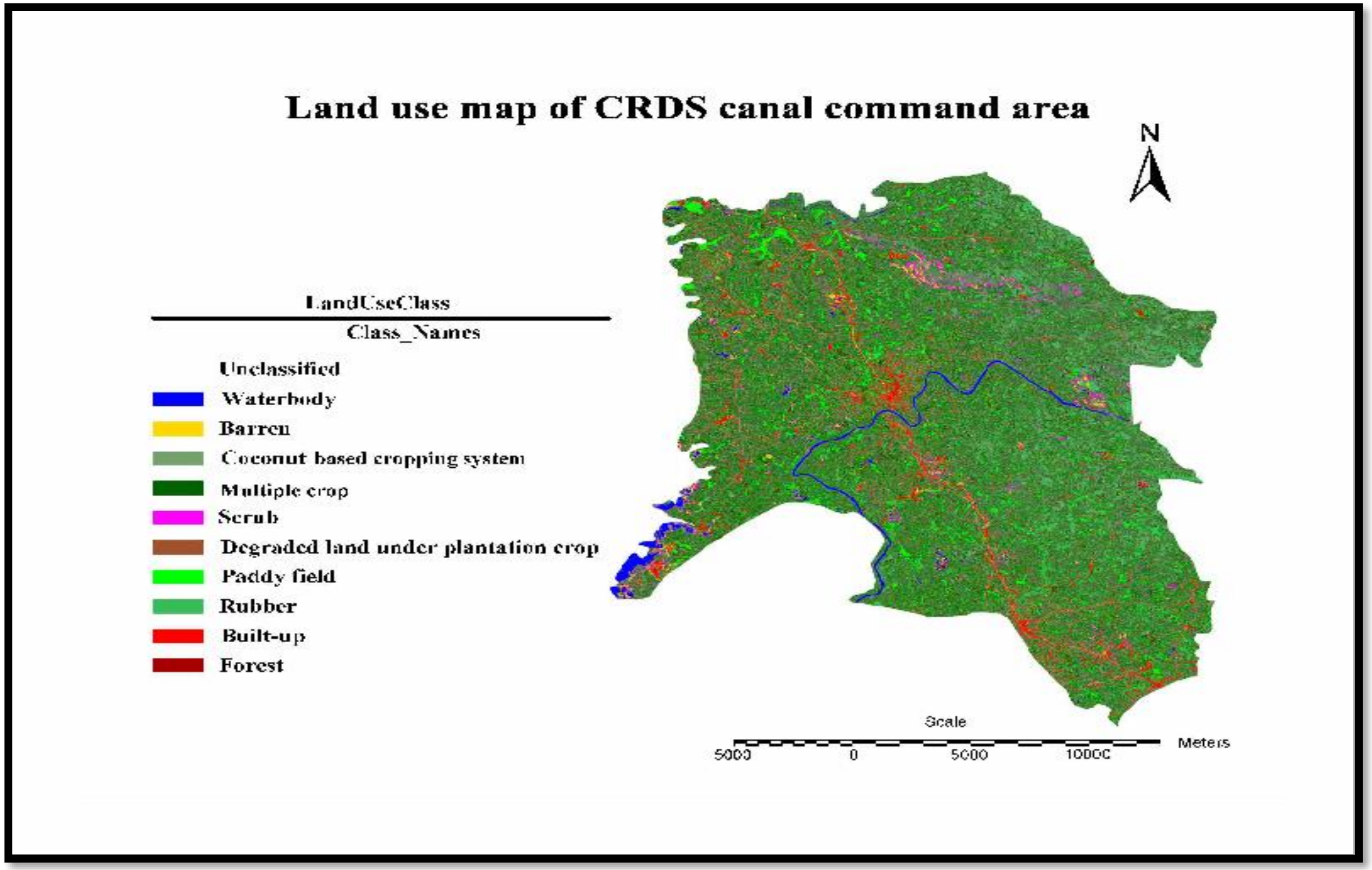


Fig. 4.2 Land use/land cover map of CRDS command area.

identified in the area. Since the eastern portion of the command area is highland, forest is also taken as another class. The land use/land cover map of CRDS command area is shown in Fig.4.2.

The various land use classes and area covered by each land-use class is shown in Table 4. 1. The paddy area covers 10.51 per cent of the command area. The multiple crop and coconut based cropping system are almost equal in the command area. They are the important land use classes in this command. They cover 37.77% and 31.83% area of the canal command respectively. The rubber plantation covers 12.80% of the command area. The ground truth verification was done to check the land use in the map and in the actual field condition. The result was satisfactory.

Table 4.1 Details of various land use classes and its areal extent

S1. No.	Land use class	Area (km^2)
1	Barren land	2.83
2	Built up	14.65
3	Coconut based cropping system	128.29
4	Degraded land under plantation crops	2.93
5	Multiple crop	152.27
6	Paddy	42.38
7	Rubber	51.61
8	Scrub	1.90
9	Water body	4.87
10	Forest	1.38

4.2. ASSESSMENT OF IRRIGATION REQUIREMENT

Development of a conjunctive water management model requires an accurate assessment of irrigation requirement of the command area. Hence the area occupied by each crop and the cropping pattern was extracted from the prepared land use map to compute the total volume of irrigation requirement.

4.2.1 Cultivable command area of canal branches

The cultivable command area of CRDS is occupied by two major cropping patterns in the upland, multiple cropping and coconut based cropping systems. A field survey conducted in the area revealed that nutmeg is the major crop in the coconut based cropping system, which is high water demanding crop. Banana is another major crop in these cropping patterns. Paddy is growing in low land. Vegetables are also growing in the low land as the summer crop. The cultivable command area of CRDS canal branches extracted from the land use map of the area is shown in Fig. 4. 3.

Tables 4.2 & 4.3 showed the cultivable command area (CCA) of LBC and RBC of CRDS respectively. From the tables, it is clear that the CCA (13,865ha) extracted from land use map using the ‘buffer’ tool of ArcGIS agrees with the reported value of CCA (13,895ha) of CRDS (Anon., 2018; Madhusoodhanan and Eldho, 2012). The left bank canal supplies water to 56 per cent of the area and right bank canal to the rest of the area. Hence it was found that about 35 per cent of the gross command area is cultivable.

Left bank canal has fourteen branches and total cultivable command area of all these branch canals together constitute 7786.27 ha. The cultivable command area was found almost proportional to its length (Table 4.2). Among the different branches of LBC, Kalady branch which is 16 km long has the maximum CCA of 2896.19 ha while the Chirangara branch which is the smallest (1.01 km) has a CCA of 101.79 ha. The Right Bank Canal supplies water through twenty four branch canals and their distributaries to a CCA of 6078.73 ha (Table 4.3). The longest branch in the RBC, Mattathur, (18.3 km), supplies water to a CCA of 672. 84 ha which is the maximum in the command area.

The CCA of branch canals are occupied with cultivated crops and other land use viz. built-up, rubber and scrub. Paddy, multiple crop and coconut based cropping systems are the highly irrigation demanding crops and cropping patterns in the command area. Hence in order to calculate the irrigation requirement the area covered by each crop and cropping pattern corresponding to each branch canal was identified.

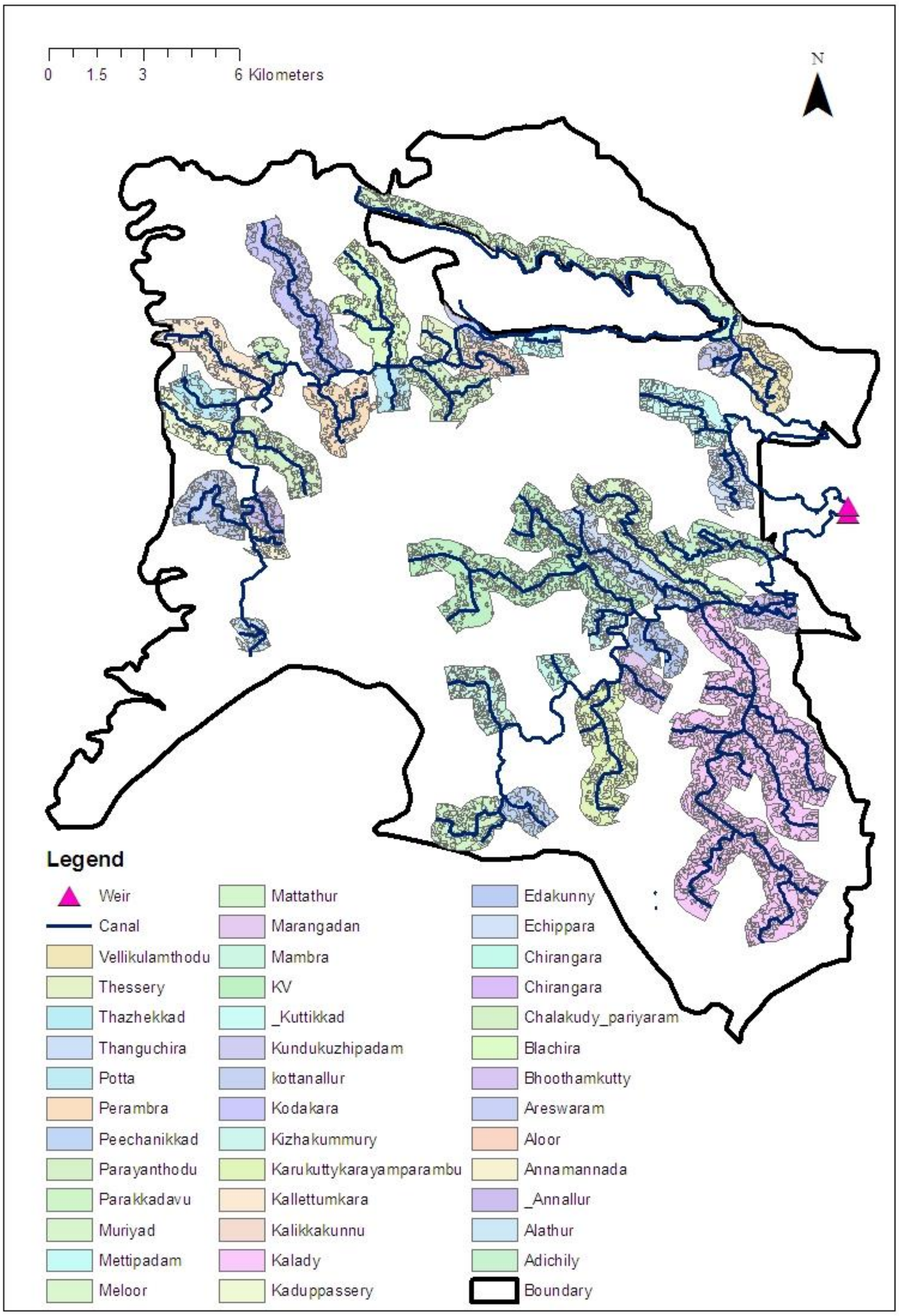


Fig.4.3 Cultivable Command Area of CRDS branch canals

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Table 4.2 Cultivable Command Area of Left Bank Canal

Branch	Length (km)	CCA (ha)	Cropping pattern
Adichily	7.70	337.66	Multiple crop (21%), Coconut based cropping system (48%)
Boothamkutty	6.40	201.11	Paddy (8%), Multiple crop (30%), Coconut based cropping system (12%)
Chirangara	1.01	101.79	Paddy (13%), Multiple crop (50%), Coconut based cropping system (37%)
Edakunny	3.80	209.80	Paddy (4%), Multiple crop (18%), Coconut based cropping system (50%)
Kalady	16.0	2896.19	Paddy (18%), Multiple crop (8%), Coconut based cropping system (28%)
Karukutty_Karayamparambu	8.20	579.73	Paddy (6%), Multiple crop (38%), Coconut based cropping system (43%)
Kizhakkummury	2.70	147.73	Multiple crop (44%), Coconut based cropping system (39%)
KV main	13.80	1308.44	Paddy (1%), Multiple crop (56%), Coconut based cropping system (28%)
Mambra	3.00	284.28	Paddy (24%), Multiple crop (41%), Coconut based cropping system (29%)
Marangadan	1.47	194.90	Multiple crop (28%), Coconut based cropping system (43%)
Meloor	9.90	638.08	Paddy (2%), Multiple crop (32%), Coconut based cropping system (37%)
Parakadavu	3.50	284.28	Paddy (15%), Multiple crop (24%), Coconut based cropping system (34%)

Peechanikkadu	3.20	178.76	Multiple crop (51%), Coconut based cropping system (2%)
Thanguchira	4.53	423.32	Paddy (10%), Multiple crop (30%), Coconut based cropping system (36%)
Total		7786.27	

4.2.2 Estimation of irrigation requirement of CRDS command area

TheCROPWAT 8.0 software was used to compute the crop water requirement of the CRDS command area. In this software reference crop evapotranspiration is estimated by Penman-Monteith equation. The reference crop evapotranspiration multiplied with crop coefficient yields the crop water requirement. The effective rainfall which is also an output of the software was subtracted from the crop water requirement to get the irrigation requirement of the area. The climate parameters were used as input to the CROPWAT 8.0. to estimate the reference ET. The average rainfall over the command area was computed using Thiessen polygon method in ArcGIS and this value was fed to the CROPWAT 8.0 software.

Table 4.3 Cultivable Command Area of Right Bank Canal

Branches	Length (km)	CCA (ha)	Cropping pattern
Alathur	1.32	90.62	Paddy (12%), Multiple crop (56%), Coconut based cropping system (32%)
Aloor	1.20	2.48	Multiple crop (50%), Coconut based cropping system (50%)
Annallur	1.49	125.38	Multiple crop (55%), Coconut based cropping system (42%)
Annamannada	1.45	88.14	Multiple crop (62%), Coconut based cropping system (37%)
Areswaram	6.04	60.83	Multiple crop (73%), Coconut based cropping system (18%)

Blachira	6.80	542.49	Paddy (3%), Multiple crop (73%), Coconut based cropping system (21%)
Chalakudy-Pariyaram combined	14.39	320.28	Paddy (3%), Multiple crop (60%), Coconut based cropping system (34%)
Echippara	3.40	228.42	Paddy (2%), Multiple crop (30%), Coconut based cropping system (27%)
Kaduppassery	13.14	244.56	Paddy (4%), Multiple crop (76%), Coconut based cropping system (20%)
Kalikkakunnu	2.61	188.69	Paddy (10%), Multiple crop (35%), Coconut based cropping system (44%)
Kallettumkara	3.42	422.08	Paddy (44%), Multiple crop (59%), Coconut based cropping system (36%)
Kodakara	7.04	621.94	Paddy (15%), Multiple crop (50%), Coconut based cropping system (32%)
Kottanallur	4.10	332.70	Paddy (4%), Multiple crop (68%), Coconut based cropping system (27%)
Kundukuzhipa dam	2.09	119.17	Multiple crop (28%), Coconut based cropping system (55%)
Kuttikad	5.10	343.87	Paddy (1%), Multiple crop (33%), Coconut based cropping system (39%)
Mattathur	18.30	672.84	Paddy (11%), Multiple crop (28%), Coconut based cropping system (55%)
Mettippadam	5.54	111.73	Multiple crop (29%), Coconut based cropping system (43%)
Muriyad	8.20	98.07	Multiple crop (53%), Coconut based cropping system (47%)
Parayanthodu	3.79	358.77	Paddy (1%), Multiple crop (69%), Coconut based cropping system (25%)

Perambra	6.27	328.97	Multiple crop (68%), Coconut based cropping system (31%)
Potta	2.10	139.04	Multiple crop (81%), Coconut based cropping system (19%)
Thazhekkad	2.41	207.31	Paddy (19%), Multiple crop (55%), Coconut based cropping system (20%)
Thessery	1.64	153.93	Paddy (19%), Multiple crop (68%), Coconut based cropping system (10%)
Vellikulamthodu	17.13	276.83	Paddy (10%), Multiple crop (14%), Coconut based cropping system (35%)
Total		6078.73	

4.2.2.1 Estimation of average rainfall over the command area

In order to calculate the average rainfall over the area, the rainfall data, for a period of 1991 to 2014, was collected from Agronomic Research Station, Chalakudy, and two IMD stations. It was observed that the average annual rainfall over the study area during the period from 1991 to 2014 varied widely (Table 4.4). Since rainfall data for thirty years (1987-2016) was available from Agronomic Research Station Chalakudy, its average (normal rainfall), 3044.81 mm, was taken for categorizing the average annual rainfall over the command area.

During this period excess rainfall was received in six years. The rainfall was deficit during four years. Minimum average rainfall, 2135.3 mm occurred in the year 2012. The years 2003, 2005 and 2008 were the other deficit years. On the other hand, during the year 2007 the rainfall was as high as 4087.1 mm. The years 1992, 1994, 2010, 2013 and 2014 were also excess rainfall years.

Table 4.4 Average annual rainfall over the command area, 1991-2014

Year	Average Rainfall (mm)	Status
1991	3539.5	Normal
1992	3828.8	Excess
1993	3451.8	Normal
1994	3899.7	Excess
1995	3498.6	Normal
1996	2567.6	Normal
1997	3269.0	Normal
1998	3265.6	Normal
1999	3041.1	Normal
2000	2492.2	Normal
2001	3261.3	Normal
2002	2714.1	Normal
2003	2411.4	Deficit
2004	3326.8	Normal
2005	2451.0	Deficit
2006	3439.2	Normal
2007	4087.1	Excess
2008	2453.0	Deficit
2009	3282.8	Normal
2010	3824.1	Excess
2011	3090.7	Normal
2012	2135.3	Deficit
2013	3670.8	Excess
2014	3642.5	Excess

To compute average rainfall, Thiessen polygons were prepared in ArcGIS software. The position of rain gauge stations and Thiessen polygons constructed are shown in Fig. 4.4.

From the figure, it is clear that there are three rain gauge stations, one inside the command area and two outside the command area that has influence on the average rainfall of the area. The weighted average of the rainfall recorded at the three stations, Chalakudy, Kodungallur and Perumbavoor, was taken as the average rainfall of the command area. The rainfall recorded at Kodungallur station and Perumbavoor stations have influential area of 10 km2and 40 km2respectively. The rest of 350 km2 area is influenced by the rainfall recorded at Chalakudy station. The average monthly rainfall thus calculated was in close agreement with the average of rainfall recorded at Chalakudy station.

The average monthly rainfall computed by Thiessen polygons is shown in Table 4.5.

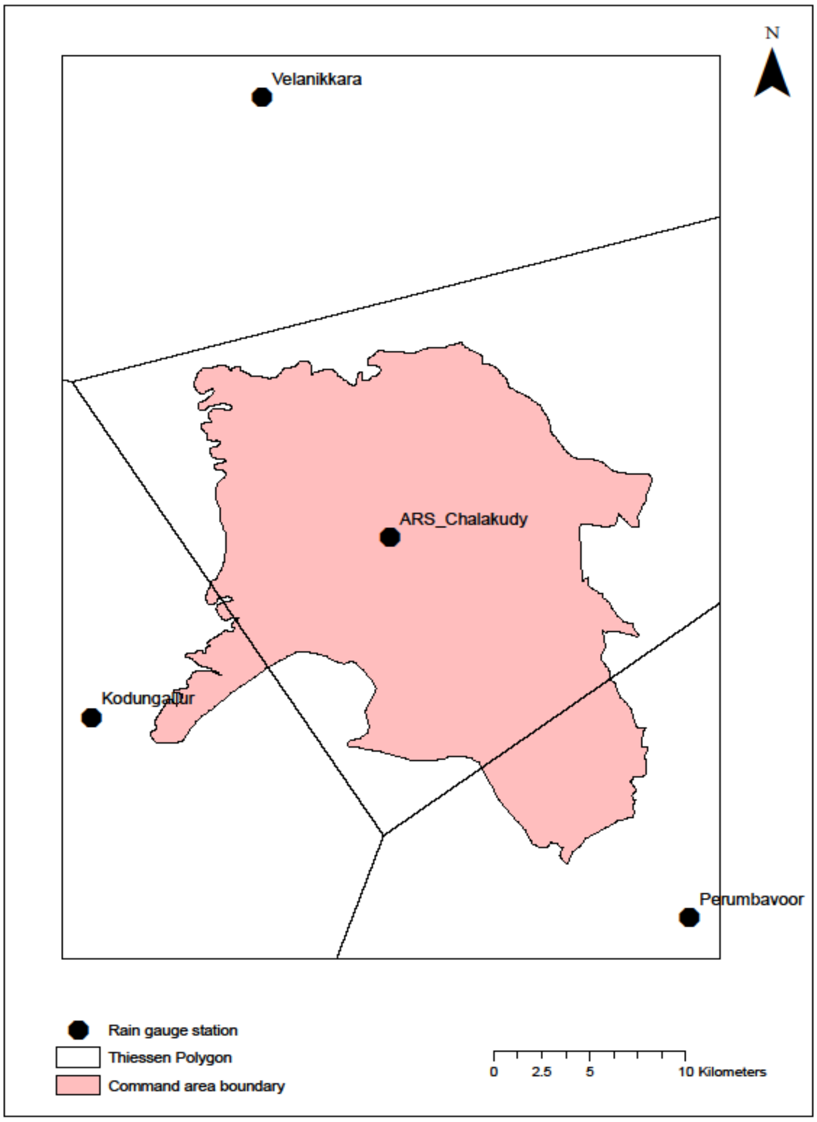

Fig. 4.4 Thiessen polygons for computation of average rainfall

Table 4.5Average monthly rainfall (1991 – 2014) computed by Thiessen polygons

	ARS Chalakudy	Kodungallur	Perumbavoor	CRDS
Influential Area (km^2)	350	10	40	
Month	Rainfall (mm)	Rainfall (mm)	Rainfall (mm)	Average Rainfall (mm)
January	6.30	14.65	15.59	7.3
February	12.89	50.42	22.26	15.2
March	22.55	180.49	35.64	29.7
April	101.67	403.47	141.20	117.2
May	225.67	530.27	222.57	236.4
June	710.17	776.77	676.25	708.7
July	697.03	702.88	711.57	698.5
August	475.65	455.11	467.64	474.3
September	341.36	234.90	394.27	343.6
October	379.61	315.15	341.64	372.9
November	165.16	96.70	186.01	165.3
December	22.98	15.92	37.72	24.4

From the average rainfall, the effective rainfall was computed by CROPWAT 8.0 using the USDA Soil Conservation Service method. The mean monthly rainfall and effective rainfall computed by the software is presented in Table 4.6. It was found that during summer and winter months, most of the rainfall is retained in the root zone as effective rainfall while runoff losses were high during monsoon periods.

The results are in conformity with the findings of Gowda et al., 2013 and Saravanan and Saravanan, 2014. The mean monthly variation of rainfall and effective rainfall is illustrated graphically in Fig.4.5.

Table 4.6 The mean monthly rainfall and effective rainfall (1991 – 2014) from CROPWAT

Month	Rainfall (mm)	Effective Rainfall (mm)
January	7.3	7.1
February	15.2	14.8
March	29.7	28.1
April	117.2	94.7
May	236.4	144.0
June	708.7	195.9
July	698.5	194.9
August	474.3	172.4
September	343.6	159.4
October	372.9	162.3
November	165.3	113.9
December	24.4	23.3
Total	3193.5	1310.9

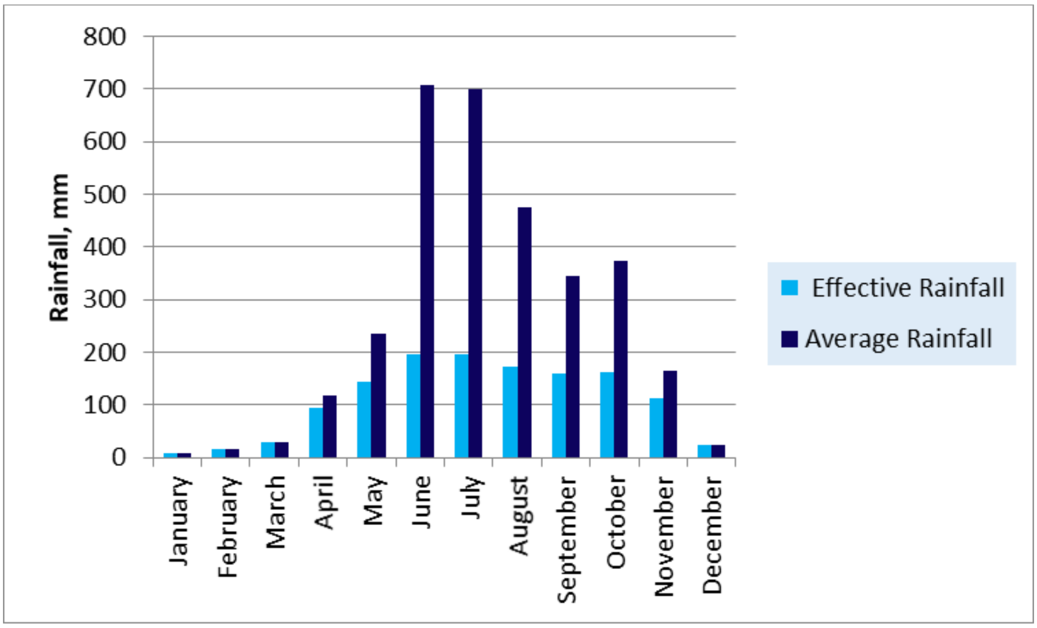

Fig. 4.5 Mean monthly variation of average rainfall and effective rainfall

4.2.2.2 *Reference crop evapotranspiration*

The reference crop evapotranspiration computed by CROPWAT 8.0 software on a daily basis. The average daily ET_0 was found maximum during the month of March and minimum during the month of July (Table 4.7). The high temperature in March causes maximum ET_0 during this month, whereas due to low temperature and low sunshine during July, the ET_0 value got reduced. The south west Monsoon also caused the reduction in ETo.

This was in conformity with the findings of Surendran *et al.* 2015 and Gangwar *et al.* 2017. This variation in ET_0 has a profound influence on irrigation demand of crops.

Table. 4.7 Mean daily weather parameters and ET_0 computed by CROPWAT 1990 - 2016

Month	Mini Temp (°C)	Max Temp (°C)	Humidity (%)	Sun shine hours (h)	Radiation (MJm-^{2}day^{-1})	ETo (mm day^{-1})	ETo (mmmonth^{-1})
January	20.2	33.4	73	8.4	19.7	4.58	141.98
February	21.4	34.5	73	8.5	21.1	5.00	140.0
March	23.5	35.4	75	8.0	21.5	5.23	162.13
April	24.5	34.8	78	7.2	20.6	4.99	149.7
May	24.4	33.6	79	6.6	19.4	4.64	143.84
June	23.3	30.3	83	5.0	16.6	3.74	112.2
July	22.8	29.4	84	4.7	16.3	3.59	111.29
August	23.0	29.7	84	4.7	16.5	3.66	113.46
September	23.0	30.7	82	5.3	17.4	3.92	117.6
October	22.6	31.3	80	5.9	17.4	3.96	122.76
November	22.0	32.0	78	6.7	17.4	4.02	149.7
December	21.4	32.7	76	7.3	17.7	4.12	127.72

4.2.2.3 Irrigation Requirement of the branch canal command area

Cultivable command area of each branch canal (Fig. 4.3) is occupied not only by crops, but also by built-up and other land use classes. Hence, the irrigation requirement of each branch canal CCA was found proportional to the area occupied by the irrigation demanding crops. It is evident from the Tables 4.8 and 4.9, which shows the irrigation water requirement of each branch canal along the LBC and RBC respectively. Among the branches of LBC, Kalady branch which is having a cropped area of 1563.94 ha required maximum irrigation water, 7.062 Mm^3, annually. Chirangara branch with a cropped area of 101.79 ha had a minimum annual net irrigation requirement, 0.419 Mm^3, even if the cropped area was slightly higher than that of the Bhoothamkutty branch. This is because, paddy, the most water demanding crop, occupied more area in the CCA of the Bhoothamkutty branch compared to the Chirangara branch (Table 4.2). In the case of RBC also, the branch with maximum cropped area, Mattathur (638.08 ha) showed a maximum annual net irrigation requirement of 2.974 Mm^3. Computation of irrigation requirement of the branch canals are shown in Appendix XI.

Table 4.8 Annual net irrigation requirements of the branch canal command areas of LBC

Branches	Cropped area (ha)	Annual net irrigation requirement (Mm^3)
Adichily	232.99	0.909
Bhoothamkutty	100.55	0.450
Chirangara	101.79	0.419
Edakunny	151.05	0.611
Kalady	1563.94	7.062
Karukutty_Karayamparambu	504.37	2.149
Kizhakkummury	122.61	0.489

KV main	1112.17	4.548
Mambra	267.22	1.274
Marangadan	138.38	0.564
Meloor	453.04	1.860
Parakadavu	207.52	0.900
Peechanikkadu	94.74	0.384
Thanguchira	321.72	1.413
Total	5372.09	23.03

The seasonal and annual net irrigation requirements of LBC and RBC area are shown in Table 4.10. It was found that the irrigation requirement was the lowest during Kharif/ Virippu season and highest during summer/puncha season.

Table 4.9 Annual net irrigation requirements of the branch canal command areas of RBC

Branches	Cropped area (ha)	Annual net irrigation requirement (Mm^3)
Alathur	90.62	0. 437
Aloor	2.48	0.01
Annallur	121.62	0.491
Annamannada	87.26	0.365
Areswaram	55.35	0.245
Blachira	526.22	2.257
ChalakudyPariyaram combined	310.67	1.377
Echippara	134.77	0.582
Kaduppassery	244.56	0.980
Kalikkakunnu	167.94	0.797
Kallettumkara	417.86	1.693

Kodakara	603.28	2.669
Kottanallur	330.21	1.302
Kundukuzhipadam	99.31	0.405
Kuttikad	252.00	1.042
Mattathur	638.08	2.974
Mettippadam	80.69	0.328
Muriyad	98.07	0.385
Parayanthodu	340.14	1.359
Peranbra	326.49	1.346
Potta	139.04	0.584
Thazhekkad	194.90	0.817
Thessery	147.73	0.677
Vellikulamthodu	162.62	0.745
Total	5532.04	23.87

The high rainfall and low evapotranspiration (ET_0) during the Kharif season contributed to the low net irrigation requirement. During this season water is required only for land preparation and growing paddy nursery. But the low rainfall and high temperature increased the irrigation requirement during summer. Banana and nutmeg are the two major water demanding dry crops in the multiple cropped area of the command area. These crops are highly water demanding during summer. These results were in agreement with the findings of Surendran *et al.*, 2015.

Table 4.10 Average annual and seasonal net irrigation requirement during 1991-2014.

Canal segment	Area(ha)		Net irrigation requirement (Mm^3)			
	CCA	Cultivated area	Kharif/ Virippu	Rabi/ Mundakan	Zaid/ Puncha	Annual net irrigation requirement
LBC	7786.27	5372.09	1.452	5.461	16.119	23.03
RBC	6078.73	5532.04	1.158	4.953	17.754	23.87
Total	13865.00	10904.13	2.610	10.414	33.873	46.90

The water requirement of the canal command area was found proportional to the type of crop and their areal extent. The cultivated area of LBC (5372.09 ha) is less than that of RBC (5532.04 ha). Correspondingly the annual irrigation requirement of LBC (23.03 Mm^3) was also found less than that of RBC (23.87 Mm^3). The total average annual net irrigation demand of the CRDS command area was obtained as 46.90 Mm^3.

4.3. ASSESSMENT OF ADEQUACY OF CANAL WATER

For the development of the conjunctive management model it is necessary to know the availability of canal water in the field. Conveyance efficiency of the canal water distribution system is the important factor that determines the water availability in the field. So, for the computation of conveyance efficiency of the CRDS canal system, measurements of flow through the canal system and seepage loss were conducted during the study.

The quantity of water diverted through the CRDS canal system for the last 15 years is presented in Table 4.11. This data showed a decreasing trend from 2004 to 2018 (Fig. 4.6). The average water diverted was 201.11 Mm^3 per year. During summer, the water diversion depends only on the tail water release of Poringalkuthu dam.

Table 4.11 Water diverted through CRDS canal system from 2004 to 2018

Year	Water diverted from Thumburmuzhi weir		Total (Mm^3)
	LBC(Mm^3)	RBC (Mm^3)	
2004	117.20	110.71	227.91
2005	140.74	168.47	309.21
2006	109.85	130.20	240.05
2007	122.57	138.68	261.25
2008	108.47	110.41	218.88
2009	106.89	87.66	194.55
2010	105.51	91.99	197.50
2011	119.96	93.05	213.01
2012	115.89	80.64	196.53
2013	95.94	72.02	167.96
2014	108.45	70.10	178.55
2015	108.90	62.37	171.27
2016	82.73	68.43	151.16
2017	62.42	65.22	127.64
2018	95.60	65.61	161.21
		Average of last five years	157.97

Due to this, the last five years average water release, 157.97 Mm^3 per year, was considered for the study. It was found that during December itself major part of the canal water was used for filling the ponds and chira or bund in the command area. This diverted water was used for irrigating areas other than cultivable command area of the canal system through lift irrigation. Table 4.12shows the details of the ponds and their capacity. Hence this water stored in the ponds could be considered as the surface water that was not utilized in the cultivable command area of CRDS and it is deducted from total water diverted from the weir. Thus the average annual water diversion of 153.3 Mm^3 to the cultivable command area of CRDS was taken for further computations in this study.

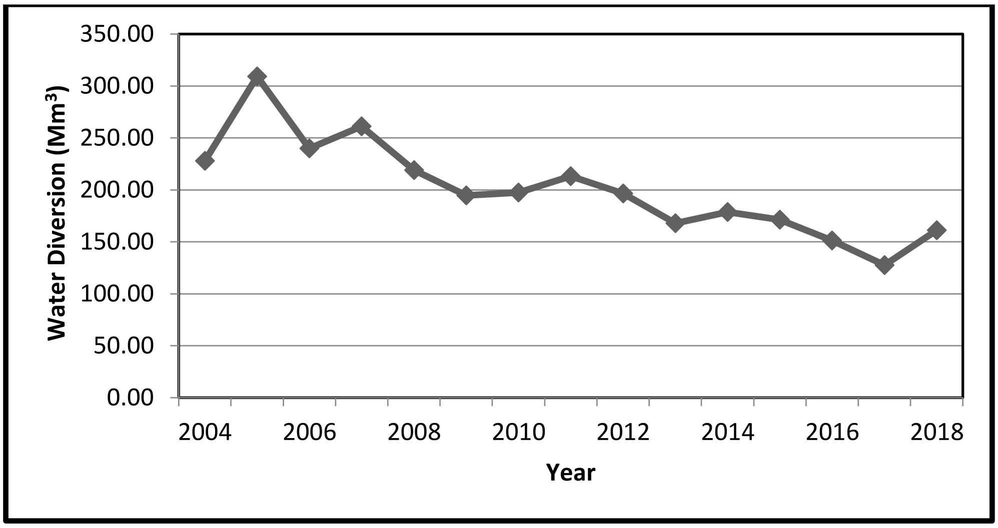

Fig. 4.6 Annual water diversion through CRDS canal system

Table4.12 Diversions from canal to fill ponds and 'chira'

Particulars	Number	Total capacity (Mm^3)
Ponds filled by LBC	2	0.05
Ponds filled by RBC	7	0.04
'Chira' filled by RBC	6	4.57
Grand total		4.66

A rotational water delivery system is followed, separately for both LBC and RBC to deliver water to the field. The rotation is completed during a period of 20-22 days. Each branch canal has water for two days during this period. Gates are provided at the entrance of each branch canal to control the flow and the un-gated spouts along the branch canal to deliver water to the field. Unavailability of water towards the tail end was the major complaint of the tail end farmers.

4.3.1 Assessment of water availability in the field

In order to check the current status of canal water availability in the field, the flow rates were measured in selected branches of the canal system during the month of March, 2019. For accuracy of measurement, two branch canal from each of the head, middle and tail sections of both LBC and RBC were considered. The measured flow velocity and discharge are shown in Table 4.13.

Table 4.13 Flow through selected branch canals

Branch	Distance from head end (km)	Flow velocity (m/s)	Cross sectional area (m^2)	Discharge (l/s)
Meloor	0.03	0.387	1.056	408
	1.00	0.620	0.406	252
	1.20	0.602	0.406	244
	3.00	0.233	0.182	42
	3.50	0.000	0.182	0
Edakkuny	0.02	0.200	1.181	236
	0.45	0.185	1.181	219
	1.10	0.107	0.778	83
	1.60	0.063	0.511	32
	2.50	0.000		0
Mambra	0.01	0.277	0.339	94
	0.33	0.257	0.304	78
	1.10	0.143	0.232	33
	1.50	0.100	0.137	14
	2.00	0.000		0
Mettippadam	0.05	0.333	1.648	549
	1.40	0.327	1.31	428
	2.20	0.280	0.513	144
	3.00	0.127	0.182	23
	3.50	0.000		0

Perambra	0.05	0.363	1.581	574
	1.00	0.297	0.923	274
	1.50	0.317	0.413	131
	2.50	0.143	0.699	100
	4.00	0.000		0
Thazhekkad	0.03	0.230	0.940	216
	0.30	0.217	0.940	204
	0.50	0.393	0.439	173
	1.50	0.057	0.438	25
	2.40	0.000		0

Meloor branch canal in LBC and Mettippadam branch canal in RBC were selected for flow measurements in head end. The water availability was comparatively more in the branch canals that draw water from the upstream section of main canals than the downstream.

The variation of discharge with distance from head end of canal in Meloor and Mettippadam branch canals are shown in Fig. 4.7 and 4.8 respectively. The rates of water flow at the entry point in Meloor and Mettippadam branches were found 408 l/s and 549 l/s respectively. But in both the canals, the water flow reduced as it advanced and reached a value of zero when it reached half of its way.

Edakkuny branch in LBC and Perambra branch in RBC were selected in the middle section for flow measurement. The water flow rate at the entry point of Edakkuny branch canal and Perambra branch canal were found 236 l/s and 574 l/s respectively. The corresponding discharge variations along the length are shown in Figs. 4.9 and 4.10.

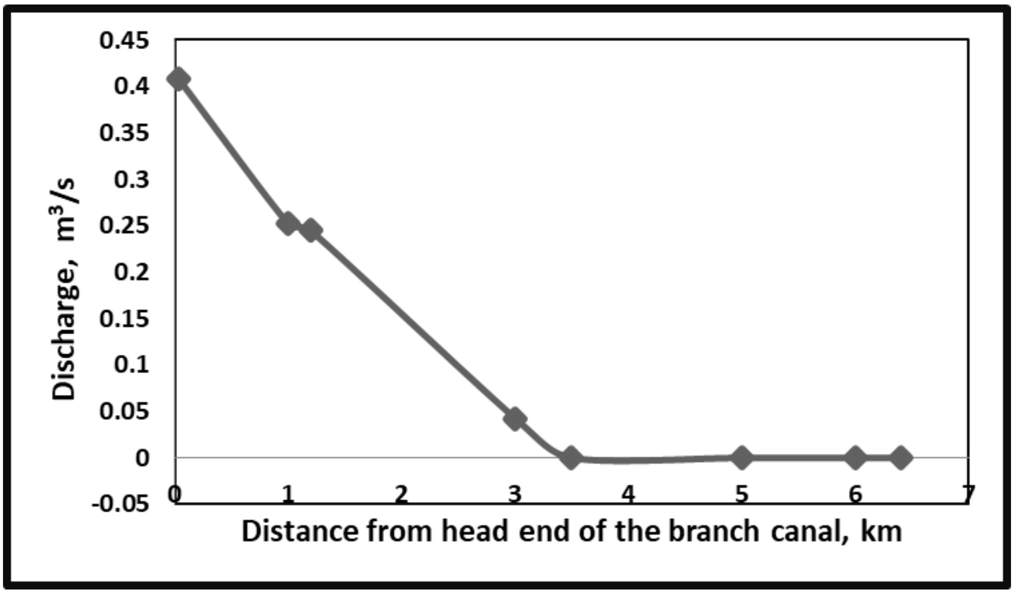

Fig.4.7 The variation of discharge with distance in Meloor branch canal

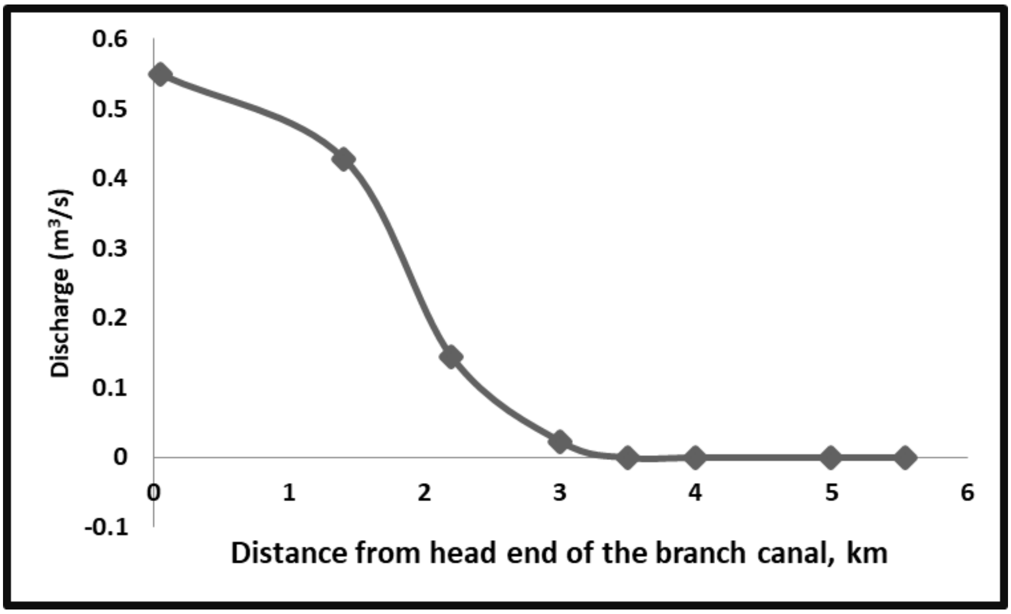

Fig.4.8 The variation of discharge with distance in Mettippadam branch canal

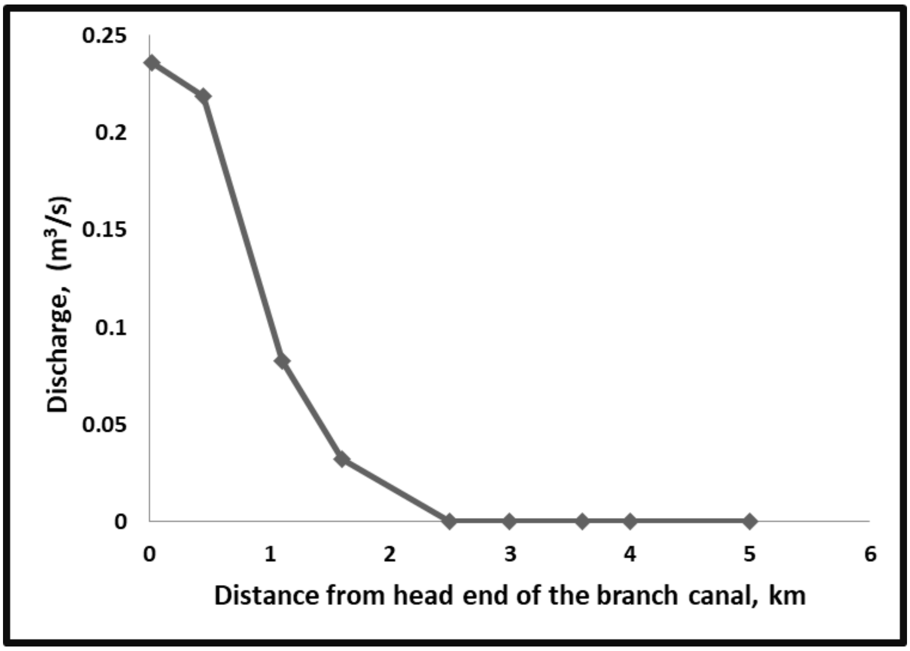

Fig.4.9 The variation of discharge with distance in Edakkuny branch canal

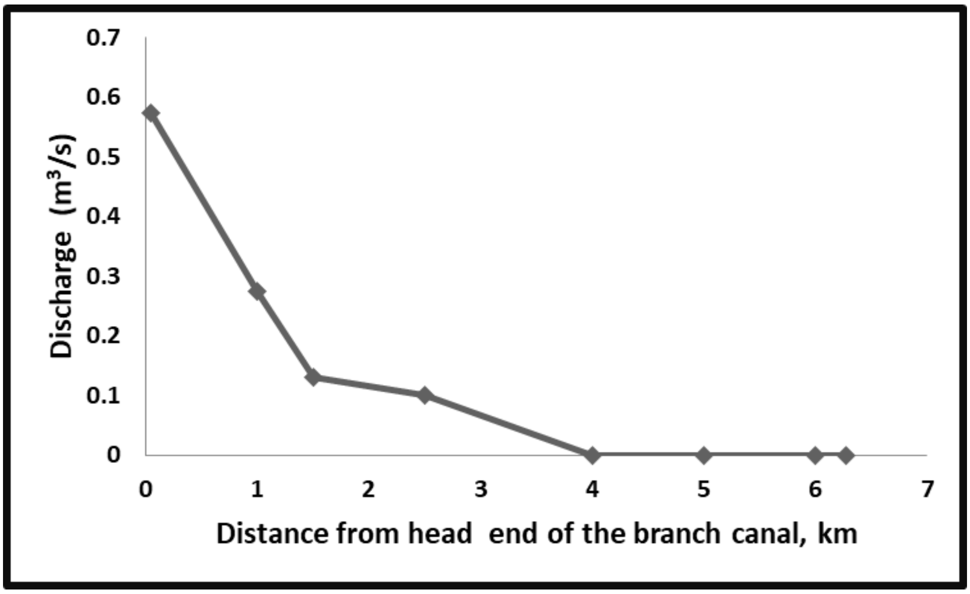

Fig.4.10 The variation of discharge with distance in Perambra branch canal

Mambra and Thazhekkad were the two branches selected at the tail end on LBC and RBC respectively. The water entry rates in these channels were found 94 l/s and 216 l/s respectively. Figures 4.11 and 4.12 show the variation of discharge along the canal length.

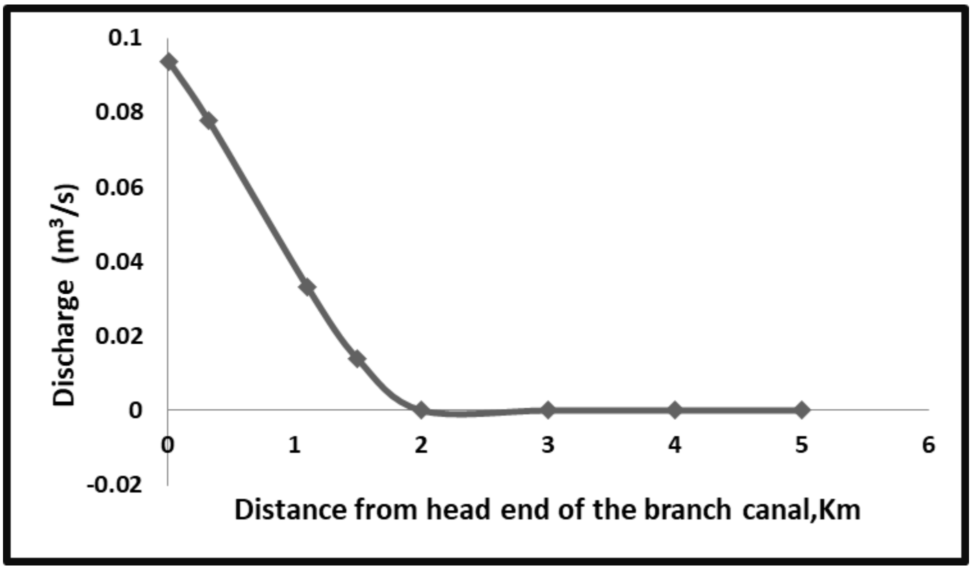

Fig.4.11 The variation of discharge with distance in Mambra branch canal

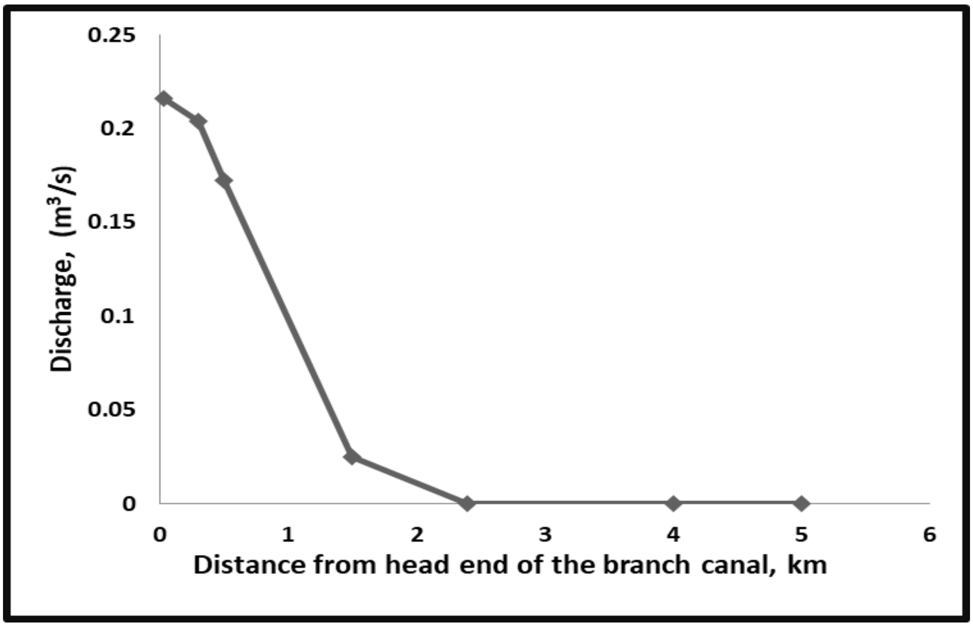

Fig.4.12 The variation of discharge with distance in Thazhekkad branch canal

It is clear from Figs. 4.7 to 4.12 and Table 4.12, that water diverted to branch canal decreased from head end to tail end. This gave an indication of high conveyance loss in the canals. The increased conveyance losses from head to tail end of canal maybe because of the poor and damaged canal lining towards the tail end.

The water is diverted to farmer's fields through the un-gated spouts provided along the branch canals. So the fields at the head end of branch canals receive more water. Besides this, flow towards the tail end of branch canals is reduced and finally, there is no flow when the channel passes half of its way due to the poor and damaged canal lining, waste dumping and presence of small plants growing in the canal. This would lead to high conveyance losses in the distribution system.

Table 4.14 Rate of seepage loss from main canal sections and selected branch canals

Main canal	Section/Branch	Inflow (m^3/s)	Outflow (m^3/s)	Length of the section (m)	Rate of seepage loss ($m^3/s/km$)
LBC	Head	4.4198	4.4011	600	0.031
	Middle	1.4872	1.4509	450	0.081
	Tail	0.2566	0.2253	320	0.098
RBC	Head	4.4006	4.3769	540	0.044
	Middle	0.1355	0.1167	340	0.055
	Tail	0.0512	0.0252	150	0.173
LBC	Meloor	0.2517	0.2444	170	0.043
	Edakkuny	0.2363	0.2186	410	0.043
	Mambra	0.0938	0.0779	315	0.051
RBC	Mettippadam	0.1436	0.1351	210	0.041
	Perambra	0.2737	0.2617	250	0.048
	Thazhekkad	0.2162	0.2037	230	0.054

4.3.1.1 Measurement of seepage loss from the canal system

Since seepage loss is one major factor affecting the availability of water in the field, the conveyance efficiency of main canals, as well as branch canals, was assessed by the measurement of seepage loss. It was found that the rate of seepage per km increased from the head to tail end of the main canals (Table 4.14).

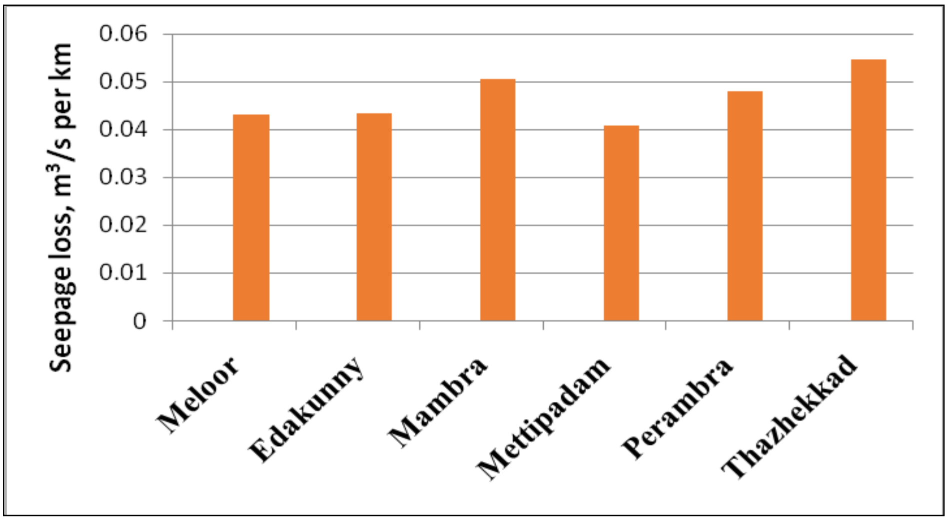

Fig. 4.13 The rate of seepage loss in selected branch canals

The observed average seepage loss rate in the head, middle and tail sections were 0.037, 0.067 and 0.135 m^3/s per km respectively. The increased seepage rate towards the tail end is due to damaged lining and poor cleaning of channel. Since the loss rate is more towards tail reach, the period of water flow is short towards tail reach. This also contributed to the reduced annual loss in tail reach. The annual seepage loss was found more in the head reach of the main canal due to a long period of flow through this reach (Table 4.15).

The average seepage loss measured from selected branch canals are shown in Fig.4.13. The branches Meloor and Mettippadam, that draw water from the head section of main canals showed less rate of seepage loss than other branches. The rate of water flow was more in these branches while the water availability was less in the middle and tail end branches. Hence the average annual seepage loss for the CRDS canal system was computed as 74.94 Mm^3 (Table 4.15).

4.3.1.2 Conveyance efficiency

The conveyance efficiency of selected branches from head to tail reach of LBC and RBC are shown in Table 4.16. The overall conveyance efficiency of the CRDS canal system is shown in Table 4.17.

Table 4.15 Average annual seepage loss from the canal system

	Reach	Seepage loss (Mm^3)
Main	Head	22.53
	Middle	17.32
	Tail	14.72
Branches		20.37
Total CRDS		74.94
Percent of the total water diverted		47.44%

The branches in the head reach of main canals which draw more water than lower reach branches showed higher water conveyance efficiency. Since the rate of water entry is high at the head reach, water moves rapidly through these branches which reduces seepage rate. Hence the rate of water delivery to field is also high at the head end. The highest conveyance efficiency of 74 per cent was observed in the Mettippadam branch whereas the lowest (19%) in Mambra branch which is at the tail end of LBC. The average value of the conveyance efficiency of these selected branches was found as 52.78%.

Table 4.16 Conveyance efficiency of selected branches of the CRDS canal system

Main Canal	Reach	Branches	Rate of water diverted to branch (m^3/s)	Rate of water delivered to field (m^3/s)	Conveyance efficiency (%)
LBC	Head	Meloor	0.408	0.258	63.15
	Middle	Edakkuny	0.236	0.128	54.27
	Tail	Mambra	0.094	0.018	19.08
RBC	Head	Mettippadam	0.549	0.406	74.03
	Middle	Perambra	0.574	0.383	66.68
	Tail	Thazhekkad	0.216	0.085	39.51
				Average	52.78

The overall conveyance efficiency of the CRDS canal system was estimated from the measured seepage loss from main canals and branches as shown in Table 4.17. It was found as 51.1% and was taken for further computations in the study. The value is near to the average value of the conveyance efficiency of selected branches. Santhosh *et al.* (2019) also reported 50 per cent seepage loss from CRDS canal water flow.

Table 4.17 Conveyance efficiency of CRDS canal system

Particulars	Volume of water (Mm^3)
Water diverted from weir (Average of last 5 years)	157.97
Water used to fill chira/Kulam	4.66
Net water diverted through the canal system	153.31
Seepage loss from canal water	74.94
Water delivered to field	78.37
Conveyance efficiency	51.1%

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4.3.1.3 Assessment of Performance indicators

The performance of any irrigation system is evaluated based on parameters like adequacy, equity and reliability. There are many indicators to measure these parameters. The Relative Water Supply and Adequacy Indicator are the two important performance indicators used to measure the adequacy of irrigation water applied in this study.

Relative water supply (RWS)

The adequacy of irrigation water supplied through the CRDS canal system in the cultivable command area was assessed by relative water supply. Table 4.18 shows the relative water supply values of selected branches and CRDS canal system.

Table 4.18 Relative water supply of selected branches and the CRDS canal system.

Main canal	Name of Branch/ Canal system	Irrigation water delivery (Mm^3)	Effective rainfall (Mm^3)	ET_{crop} (Mm^3)	Seepage & Percolation (Mm^3)	Relative Water Supply
LBC	Meloor	0.64	1.40	4.60	0.43	0.405
	Edakkuny	0.37	0.48	1.50	0.27	0.478
	Mambra	0.15	0.83	2.66	0.13	0.349
RBC	Mettippadam	0.85	0.25	0.82	0.54	0.812
	Perambra	0.89	1.02	3.43	0.60	0.476
	Thazhekkad	0.34	0.61	1.96	0.27	0.424
CRDS		153.31	43.44	113.66	114.12	0.864

From Table 4.18 it is clear that the adequacy of irrigation water was not fulfilled in the command area of CRDS canal system as the RWS value (0.864) is less than one. Data on water diverted from Thumburmuzhi weir for the last five years clearly indicated that water diverted from the weir was several times higher than that of the net irrigation requirement of the command area (Tables 4.10 and 4.11). Even then relative water supply values were found less than one. This indicated the low efficiency of water conveyance through the canal system. The Mettippadam branch canal in the upper reach of RBC showed the highest value of relative water supply (0.812). This branch has relatively high conveyance efficiency also as shown in Table 4.16. This might be due to its position in the upper reach and low water requirement in its CCA. Hence the relative water supply and overall conveyance efficiency of the CRDS canal system was estimated as 0.864 and 51.1% respectively. All these highlight that unless and until the canal systems are well maintained and lined regularly, there will not be adequacy of irrigation water in the command area.

Adequacy indicator

Adequacy indicator is a measure to evaluate the performance of any irrigation system. Table 4.19 shows the adequacy indicator computed using the flow measurement data of selected branch canals.

Table 4.19 Adequacy indicator of CRDS canal system

Main canal	Name of Branch/ Canal system	Irrigation water delivery (Mm^3)QD	Irrigation requirement (Mm^3)QR	Adequacy indicator, P_A	Performance
LBC	Meloor	0.64	5.89	0.108	Poor
	Edakkuny	0.37	2.25	0.163	Poor
	Mambra	0.15	13.35	0.011	Poor
RBC	Mettippadam	0.85	0.88	0.963	Good
	Perambra	0.89	4.04	0.221	Poor
	Thazhekkad	0.34	4.14	0.081	Poor
CRDS		153.31	183.50	0.861	Fair

Among the different branches above, all the branches except Mettippadam that draw water from head reach of RBC falls in the performance category ‘poor’. Cropped area within the CCA of Mettippadam branch is less than that of the other selected branches which results in low irrigation requirement. In addition to this, the high water delivery rate also contributed to 'good' adequacy performance in this branch canal. The adequacy indicator of CRDS canal system was computed from the data of water diverted through the canal system and irrigation requirement of the command area. The overall adequacy performance of CRDS canal system was found fair. As it is not practically possible to line the entire length of canals up to the field level in order to raise the irrigation water availability adequate enough, water supply from another source is to be sought of and dependency on surface water through canals are to be regulated in order to satisfy the irrigation demand of the command area.

4.3.2 Present status of conjunctive water use in the area

The CRDS canal system supplies water to almost all parts of the command area. The groundwater use for irrigation is relatively nil in this area. There are several lift irrigation schemes in the command area to irrigate the area outside the CCA of the canal system. The number of schemes, their capacity and the source of water are shown in Table 4.20. It is clear from the table that the source of most of the lift irrigation schemes is river itself. A few of them take water from ponds and quarries to cater to the irrigation needs of the command area. No lift irrigation scheme in the command area uses water from wells or tube wells.

Table 4.20 Details of lift irrigation schemes in the command area

Minor Irrigation section	No. of schemes	Source of water	Ayacut area (ha)	Annual water withdrawal (Mm^3)
Chalakudy	27	River and pond	1417.54	14.65
Kodakara	6	River and pond	736.96	6.15
Mala	19	River	2217.42	33.94
North Paravur	6	River and quarry	550.5	3.56
Total			4922.42	58.30

Thus the use of groundwater for irrigation is almost zero even though groundwater is available. By utilising groundwater for irrigation, the storage space for harvesting the rainwater could be created in the aquifer. This may reduce the chance of flooding in the Chalakudy area which was highly affected during the extreme rainfall events that happened in August 2018 and 2019.

4.3.2.1 Level of conjunctive water use needed in CRDS command area

The water effectively diverted (153.3 Mm^3) to the command area does not fully reach the fields due to the seepage loss in the canal system. The average conveyance loss in the canal system was estimated as 74.94 Mm^3 (Table 4.15) per year and water delivered to the field was 78.37 Mm^3 with an average conveyance efficiency of 51.1 per cent.

Table 4.21 Irrigation water deficiency in the command area

Particulars	Volume of water (Mm^3)
Water diverted to canal	153.31
Seepage loss from canal water	74.94
Water delivered to field	78.37
Conveyance efficiency	51.1%
Net irrigation requirement	46.90
Field application efficiency	50.00%
Gross irrigation requirement	183.56
Deficiency	30.25

Surface irrigation methods are practised commonly in all fields for utilizing the canal water. Field application efficiency of these surface irrigation methods are generally below 50 per cent. Thus the average annual gross irrigation requirement of the command area is 183.56 Mm^3. Hence in order to satisfy the water requirement of the cultivable command area of CRDS, provision for some additional quantity (30.25 Mm^3) of water is to be found out (Table 4.21). The performance indicators of canal irrigation system computed from the flow measurement data also highlighted the need of planning conjunctive water management in the command area.

4.4 DYNAMIC RESPONSE OF THE AQUIFER IN THE STUDY AREA

The study of aquifer characteristics and its response to water recharge and extraction are important in planning conjunctive water management. The annual groundwater balance which varies with groundwater recharge and extraction is also needed for the development of a conjunctive water management model. Hence a groundwater flow model of the area was created in Visual MODFLOW. The steady-state and transient state calibration of the model was done for the area. This calibrated and validated model was used for the prediction of groundwater levels under various scenarios to know the feasibility of groundwater withdrawal for conjunctive water use. The annual groundwater balance of the aquifer was thus obtained from the validated model. The water level observations from 17 wells and 14 pumping wells in the command area were used for the study.

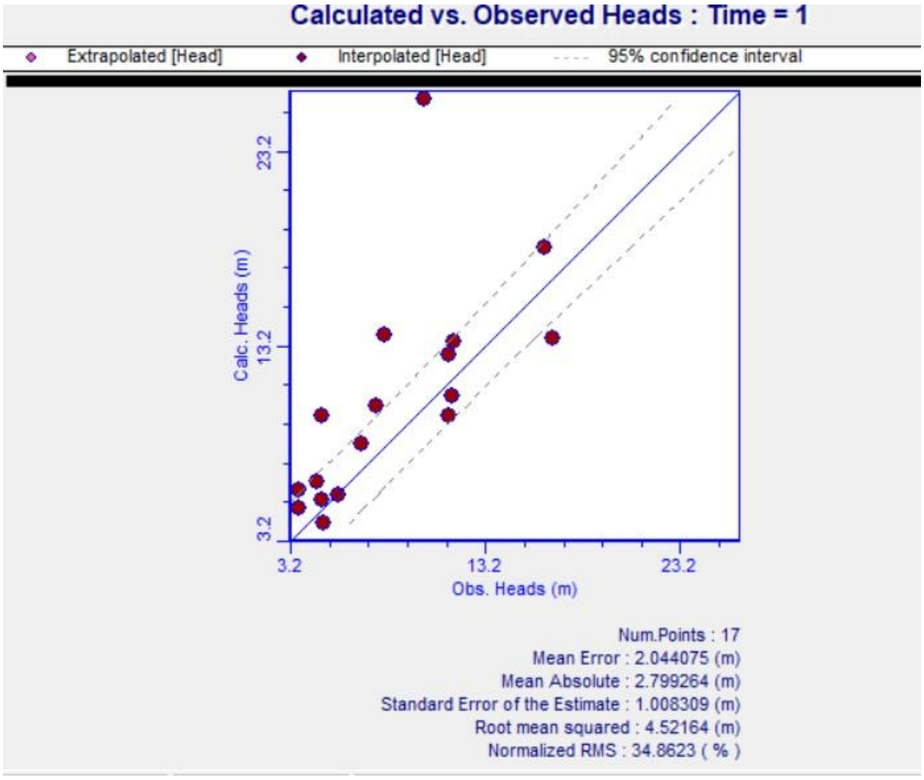
4.4.1 Steady-state calibration

The groundwater flow model was calibrated for the steady-state groundwater flow. The aquifer condition of the year 1996 was taken as the initial condition for calibration. The calculated water levels were compared with the observed water levels of 17 observation wells, including 3 bore wells, in the command area. The hydraulic conductivity was the main input parameter that was changed iteratively to get a calibrated model. The Root Mean Square Error (RMSE) value below 5 ie, at 95% confidence level was used to check the accuracy. The RMSE value obtained in the steady-state calibration, 4.52, was found within the acceptable limit. The plot of calculated versus observed water level of 17 observation wells is shown in Fig.4.14. From the figure, it is clear that there was a good agreement between calculated and observed water levels in most of the wells. Table 4.22 shows the hydraulic conductivity values of the aquifer after calibration.

The hydraulic conductivity of the laterite layer is high and similar to that reported by Bonsor *et al*., 2014.

Table 4.22 Hydraulic conductivity of aquifer after calibration

Aquifer layers	Horizontal hydraulic conductivity (m/day)
Laterite	544.32
Weathered rock	0.432



Num.Points : 17
Mean Error : 2.044075 (m)
Mean Absolute : 2.799264 (m)
Standard Error of the Estimate : 1.008309 (m)
Root mean squared : 4.52164 (m)
Normalized RMS : 34.8623 (%)

Fig. 4.14 Steady-state calibration – Observed vs. Calculated water levels.

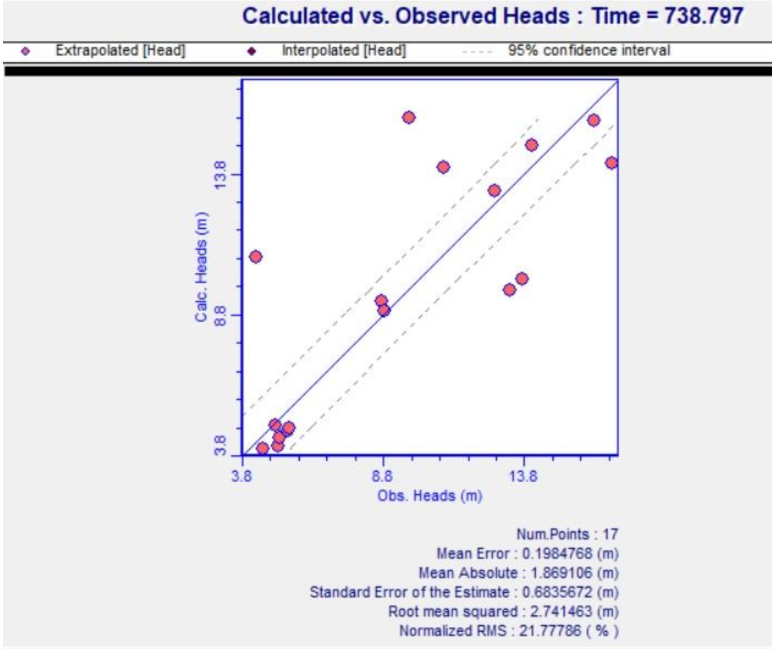
The general soil type in the command area was lateritic, with high porosity and specific yield. Table 4.23 shows the storage properties of the lateritic aquifer after calibration.

Table 4.23 Storage properties of the aquifer after calibration

Specific Storage (Ss) (m^{-1})	0.0009
Specific yield (Sy)	0.38
Effective porosity	0.40
Total porosity	0.45

4.4.2 Transient state calibration

For the transient state calibration, the model computed the water levels in each time step. The water level data from 1996 to 2010 were used for calibration in 60-time steps. The values of hydraulic conductivity, specific storage, specific yield and discharge through the drain were altered in a systematic manner to obtain the computed heads as close to the observed heads as possible.



```
Num.Points : 17
Mean Error : 0.1984768 (m)
Mean Absolute : 1.869106 (m)
Standard Error of the Estimate : 0.6835672 (m)
Root mean squared : 2.741463 (m)
Normalized RMS : 21.77786 ( % )
```

Fig. 4.15 Transient state calibration, observed vs. calculated water levels on 738th day

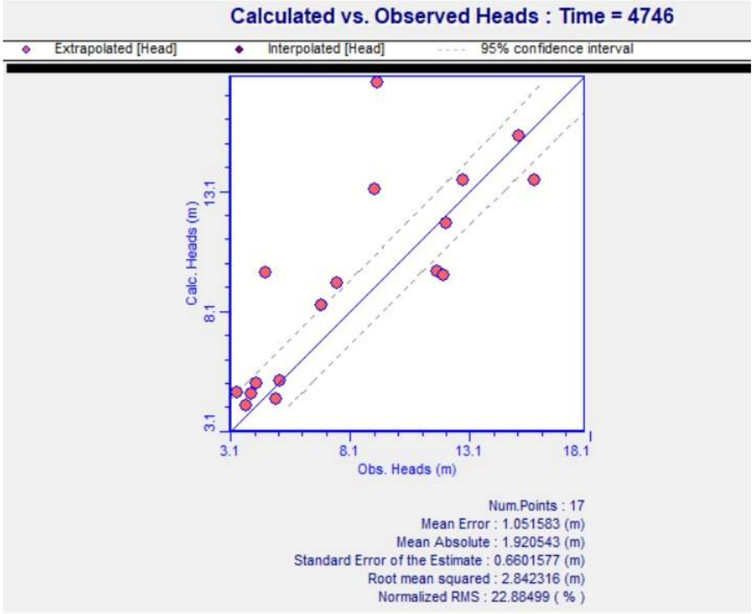


Fig. 4.16 Transient state calibration, observed vs. calculated water levels on 4746thday

The variation of computed versus observed water levels for two different days (738th day and 4746th day) are shown in Fig. 4.15 and 4.16 respectively. The RMSE of these two days were found 2.74 and 2.84 respectively. The closeness of computed and observed water levels is seen clearly in the figures. Khadri and Pande reported similar results in 2016. The computed and observed water level hydrographs of selected wells are shown in Fig.4.17 a, b, c, d. From the figures, it is observed that computed hydrographs are comparable with the observed hydrographs.

The Water table contour map of the study area obtained from the model is shown in Fig.4.18. It is clear from the figure that water table elevation is as high as 15 to 20 m towards the northeast portion of the area. This is because of the higher surface elevation in that area. The water level elevation decreased towards the south-west direction as the topography of the area is sloping towards the southwest. The highest water table elevation observed was 20 m above MSL and the lowest value was 6 m above MSL in the paddy area.

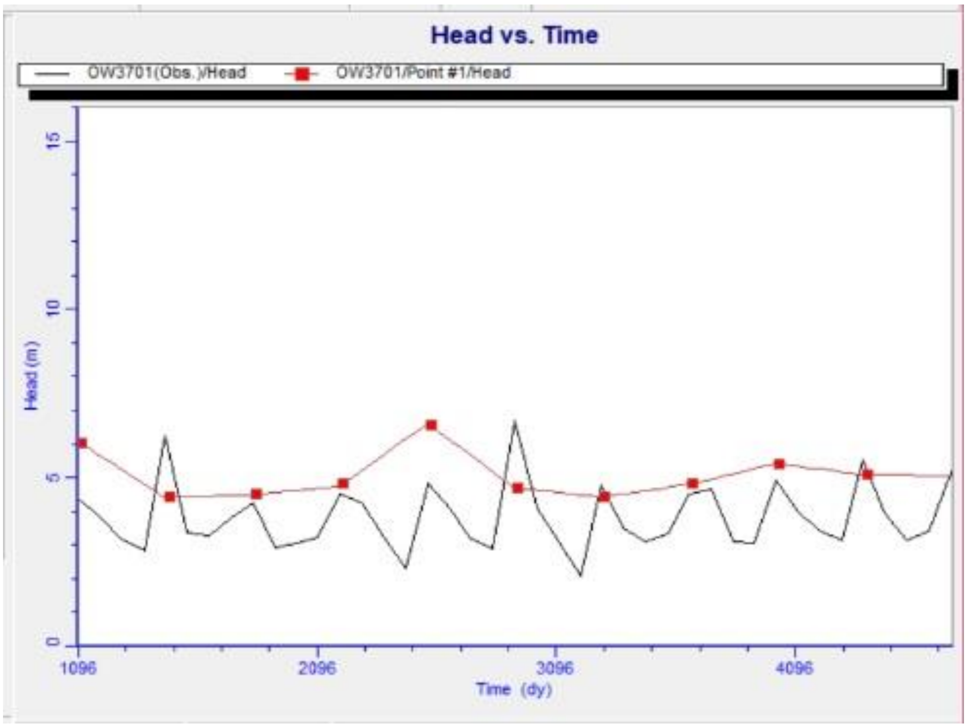


Fig.4.17. (a) Computed vs observed water level hydrograph - Muringoor

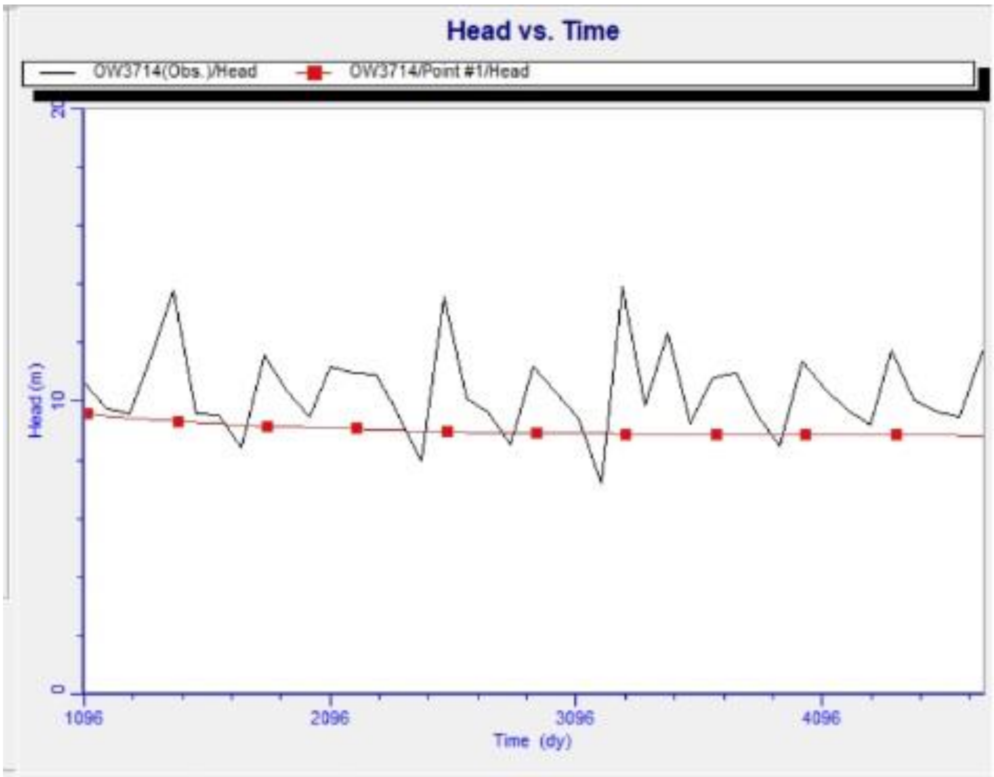


Fig.4.17. (b) Computed vs observed water level hydrograph- Muriyad

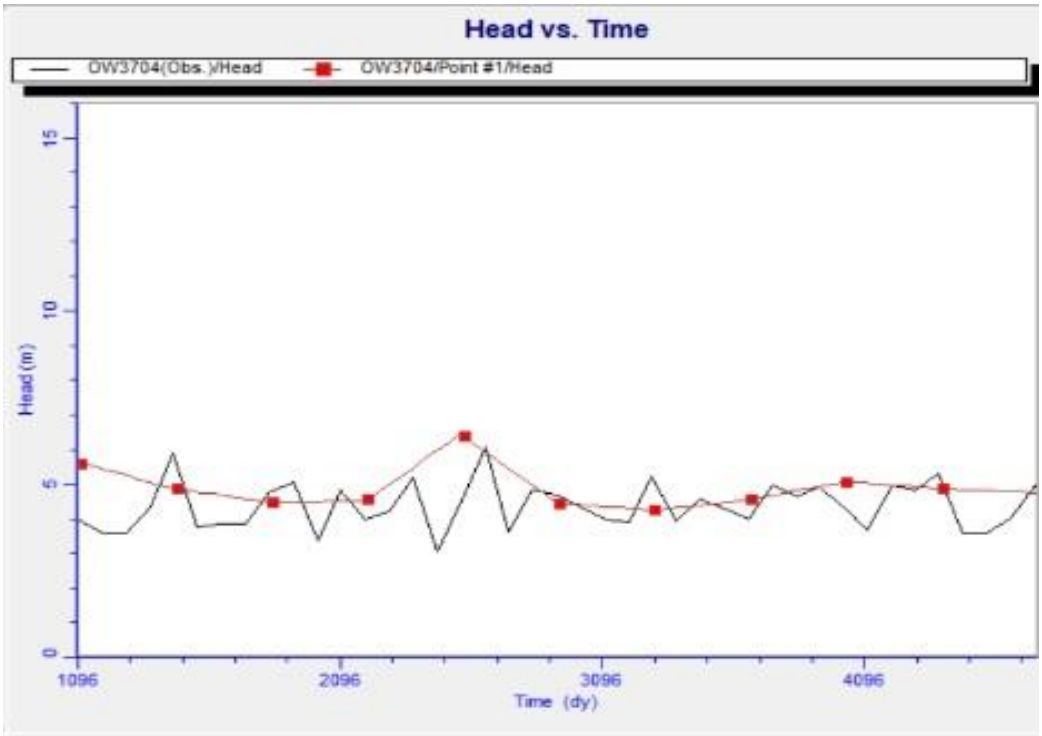


Fig.4.17. (c) Computed vs. observed water level hydrograph - Potta

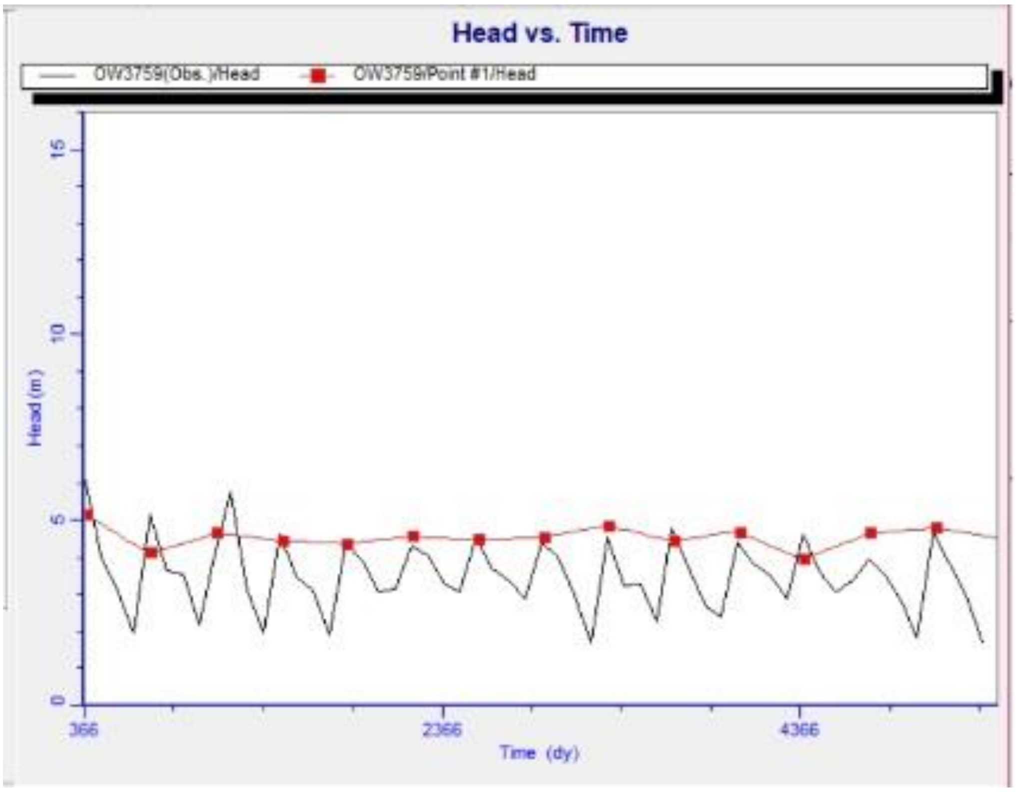
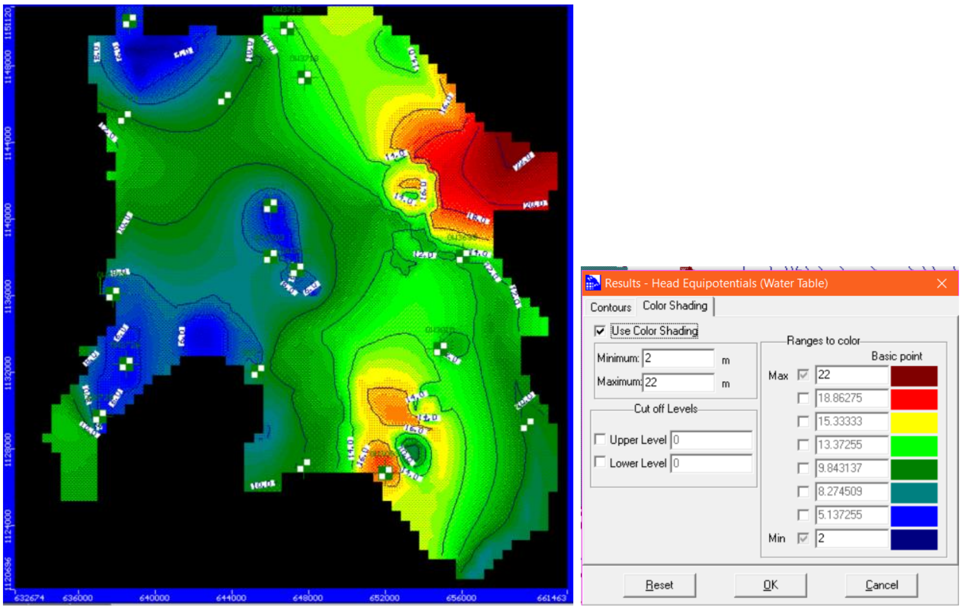


Fig.4.17. (d) Computed vs. observed water level hydrograph - Puthenchira



Results - Head Equipotentials (Water Table)

Color Shading

☑ Use Color Shading

Minimum: 2 m

Maximum: 22 m

Cut off Levels

☐ Upper Level 0

☐ Lower Level 0

Ranges to color

		Basic point	
Max	☑	22	🟥
	☐	18.86275	🟥
	☐	15.33333	🟨
	☐	13.37255	🟩
	☐	9.843137	🟩
	☐	8.274509	🟦
	☐	5.137255	🟦
Min	☑	2	🟦

Fig. 4.18 Water table contour map of the study area after calibration

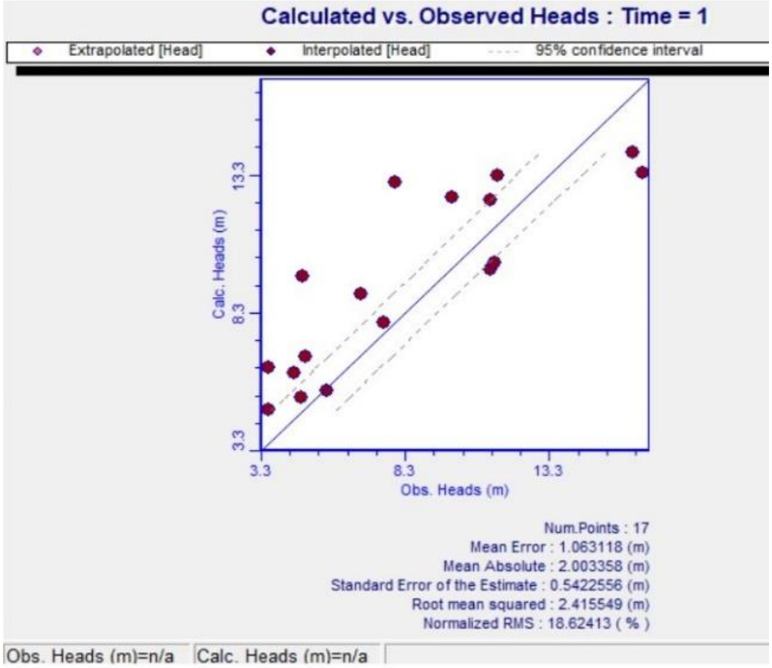
Drastic change in water table was observed towards the low lying paddy area. Majority of the command area has water table elevation in the range of 9 m to 14 m. Chalakudy river flows through the centre of the command area, from east to west. Hence the water table contour value decreases from east to west in this region.

4.4.3 Model validation

The model was validated using water level data from 2011 to 2014. Figures 4.19 and 4.20 show the scatter diagram of computed vs. observed water levels in the command area in steady-state and transient state validation respectively. The RMSE values obtained for steady-state and transient state validation were 2.41 and 2.50 respectively. Table 4.24 shows the computed and observed water levels and corresponding RMSE after validation.

From the figures and table, it is obvious that there is good agreement between computed and observed water levels after validation. Hydrographs of selected wells after validation (Figs.4.21 a, b, c, d) also shows the same result.

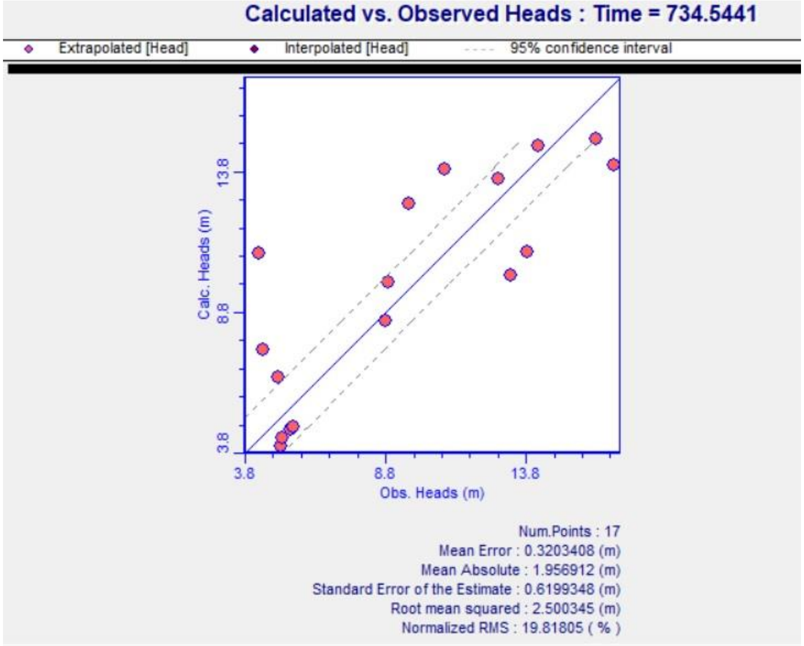
Hence the model was used for predicting future groundwater conditions of the region.



```
Num.Points : 17
Mean Error : 1.063118 (m)
Mean Absolute : 2.003358 (m)
Standard Error of the Estimate : 0.5422556 (m)
Root mean squared : 2.415549 (m)
Normalized RMS : 18.62413 ( % )
```

```
Obs. Heads (m)=n/a   Calc. Heads (m)=n/a
```

Fig.4.19 Computed vs. Observed water levels after validation (Steady state)



```
Num.Points : 17
Mean Error : 0.3203408 (m)
Mean Absolute : 1.956912 (m)
Standard Error of the Estimate : 0.6199348 (m)
Root mean squared : 2.500345 (m)
Normalized RMS : 19.81805 ( % )
```

Fig 4.20 Observed vs. calculated heads after validation, transient state, 734th day

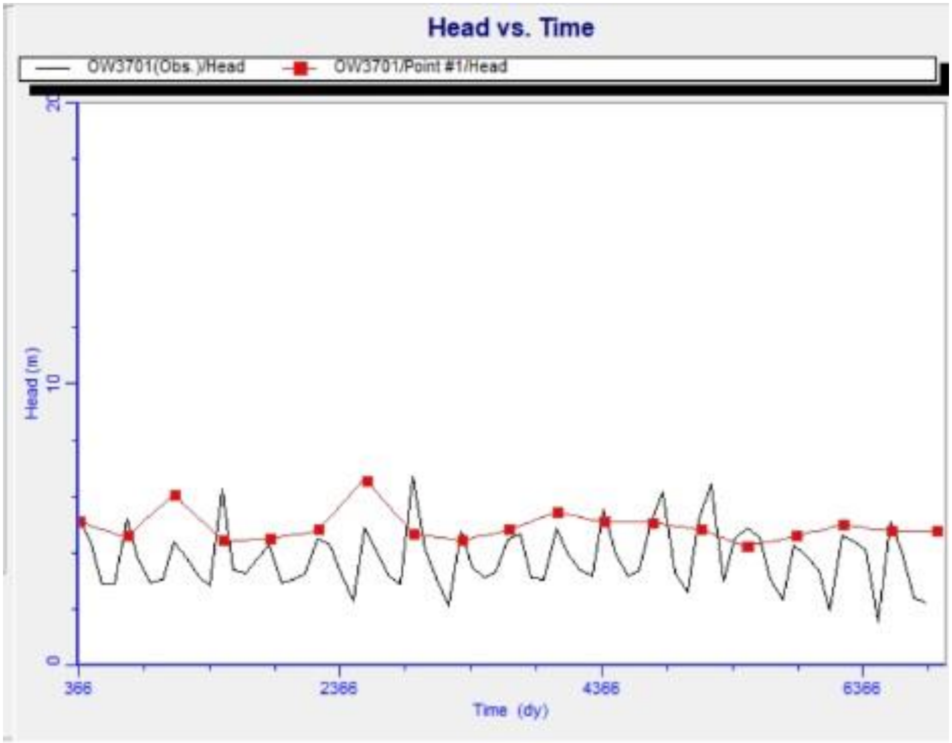


Fig.4.21. (a) Computed vs. observed water level hydrograph - Muringoor

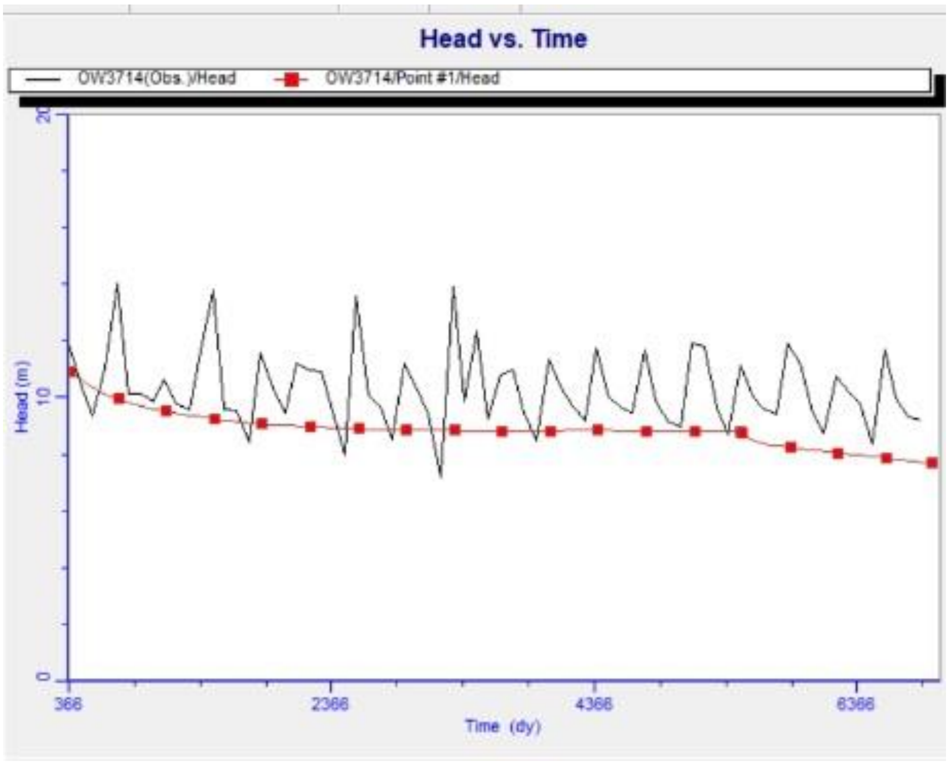


Fig.4.21. (b) Computed vs. observed water level hydrograph- Muriyad

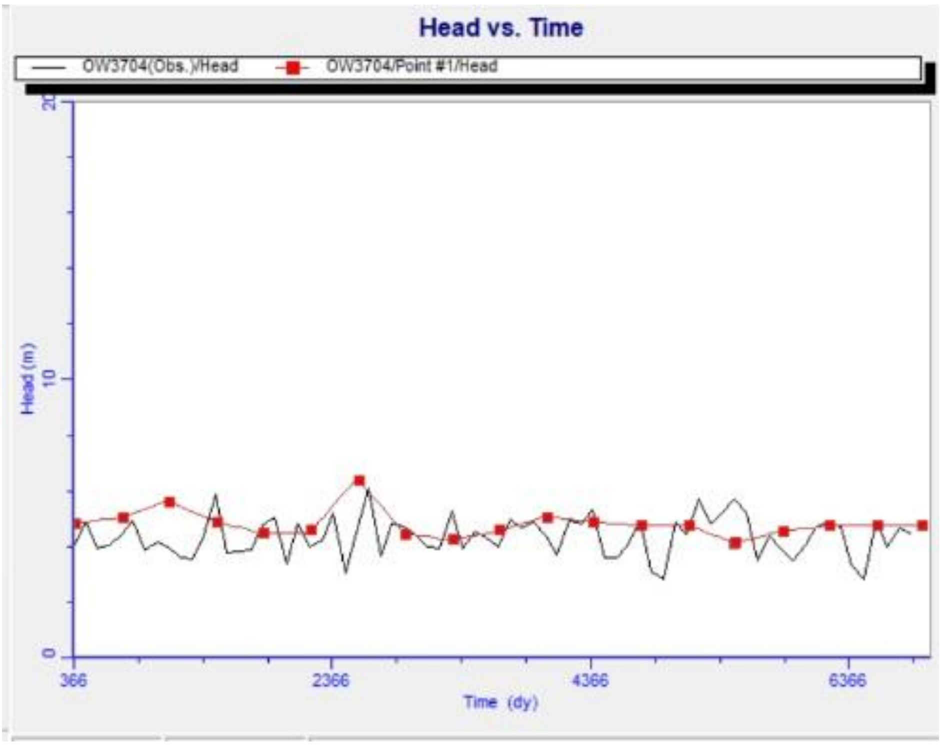


Fig.4.21. (c) Computed vs. observed water level hydrograph- Potta

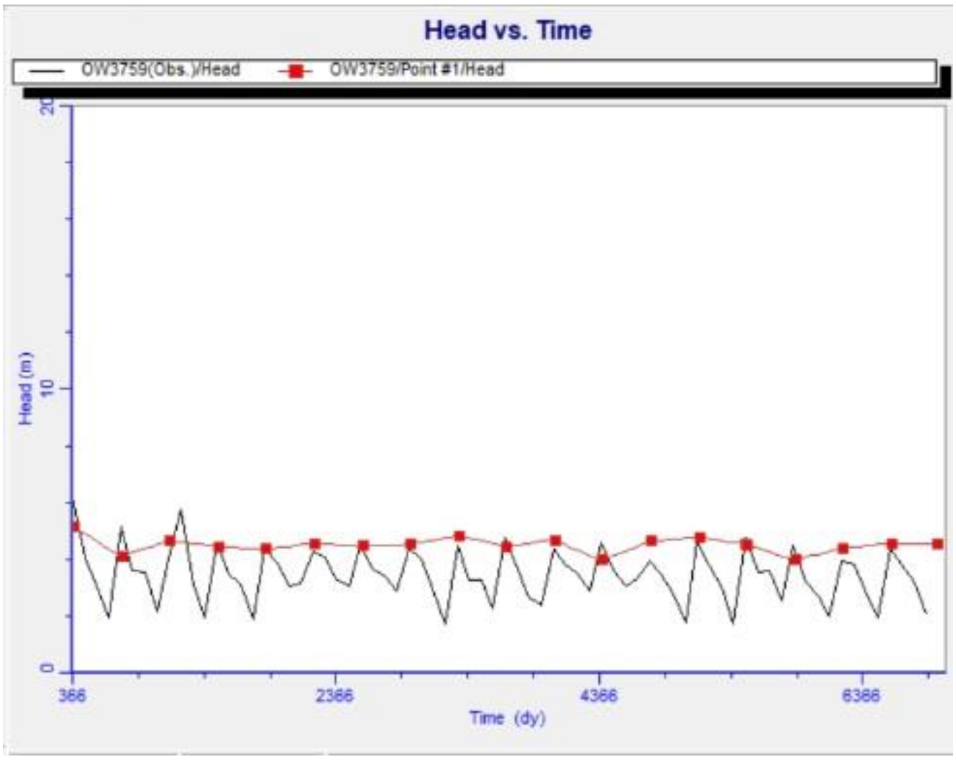


Fig.4.21. (d) Computed vs. observed water level hydrograph - Puthenchira

From the table it is clear that the root mean square error (RMSE) values of wells after validation are low and within the acceptable limits. The well located at Poyya showed minimum deviation between observed and calculated water level with a root mean square error of 0.083. The dug wells located at Annamannada and Muringoor also showed good agreement between calculated and observed values with RMSE values 0.399 and 0.540 respectively. Poyya and Annamannada are the locations towards the south west portion of the command area where ground level elevations are lower than the eastern portion of the command area.

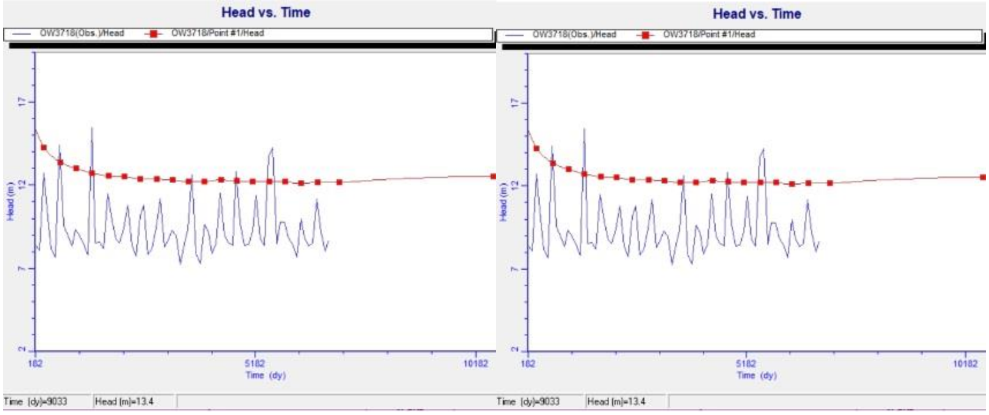
Table 4.24 Observed and calculated water levels after validation

Well Number	Observed water level (m above MSL)	Calculated water level (m above MSL)	RMSE
3704	4.85	6.77	1.919
3729	5.62	5.54	0.083
3701	4.74	5.28	0.540
3715	3.60	6.34	2.744
3759	4.49	6.16	1.673
3728	3.61	4.82	1.211
3703	6.82	9.00	2.182
3727	7.59	7.99	0.399
3015	11.31	9.91	1.397
3718	11.53	13.32	1.792
3699	11.31	12.41	1.099
3058	9.98	12.51	2.530
3010	7.98	13.07	4.985
3714	11.42	10.14	1.277
3009	16.22	14.16	2.061
3719	16.57	13.40	3.173
3717	4.79	9.68	4.889

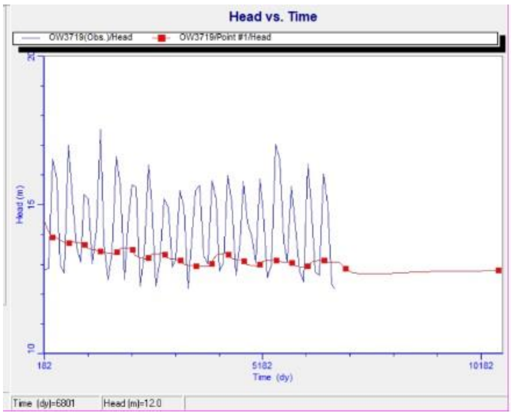
4.4.4 The Predicted future water levels

The predicted water levels of selected wells in the command area are shown in figures 4.22 a, b, c and 4.23. a, b, c. The fig.4.22 depicts the predicted water level in the command area during 2024 (i.e Ten years after the validation period) according to the scenario I (i.e. if recharge and pumping rate continues as per the present condition). It is clear that water level was maintained almost the same level even 10 years after the validation period.

Fig. 4.23 shows the predicted result of selected wells when the model runs according to scenario II (i.e. recharge to the aquifer decreases at the rate of 5 per cent annually and pumping increases at the rate of 10 per cent from the end of the validation period). It is clear that water levels showed a decreasing trend as the years advance from the end of the validation period.



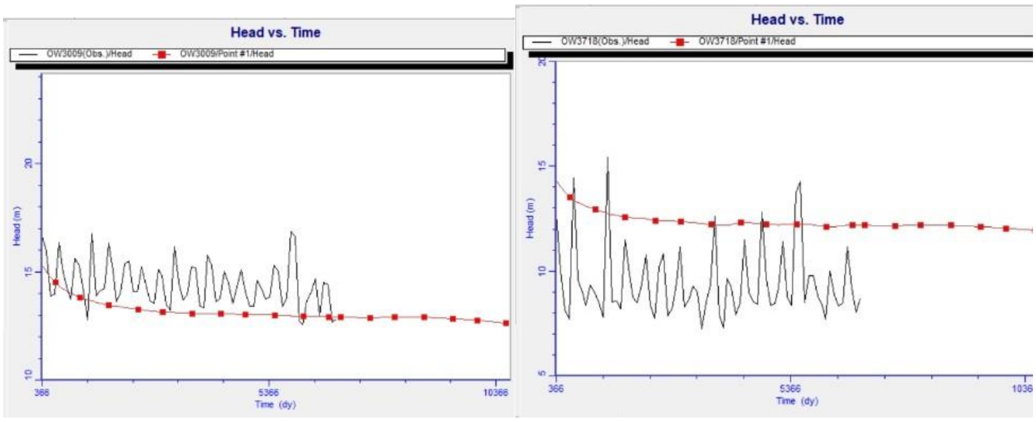
(a) Well at Angamaly (b)Well at Mattathur



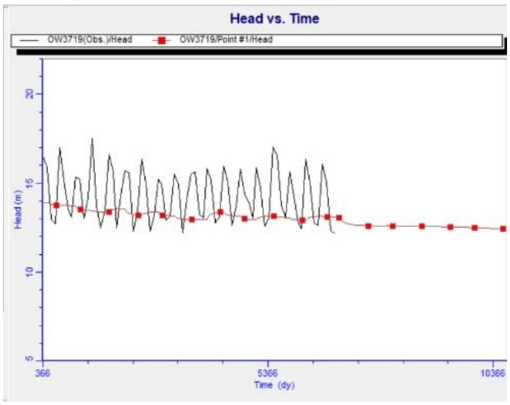
(c)Well at Mupliyam

Fig.4.22 Scenario I – Predicted water levels of selected wells

The change in rainfall pattern, reduction in surface water availability due to this induced change, reduction in rechargeable soil surface due to urbanization, etc. might be the reasons to reduce the aquifer recharge considerably. On the other hand withdrawal rate of groundwater may increase due to an increase in population, urbanization, industrialization, and change in irrigation demands. The developed model showed a response to all these expected changes.



(a)Well at Angamaly (b)Well at Mattathur



(c) Well at Mupliyam

Fig.4.23. Scenario II – Predicted water levels of selected wells

Even though the model showed the impact of reduced recharge and increased pumping rate on groundwater levels, the decline of groundwater levels are not much drastic. The average decline in groundwater level was 0.55 m during a period of 10 years. Thus it showed that there is immense scope for conjunctive use of surface and groundwater in the command area.

4.4.5 Mass balance of the aquifer

The groundwater balance obtained as output from Visual MODFLOW software is termed as the zone budget. It gives groundwater inflow and outflow components during each stress period. After validation of the model, the mass balance was obtained as an output for all the nineteen years from 1996 to 2014. Table 4.25 shows the groundwater balance of the command area from 1996 to 2014.

Table 4.25 Ground water balance of the command area during 1996-2014

Year	Total inflow (m^3/day)	Total outflow (m^3/day)	Net groundwater inflow (m^3/day)
1996	8026697.0	8122121.3	-95424.3
1997	5738986.1	5858810.4	-119824.3
1998	5049730.8	5130.421.3	-80690.5
1999	4740593.5	4832322.4	-91728.9
2000	4425135.0	4501588.3	-76453.3
2001	4675420.1	4693555.3	-18135.1
2002	4186100.9	4238613.5	-52512.6
2003	4160058.1	4166834.6	-6776.5
2004	4358077.1	4391569.0	-33491.9
2005	4175279.4	4210154.1	-34874.7
2006	4168393.8	4174008.9	-5615.1
2007	6640973.3	6636623.1	4350.1
2008	4189921.1	4197422.5	-7501.4
2009	4144295.6	4167062.8	-22767.2
2010	4456100.0	4453359.9	2740.1
2011	4217040.4	4226454.9	-9414.4
2012	3830444.0	3840454.0	-10010.0
2013	4341352.1	4332863.0	8489.1
2014	4275817.9	4265607.4	10210.5

The net groundwater inflow during every year was computed. From the table, it is seen that net groundwater inflow is positive only during excess rainfall years 2007, 2010, 2013 and 2014. During other years the aquifer contributes water to the downstream areas. This net groundwater inflow obtained by running MODFLOW was taken as the input to the groundwater balance model for developing the stable conjunctive use policy for the command area.

4.5 CONJUNCTIVE WATER MANAGEMENT MODEL FOR THE COMMAND AREA

Thepresent condition of canal water availability in the CRDS command area necessitates the need of conjunctive water management to maximize the relative yield of all the crops in the command area. Optimization modelling is the best and most suitable method for effective conjunctive water management planning. In this study, it is assumed that there exists a linear relationship between the quantity of water used and the relative yield of crops. Hence a linear programming optimization model has been developed to maximize the sum of relative yield of all crops in the command area as detailed in section 3.5, Chapter 3.

The developed LP model was run using the LINGO 18.0 software for different pre-determined ratios of surface water and groundwater. Objective function and constraints were formulated in such a manner compatible to LINGO 18.0 software as shown below. The solution of the model gives the maximum relative crop yield as the objective function value and the quantity of water to be allotted from both the sources to attain this maximum value, for the given surface water ratio, $S_{r.}$.

The normal annual rainfall of Kerala is 2817 mm as reported by Krishnakumar*et al.*, 2009, and the 24 year average annual rainfall of the CRDS command area as per this study is 3193.5 mm. Hence the year, 2011 with an average rainfall of 3090.7 mm was selected as the normal year for the study. Due to the normal rainfall during the year 2011, the annual surface water availability in the next irrigation period was found to be 191.87 Mm^3.

The potential irrigation requirement of all the crops in the command area was computed using CROPWAT 8.0 software as given in Table 4.26. While running the model in the LINGO software with a particular surface water ratio, $S_{r,}$ the results obtained were the sum of the relative yield of all crops in the command area and the required allocation from surface water as well as groundwater to get this relative crop yields.

Linear Programming model written in Lingo 18.0 software: Year- 2011, S_r - 0.76

```
SETS:
Crops /1..11/:Ky, ID, IA, SW,GW;
ENDSETS
DATA:
Ky   = 0.8 1.0 0.8 0.8 1.1 1.0 1.1 1.0 1.1 1.1 1.1;
ID   = 22.89 7.99 1.41 10.61 1.47 3.66 0.03 0.49 3.86 6.71 0.53;

ENDDATA
!Objective function 1;
Max = @sum(Crops(a): 1-(Ky(a)*(1-(IA(a)/ID(a)))));

!Constraints;
@for(Crops(a):

IA(a)= 0.5*(0.51*SW(a)+GW(a));

SW(a)= 0.76*(SW(a)+GW(a));
GW(a)= 0.24*(SW(a)+GW(a));

IA(a)<= ID(a);

@sum(Crops(a): SW(a))<= TSW;
 TSW= 191.87;

@sum(Crops(a): ID(a)-(0.5*(0.51*(SW(a))+GW(a))))>=0;

SW(a)>=0;  GW(a)>=0;
);
END
```

The maximum value of the relative yield of a single crop is one. Since there are eleven irrigated crops in the command area the maximum value of sum of the relative yield of all these crops is 11. The results obtained by running the LP model with S_r as0.76 for the year 2011 is shown in Table 4.26. From table it is clear that with this particular surface water ratio, 0.76, all the irrigated crops in the command area are able to attain their maximum relative yield. The annual allotment of surface water and groundwater required for obtaining the maximum relative crop yield are also shown in the table.

Table 4.26 Solution of conjunctive water management model for the year 2011with S_r 0.76

Crop	Gross irrigation requirement (Mm^3)	Net irrigation requirement (Mm^3)	Allotment of Canal water (Mm^3)	Allotment of Groundwater (Mm^3)	Objective value (Relative crop yield)
Coconut	72.93	22.89	55.43	17.50	1
Arecanut	4.50	1.41	3.42	1.08	1
Banana	25.46	7.99	19.35	6.11	1
Nutmeg	33.80	10.61	25.70	8.10	1
Tapioca	4.68	1.47	3.56	1.12	1
Pepper	0.09	0.03	0.07	0.02	1
Vegetable-Mundakan	11.67	3.66	8.87	2.80	1
Vegetable-Puncha	1.56	0.49	1.19	0.37	1
Paddy-Virippu	12.30	3.86	9.35	2.95	1
Paddy-Mundakan	21.38	6.71	16.25	5.13	1
Paddy-Puncha	1.70	0.53	1.29	0.41	1

4.5.1 Stable policy for the command area

The developed optimization model was used for evolving a stable conjunctive use policy for the CRDS command area. A conjunctive use policy is the proportion of surface and groundwater allocation for conjunctive use of these resources in an area. A conjunctive use policy is said to be stable, when, on application of that policy, the change in groundwater storage of the area is negligible for a normal rainfall year.

It is possible to maximize the relative yield of all crops in a command area, by the unrestricted use of groundwater when surface water availability is scarce. But this may cause a decline of groundwater levels. To avoid this there should be some criteria for groundwater usage. The safest criterion is that the present status of groundwater storage should be maintained as far as possible. So the proportion of surface and groundwater allocation which will not cause considerable change in groundwater level need to be identified. The developed optimization model was run for several pre-determined proportions of surface and groundwater for a normal rainfall year and the change in groundwater storage was observed using the results of each run. The model was run for the year 2011 for several surface water ratios (S_r) and the solution gave the groundwater allotment corresponding to each S_r. This groundwater allotment value was used to compute the change in groundwater storage of the command area by the application of each policy or S_r. The results of the process are shown in Table 4.27. Since there are eleven crops in the command area, the maximum possible value of relative yield of all the crops is eleven.

Table 4.27 Results of LP runs for different policies over a normal year (2011)

Policy	Relative yield of all crops (11 crops)	Change in groundwater storage (mm)
60:40	11	-164.17
70:30	11	-69.76
75:25	11	-17.07
76:24	11	1.74
77:23	11	5.17
80:20	11	39.87
85:15	11	101.59
90:10	10.99	168.91
95:05	10.80	249.66

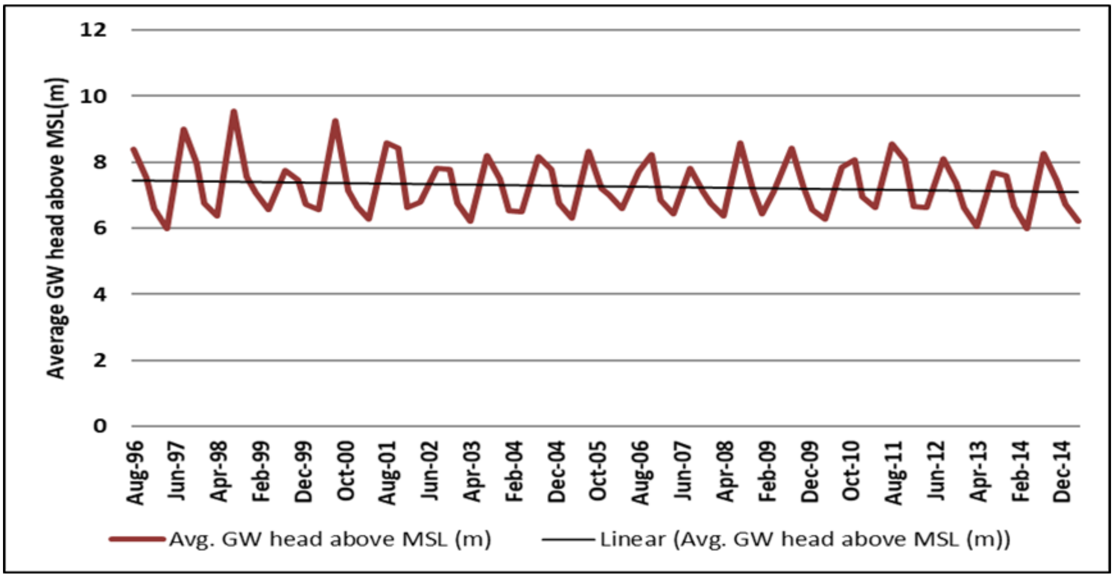


Fig. 4.24. General groundwater head of the command area, above MSL

From the table, it is observed that minimum change in groundwater storage occurred when 76:24 policy was adopted for the conjunctive water use. The maximum relative crop yield of 11 was also obtained for this policy. The relative crop yield was low for the policies 90:10 and 95:05. This clearly indicated that surface water availability is low during the year to meet the irrigation requirement of all crops grown in the command area. Groundwater allocation in the ratio of 5 per cent or even 10 per cent of total allocation was not sufficient to compensate the scarcity of surface water. The withdrawal of 15 % of groundwater will raise the relative crop yield to the maximum value (11). All these three policies would cause an increase in groundwater storage. That might create a waterlogged condition after several years. So groundwater allocation for irrigation needs to be increased. A policy with 76% surface water and 24% groundwater would change the groundwater storage in a negligible manner (1.74 mm). Even though it is negligible, it would create a positive change in groundwater storage. The general groundwater level of the area shows a declining trend over the past years as shown in fig. 4.24. Therefore, the present policy that would create a negligible positive change in groundwater storage is well suited to the area. Hence, this policy could be accepted as a stable conjunctive water use policy for the CRDS command area. Figure 4.25 shows the graphical illustration of the stable policy. Next possible policy solution is 77:23 which would create a change in groundwater storage as 5.17 mm. The results similarize the study conducted by Vedula *et. al* (2005) for developing a stable conjunctive use policy of 70:30 for the command area of VanivilasaSagar reservoir in Karnataka with a negligible change in groundwater storage of 0.69 mm.

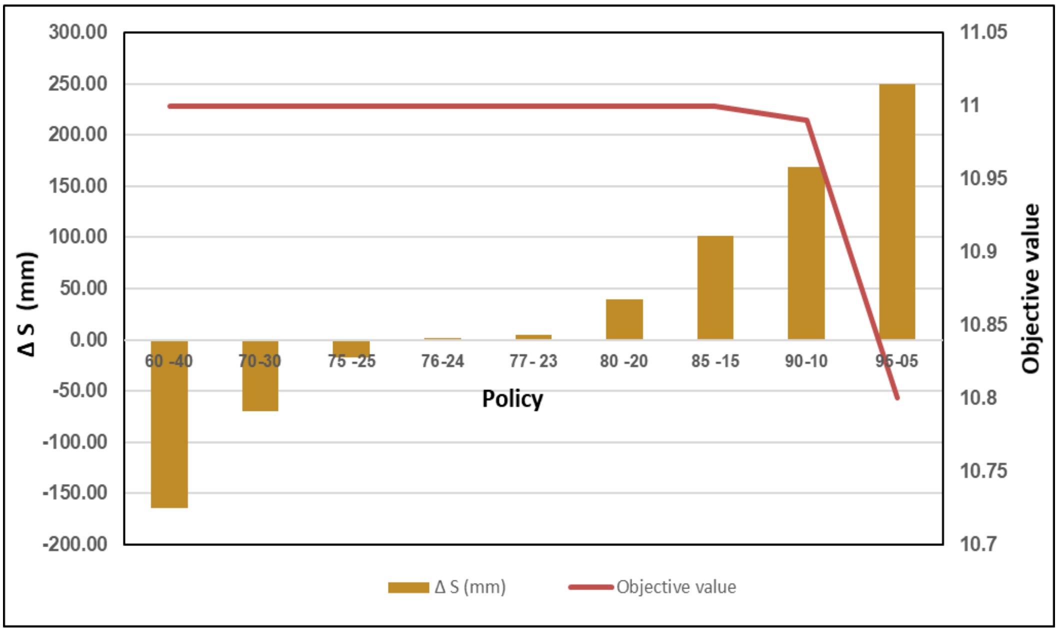


Fig. 4.25 Variation of objective value and groundwater storage change for different policy ratios

4.6 TEMPORAL ALLOCATION PATTERN OF STABLE CONJUNCTIVE USE POLICY BY SIMULATION RUNS

The stable conjunctive use policy for the command area was developed on an annual basis. But water is diverted through the CRDS canal system only for six months from December to May in a year. The flow through the canal also varies with the availability of water at the weir site. So the crop water demand should be met from this availability and it also varies according to the month and season. Hence temporal allocation of surface and groundwater based on the stable conjunctive use policy in a year is very important to ensure proper utilization of these water resources. The parameter, surface water ratio, S_r was chosen for identifying this temporal allocation pattern. It is actually the ratio of surface water allocation to the total water allocation for a specific time period.

Table 4.28 Results of simulation runs of the optimization model for 2011with 76:24 policy

Time period	Surface water ratio, S_r	Gross irrigation requirement (Mm^3)	Surface water allotment (Mm^3)	Groundwater allotment (Mm^3)
June	0	0	0.00	0.00
July	0	0	0.00	0.00
August	0	0	0.00	0.00
September	0	9.49	0.00	9.49
October	0	5.28	0.00	5.28
November	0	7.08	0.00	7.08
December	0.60	26.48	15.89	10.59
January	0.85	40.60	34.51	6.09
February	0.90	29.67	26.70	2.97
March	0.90	33.96	30.56	3.40
April	1.00	19.63	19.63	0.00
May	1.00	18.82	18.82	0.00
Total		191.01	146.11	44.90

In this study, the monthly interval was taken for computing the parameter $S_{r,}$ using the simulation runs of the optimization model. The results of this simulation runs are shown in Table 4.28. Crop water requirement for the normal year 2011 that was used for the development of stable policy was used for these simulation runs also.

It was observed from Table 4.28 that there was no irrigation requirement during the months from June to August due to the availability of sufficient rainfall in these months. During the next three months, irrigation requirement was needed in small quantity only for the land preparation and nursery management of the Mundakan paddy and also to compensate the lack of soil moisture due to the time-gap between rainfall events in the season.

The water diversion through the canal system starts during December every year and ends by May. The unavailability of canal water during the months from September to November could be overcome by allotting water from groundwater to meet the gross irrigation requirement. The groundwater availability is maximum during these months due to the already available southwest monsoon. During December irrigation requirement is relatively high as it is the time of irrigation for almost all the non-paddy crops. Surface water through the canal was found to be sufficient to meet 60 per cent of requirement and the rest 40%could be met from groundwater.

Both the irrigation requirement and canal water availability are more during the next three months. Hence surface water could be allotted in the ratio of 0.85, 0.90 and 0.90 during January, February and March respectively. Irrigation demand is low during the months of April and May since most of the seasonal crops enter into the harvest period in these months. Moreover, summer rains were received in the command area during this period and effective rainfall is high (Table 4.6). Since canal water availability is plenty during this period the proportion of canal water allotment would be taken as 100%.

The allocation of 100% surface water during April and May is beneficial to head-end farmers and all the beneficiaries. This is because, during these months groundwater level goes far below the ground level in the elevated portions or head-end portions of the command area. The recharge to groundwater from canal seepage also helps to meet the drinking water requirements to some extent. But, towards the tail end groundwater situation is not so poor and the same conjunctive use policy (76:24) could be used to meet the irrigation demand. Here the withdrawal of groundwater during these months would increase the intake capacity of the aquifer to receive rainwater by the onset of southwest monsoon.

Table 4.29 Result of simulation runs of the optimization model for irrigation ratio a^c_t, with 76:24 policy

Time period	Coconut	Arecanut	Banana	Nutmeg	Tapioca	Pepper
June						
July						
August						
September	1.00	1.00		1.00		
October	1.00	1.00		1.00		1.00
November	1.00	1.00	1.00	1.00		1.00
December	1.00	1.00	1.00	1.00	1.00	1.00
January	1.00	1.00	1.00	1.00	1.00	1.00
February	1.00	1.00	1.00	1.00	1.00	1.00
March	1.00	1.00	1.00	1.00	1.00	1.00
April	1.00	1.00	1.00	1.00	1.00	
May	1.00	1.00	1.00	1.00		

It is also necessary to check whether this temporal allocation will meet the irrigation requirement of all the crops in the command area. This was ensured by computing the irrigation ratio a^c_t for monthly time steps. Irrigation ratio is the ratio of the actual irrigation water allotted to the potential irrigation demand of a given crop in a time period of ‘t’. The results of the simulation run for this purpose are shown in Tables 4.29 and 4.30. The maximum value of the ratio is obtained as one for each crop. Hence all the crops in the command area would get 100 per cent of irrigation water conjunctively from both sources with this temporal allocation for a normal year. Thus the suggested temporal allocation of irrigation water for the command area was found acceptable.

4.6.1 Impact of stable policy on aquifer storage response over the years

After identifying stable conjunctive use policy for the CRDS command area, its effect on groundwater storage over several years was checked, with the past data on water diversion through canal system and rainfall. Eight years of data from 2005 to 2012 were used for the analysis. The results are shown in Table 4.31

Table 4.30 Result of simulation runs of the optimization model for irrigation ratio $a^c_{t,}$ with 76:24 policy

Time period	Vegetable - Mundakan	Vegetable - Puncha	Paddy - Virippu	Paddy - Mundakan	Paddy - Puncha
June					
July					
August					
September			1.00	1.00	
October				1.00	
November				1.00	
December	1.00			1.00	
January	1.00			1.00	1.00
February	1.00				1.00
March	1.00	1.00			1.00
April		1.00	1.00		1.00
May		1.00	1.00		1.00

From the Table 4.31 it is clear that the application of stable policy would create a negative change in groundwater storage of the command area during the years 2005, 2008 and 2012. Average annual rainfall received in the command area was very low during these years. The negative changes are due to deficiency in rainfall and hence the reduced water diversion through the canal. These negative changes were compensated by the positive change in groundwater storage due to the application of stable policy during the otheryears, especially during the excess rainfall years 2007 and 2010. The change during the year 2011, for which the policy was developed was found positive and negligible. The overall change in storage that would occur by the application of the stable conjunctive use policy over a period of 8 years is 74.72 mm.

Table 4.31 The results of application of stable conjunctive use policy for past years

Year	Change in groundwater storage (mm)	Average annual rainfall (mm)
2005	-37.41	2451.0
2006	10.76	3439.2
2007	48.29	4087.1
2008	-8.70	2453.0
2009	31.38	3282.8
2010	113.19	3824.1
2011	1.74	3090.7
2012	-84.54	2135.3
Total	74.72	

This implies a change in groundwater storage of 9.34 mm/year. Since the specific yield of the aquifer is 0.38, this change in storage would result in a rise of groundwater level of 24.6 mm per year, which is considered as negligible. Hence it can be concluded that the developed stable conjunctive use policy could be applied to the command area of CRDS without causing significant fluctuations in the groundwater level over the years.

CHAPTER 5

SUMMARY AND CONCLUSION

The impact of climate change on the water resources sector is significant as evidenced by several studies all over the world. The irrigation sector is the largest user of water resources among all other sectors like domestic, industrial, recreational and commercial. Chalakudy River Diversion Scheme is one of the prominent large scale irrigation schemes in central Kerala. It diverts water from the Chalakudy river through a network of canal systems to the field. The scheme was commissioned in the year 1957, and as time progressed, water diversion through the canal decreased due to various reasons. Moreover, the conveyance efficiency of the canal system reduced because of damaged lining, waste dumping and excessive vegetative growth. Un-gated spouts released more water at the head end of the branch canals resulting in water scarcity towards the tail end. All these necessitated analyzing whether any innovative alternate approach could be resorted for managing the irrigation demands of this canal command without seriously tapping the groundwater resources of the area. It is with this idea that this study was initiated to develop a conjunctive water management model for the multi-cropped command area of CRDS. As the seepage loss from the canal contributes recharge to the underground aquifer, groundwater could be used as a secondary source of irrigation water. Hence, the study focuses on developing an optimal conjunctive water management policy for the command such that the irrigation demand could be met sufficiently while the groundwater fluctuation in the area is negligible.

Knowledge about the crops and cropping patterns of the area is the primary requirement for estimating the average irrigation needs of the area and planning conjunctive water management. To gather this knowledge a land-use map of the command area was prepared using the ERDAS Imagine 2015 software in the geospatial laboratory at KCAET, Tavanur. Unsupervised classification method was used for the preparation of land use map from sentinel 2 level 1C imagery downloaded from USGS website. Ten land use classes were identified. Among them, multiple crops (38%) and coconut based cropping systems (32%) were the main cropping patterns in the command area. Paddy crop occupied 10.51 per cent of the command area.

Irrigation requirement of the command area is to be estimated in order to plan a proper conjunctive water use policy. The CROPWAT 8.0 software was used for the computation of net irrigation demand of the CRDS command area. Climate data from 1990 to 2016 and rainfall data from 1991 to 2014 were used for the computation of the average irrigation requirement of the command area. The average rainfall over the command area from the year 1991 to 2014 was computed using the Thiessen polygon method using Arc GIS 10.3.1 software at the geospatial laboratory of KCAET and was taken as an input to CROPWAT 8.0 software developed by FAO. The average annual net irrigation demand of each branch canal command area was calculated separately using the soil parameters of respective agro-ecological units through which the branch canal passes. The summation of annual net irrigation demand of all the branch canal commands resulted in the average annual net irrigation requirement of the CRDS command area.

It was observed from the results that the average irrigation requirement of the branch canal command area varies with cropped area and length of the branch canal. The Kalady branch of LBC with a cropped area of 1563.94 ha showed the maximum value of average annual net irrigation requirement of 7.06 Mm^3. The left Bank Canal command area with a total cropped area of 5372. 09 ha, had an average annual net irrigation requirement of 23.03Mm^3, whereas, the same for the right bank canal command with a cropped area of 5532.04 ha was obtained as 23.87 Mm^3.The computed average annual net irrigation requirement of the CRDS command area was found to be 46.90 Mm^3.

To assess the availability of canal water to field and estimate the level of conjunctive water use needed in the command area, field measurements of flow through various reaches of the main canals and selected branches were done. Seepage loss from the canal water was estimated from field measurements using inflow – outflow method. Conveyance efficiency of the CRDS canal system was calculated from these measurements. Adequacy of irrigation water was evaluated in terms of indicators like Relative Water Supply and Adequacy Indicator.

The field measurements showed that the discharge rate through the canal branches that draw water from the upper reach of the main canals was higher than that of the branch canals towards the tail end. Also it was found that along the length of branch canals, rate of flow of water decreases from head to tail end. While the rate of flow decreases towards the tail end seepage loss rate per km length increased in the main canals as well as in branch canals. The conveyance efficiency of the canal system was found less due to high seepage loss caused by damaged lining, waste dumping and hindrances offered by small plants growing in canals. The computed conveyance efficiency of the canal system was 51.1%. The head reach branch, Mettippadam, showed the highest conveyance efficiency of 74.03%.

Computation of performance indicators showed that relative water supply (RWS) of branch canals decreases along the main canals. The head reach branch Mettippadam showed a high value for RWS (0.81) and towards the tail reach the RWS was 0.4 or less than that. The overall RWS of the CRDS canal system was found as 0.86. The adequacy indicator also gave a good picture of water delivery performance. All the selected branches except Mettippadam showed poor performance. The more amount of water delivered and the less irrigation requirement due to the less cultivated area caused the Mettippadam branch to exhibit good performance. The adequacy indicator showed that the performance of the CRDS canal system falls in the range of ‘fair’.

Knowledge of the flow of groundwater in the command area is very important in the conjunctive water management process. Visual MODFLOW software version 2.8.1 was used to simulate the dynamic responses of the aquifer. The conceptual model of the command area was created using a base-map and discretized into 60 x 60 grids of size 0.5 km x 0.5 km. Water level data of 17 observation wells from 1996 to 2010 were used for the calibration of the model. The hydraulic properties and boundary conditions were changed iteratively to get aquifer condition same as in the field. Validation of the model was done with another four years of data from 2011 to 2014 and then predictions of two possible scenarios were also done.

The calibrated model showed that the aquifer of the area was having high horizontal hydraulic conductivity as 544 m/day and a specific yield of 0.38. The hygrographs of the wells at Potta, Puthenchira, Muriyad, and Muringurshowed good agreement between observed and computed water levels. The calibrated and validated model was used for the prediction of two scenarios viz. (a) the continuation of present condition and (b) decrease in recharge and increase in pumping. From the predictions, it was obvious that the groundwater status of the area is sufficient for conjunctive management of water for irrigation. The zone budget output from Visual MODFLOW gave the net groundwater inflow/outflow from the aquifer under the present condition of recharge and discharge. The total inflow minus outflow was positive only in excess rainfall years. This result was used to predict the change in groundwater storage due to conjunctive water use for the pre-determined surface water ratio.

Using the results obtained from the assessment of irrigation requirement of the command area, adequacy of canal water availability to field and groundwater status of the aquifer, a linear programming optimization model was developed for the conjunctive water management of the command area. The objective function of the model was to maximize the relative yield of all the crops in the command area. Water allocation to crops, surface water availability, irrigation demand of the crops, pre-determined surface water ratio for water allocation from both sources and non negativity of surface and groundwater allocation, formed the major constraints. The model was solved in LINGO 18.0 software to get water allocation from surface water and groundwater sources corresponding to the given surface water ratio in order to maximize the relative yield of all the crops in the command area.

To derive a stable policy for water allocation from surface and groundwater sources to the crops in the command area, the change in groundwater storage that would occur with a particular policy was checked using a groundwater balance model. The net inflow/outflow of the aquifer during a particular period obtained as output from Visual MODFLOW was used as a component in the groundwater balance model. The policy which creates negligible change in groundwater storage during a normal year was taken as the stable policy. The policy was developed for the year 2011 which was taken as a normal rainfall year with a mean annual rainfall of 3090.7 mm.

After finalizing the stable policy for the command area, its temporal allocation was derived from the pattern of surface water availability and irrigation requirement of the command area. The derived temporal allocation pattern should maintain the stable policy of water allocation on an annual basis. The impact of application of the stable policy on groundwater storage over the years was tested using past years data on water diversion through canal and irrigation requirements of the command area. Water diversion data and rainfall data from the year 2005 to 2012 were used for the impact study through simulation runs of the LP optimization model.

Using the developed optimization model, a stable policy for the allotment of surface and groundwater for irrigation in the area was derived. The derived stable policy is 76:24, that is, 76 percentage of surface water and 24 percentage of groundwater for irrigation on an annual basis over a normal year. The policy created a positive and negligible change of 1.74 mm/year in groundwater storage which is well suited to the area with slightly declining trend in groundwater storage over the years. The development of a stable policy on an annual basis alone is not sufficient to decide the temporal allocation pattern of surface water and groundwater within a year. Hence the surface water ratio was adjusted temporarily within a normal year by running the optimization model for different ratios for different months. The derived temporal allocation pattern showed that only groundwater could be allocated from September to November, before starting the water diversion through the canal in a water year. Surface water ratio S_r, 0.6 and 0.85 were found suitable for December and January. Ninety per cent of irrigation water can be allocated from the canal during February and March and 100 per cent during April and May.

Impact of application of the stable policy on groundwater storage over several years was tested using the data of water diversion and rainfall from 2005 to 2012 by simulation runs of the optimization model. The change in groundwater storage that would occur by the application of a stable conjunctive use policy over a period of 8 years is 74.72 mm. This implies a groundwater storage change of 9.34 mm/year. This change in storage will result in the rise of groundwater level by 24.6 mm/year, which is positive and negligible.

The linear programming optimization model developed in the study derived a stable conjunctive water use policy, 76:24, for the CRDS command area. The study also provides a temporal allocation pattern for the stable policy. The simulation runs of the model for past eight years data assured that the developed stable policy will not cause a groundwater decline in the area over the years. From the results of the study, it could be concluded that conjunctive water management could effectively solve the problems in irrigation water allocation and uniformity of water distribution in the CRDS command area. Thus the use of developed stable policy, 76:24 for conjunctive management of surface water and groundwater can maximize the relative yield of all crops in the command area without seriously exploiting the groundwater storage in the aquifer. The developed stable policy for the conjunctive water management could be implemented in the command area for the effective utilization of the two major water resources, surface water and groundwater, and maximizing the crop production.

Scope for future study

- The procedure followed could be used for developing conjunctive water management model for other areas.
- The model could be made more compact and user friendly by interlinking surface and ground water systems and developing a decision support

system/ computer software for the conjunctive management of surface water and groundwater.

- A management model that gives optimum economic benefits by the conjunctive use of surface and groundwater could be developed by considering more independent variables like climatic parameters, energy usage for pumping, seasonal changes and socio-economic factors.
- A conjunctive water use model which suggest the most profitable cropping pattern for the area for the present as well as future climatic scenarios can be developed.