Chapter 1

Introduction

The ever-increasing demand of food grains in today’s constantly evolving world has necessitated expansion of the agricultural sector and adoption of intensive cropping systems globally. Among the different inputs of agricultural production, irrigation plays a vital role in reaching towards the goal of sustainable agriculture. However, it is a challenging task to provide assured irrigation facilities during the entire growth period of different crops. The inter-sectoral competition for water, combined with environmental and social concerns, has made the job even more difficult for the water resource managers. The recent trend of global climate change has also added to the uncertainties in the irrigation sector. It is, therefore, extremely necessary that the available water resources are utilized in a systematic and planned manner. But, in most cases, providing sufficient quantities of water to the crop all-round the year, from a single source in a planned manner, is not possible. This is because both surface water and groundwater have certain limitations regarding their application in irrigation. Surface water resources are limited by the occurrence, intensity and duration of precipitation. The storage level of surface water sources during different crop growing seasons sees a lot of fluctuation and often, the sources of surface water become inadequate during the dry periods with scanty rainfall. Even when surface water is abundant, its uncontrolled application for irrigation may lead to water logging, especially in the areas with shallow groundwater table. On the other hand, certain problems arise while utilizing only groundwater for irrigation. Excessive and unplanned use of groundwater resources can cause irreversible groundwater depletion. Moreover, the presence of certain inorganic and organic contaminants restricts the use
of groundwater for irrigation purpose. Salinity is another major problem concerning irrigation with groundwater.

In view of the difficulties faced while planning the irrigation system with a single source of water, the harmonious and balanced use of both surface water and groundwater, commonly called *conjunctive use*, is now recognized as a significant strategy for optimum utilization of the available water resources to meet the growing irrigation demand. Balanced use of both the resources satisfies crop water requirement in a more assured way, thus maximizing agricultural production throughout the year and helping in crop diversification. The undesirable fluctuations in surface water supply can be mitigated by conjunctively utilizing groundwater for irrigation. Additionally, by depressing the water table or piezometric head, water logging conditions can be improved. Conversely, the ill effects of using groundwater alone can be taken care of by the integrated use of both forms of water resources.

The concept of conjunctive use evolved during the 1950s. Todd (1959) defined conjunctive use as “the management of water resources through basin-wide strategies that include integrated utilization of surface and groundwater.” Lettenmaier and Burges (1982) distinguished conjunctive use, which deals with short-term use, from the long-term discharging and recharging process known as cycle storage.

Generally, the conjunctive use of ground and surface water sources is practised in order to attain one or more of the following objectives:

1) To increase the total amount of water supply.

2) To attain a higher flexibility in the supply according to the demand.

3) To store the excess water by using the aquifers as sub-surface reservoirs, for its subsequent withdrawal.

4) To reduce salinity by mixing different qualities of water.
Different conjunctive use strategies are possible in an irrigation command by using various combinations of space and time integration. One strategy could be to allocate a parcel of land permanently for surface water and another for groundwater. Another strategy could be the integration of surface water and groundwater in time. Surface water may be used during the period of its abundance while groundwater may be utilized during the dry period. Yet another strategy could be to integrate both time and space. In this strategy, the irrigated area may be clustered in such a way that one parcel of land is earmarked for surface water and another parcel of land for groundwater while the remaining land may be irrigated by both surface water and groundwater, depending on the seasonal availability of water.

However, there are several hindrances in implementing the above mentioned strategies, due to various reasons, a few of which are- climatic uncertainty, location of surface water reservoirs, groundwater table, cropping pattern etc.

The best way to implement conjunctive use plans is, therefore, the mathematical modelling of the complete irrigation system, incorporating various spatial and temporal phenomena pertaining to crop, soil and water.

### 1.1 Conjunctive Use Planning in India

The irrigation scenario in India has seen steady progress ever since the first five year plan was launched in 1950-51. The net irrigated area in the country has increased from 21 Million hectare (Mha) in 1950-51 to 61 Mha in 2006-07. Agricultural production in India has also elevated under irrigated conditions. About three-fifths of India’s crop harvest comes from irrigated land.

The concept of conjunctive use planning of the irrigation system came into being in India during the fourth five year plan which envisaged the co-ordinated use and management of both surface-water and ground-water for irrigation. The need of
conjunctive use planning was stressed in the National Water Policy of India (2002), which directs that conjunctive use planning should be visualized right from the project planning stage and should form an essential part of the project. The Central Ground Water Board (CGWB) under the Ministry of Water Resources, Govt. of India conducted feasibility studies for conjunctive use in 13 different irrigation commands in India during the period 1990-1995 (CGWB, 2000). These studies have established the fact that the isolated use of surface water ignoring optimal groundwater use has resulted in various environmental problems. As a result, the CGWB has come up with the recommendation that optimal conjunctive use plan should be implemented by the state agencies in co-ordination with the Command Area Development Authority (CADA). It has also suggested that groundwater flow simulation models should be incorporated as constraints to the irrigation management models for the efficient planning of the conjunctive use system.

1.2 PROBLEM IDENTIFICATION

Although various conjunctive use plans are being implemented in different states of India, the same is yet to be introduced in Assam despite the fact that the state has immense potential of both surface water and groundwater resources. About 6503 sq. km area of the state is occupied by river systems including the mighty Brahmaputra. The estimated total surface water resource of the state is about 600 Billion cubic metre (Bcm). The state also receives a high precipitation with average annual rainfall varying from 1780 mm to 3050 mm. However, most of the rainfall occurs during the period of June to September due to the effect of monsoon, thus resulting in a long dry spell for the rest of the year. Due to a high degree of temporal variation in climate, the state witnesses recurring floods during the rainy season on one hand and a prolonged water scarcity situation during the dry periods on the other.
The state also has immense groundwater potential. The annual replenishable groundwater resource of the state is about 27.23 Bcm. But so far, only 22% of the groundwater potential has been developed in the state (CGWB, 2010). Considering this huge unutilized groundwater potential and the seasonal fluctuations in surface water sources, Assam has tremendous scope for conjunctive use planning and management.

The Brahmaputra Board under the Ministry of Water Resources, Govt. of India is implementing the on-going Pagladiya Dam Project (PDP) in Assam. The PDP is a multipurpose project located on the river Pagladiya, one of the major north bank tributaries of the river Brahmaputra. It is proposed to irrigate a gross command area of about 54160 ha on the right bank of the river Pagladiya, along with its two other objectives of flood control and hydropower generation. The command area of the PDP covers parts of two districts of Assam, viz., Baksa and Nalbari. The Culturable Command Area (CCA) is about 40,743 ha out of which a Net Irrigable Area (NIA) of about 34,630 ha is proposed to be brought under irrigation. The irrigation command area (or simply, the command area) covers 145 villages under 5 development blocks of the two districts.

At present, the irrigation in the command area is mainly from groundwater through tube wells. The irrigation potential created through tube wells is very low. As per report of the Central Ground water Board (2010), only 10% of ground water potential has been created so far in the two districts, namely Baksa and Nalbari. So, there exists immense unexplored groundwater potential in the area. The water table is quite shallow; it is in the range of 2-4 m below ground level (bgl) and due to this shallow water table, the area is prone to water logging. Hence, the Brahmaputra Board has
recommended conjunctive use planning for irrigation in the command area (Brahmaputra Board, 1996).

1.3 OBJECTIVES OF THE PRESENT STUDY

This study aims at deriving optimal conjunctive irrigation strategies for the command area of the PDP. The specific objectives are outlined below:

a) To estimate the crop water requirement in the command area of the PDP under the proposed cropping pattern (Brahmaputra Board, 1996), using the CROPWAT model developed by the Food and Agriculture Organization (FAO) of the UN.

b) To develop a mathematical groundwater flow simulation model for the command area and to calibrate the model in the study area.

c) To develop a two stage irrigation management strategy, including a monthly conjunctive use optimization model using Genetic Algorithm (GA) and a Linear Programming (LP) model, for intra-seasonal irrigation allocation.

d) To apply the developed models in the command area of the PDP.

e) To develop an efficient computer code for an evolutionary search algorithm based on Artificial Immune System (AIS) and to apply the same in the above mentioned conjunctive irrigation management problems.

f) To evaluate the performances of AIS in comparison with the GA as well as the LP technique while solving the aforementioned optimization problems.

g) To draw suitable conclusions from the results obtained and to make suggestions for future works in the relevant fields.

1.4 METHODOLOGY

Mathematical modeling of the complete irrigation system involving stream-aquifer interactions in relation to crop-soil environment is necessary for deriving efficient
conjunctive irrigation management plans and strategies. The conventional mathematical techniques used in optimization of the conjunctive use system are-Linear Programming (LP), Dynamic Programming (DP) and Non-Linear Programming (NLP). The Linear programming models are based on the assumption that the set of constraints to the optimization model is linear. But non-linearity is often encountered in the physical representation of the system. For example, stream stage is a non-linear function of discharge or reservoir release. The aquifer response to groundwater withdrawal is also an example of non-linear behaviour of the conjunctive use system. Dynamic programming, however, has the advantages of applicability to non-linear system and the ability to incorporate stochasticity of the hydrologic process. But the curse of dimensionality has limited the use of DP in conjunctive use system. Again, because of the complexity and the slow rate of convergence, NLP too has seen very limited use in conjunctive use system modelling.

Due to their robust capability in finding global optima, convergence speed and the ability to handle non-linear constraints, evolutionary search techniques are now replacing the classical search methods for deriving optimal conjunctive use policy decisions. Among the different evolutionary optimization methods, Genetic Algorithm (GA) has already been established as a superior search technique for solving water resource management problems (e.g. Wardlaw and Sharif, 1999; Raju and Nagesh Kumar, 2004; Ahmed and Sarma, 2005; Karamouz et al., 2007). Another new evolutionary optimization technique, which is grabbing eyeballs in the research circle, is the Artificial Immune System (AIS), an algorithm which applies the biological principles of the human immune system. This study is an attempt to use both GA and AIS techniques to derive optimal conjunctive irrigation management strategies for the study area under consideration and then to make a comparative evaluation of the two
search methods. Moreover, an LP problem of on-field irrigation allocation will also be considered in this study.

Conjunctive use models need to represent the aquifer response to groundwater withdrawal or recharge in the management model. Management decisions as well as simulation of groundwater behaviour are accomplished simultaneously. This is generally accomplished in three ways- embedded technique, response matrix approach and linked simulation optimization method. In the embedded technique, the nodal heads are treated as additional decision variables and the finite difference or finite element groundwater flow equations are embedded as constraints to the optimization model (Gorelick, 1983; Gharbi and Peralta, 1994; Vedula et al., 2005). In this approach, the involvement of a large number of additional decision variables may increase the computational complexity. Moreover, the incorporation of the non-linear partial differential equations of groundwater flow into the constraint set makes this approach numerically inefficient, especially when applied to large aquifer systems with considerable heterogeneity (Bhattacharjya, 2012). In the response matrix (also called kernel function or influence function) approach, an independent simulation model is utilized for generating the system response to groundwater withdrawal or recharge in order to create response matrices, which are then incorporated as constraints to the management model (Maddock, 1972; Gorelick, 1983; Ghosh and Kashyap, 2012). This method is based on the principle of superposition and linearity and hence is not suitable for application in non-linear systems. The other approach known as the Linked Simulation-Optimization (LSO) technique, directly links a groundwater flow simulation model with the optimization model. This approach has no restrictions whatsoever regarding the dimensionality or linearity of the system. However, the application of this approach is limited by the computational effort
required to complete the optimization process, as the simulation model has to run several times during optimization. Various approaches have already been suggested to reduce the computational time in LSO models (Karamouz et al., 2004; Bhattacharjya and Datta, 2005; Safavi et al., 2010). In this study too, a new approach will be applied for simplification of an LSO model, and will be demonstrated through its application in conjunctive use optimization.

The irrigation management models generally consider net economic benefit from agriculture as the goal while allocating the water resources to the crops. However, there are difficulties in implementing this type of management plans. In states like Assam, the land holding pattern is such that the preferences among the individual farmers are of more importance than the combined net economic benefit from agriculture. Moreover, the stochastic nature of agricultural commodities limits the application of economic optimization from making long term irrigation management plans.

In light of the discussions made above, a two stage irrigation management strategy is proposed to be formulated in the present study. In the first stage, a monthly conjunctive irrigation management model is to be formulated using LSO approach. This model would be applied in the command area of the PDP. In the second stage, an LP problem of intra-seasonal crop water allocation is to be formulated for optimal allocation of the available water resources, which would be obtained from first stage model, to the different crops in the command area during different stages of crop growth, in decadal (10 day) periods. In order to formulate long term irrigation management strategies for the study area, optimization would be carried out under different scenarios of climatic variables, so as to represent different climatic conditions in the study area, from wet condition to water deficit condition. From the probability
analysis of rainfall in the command area and inflow into the reservoir, five optimization scenarios would be created at 10%, 30%, 50%, 70% and 90% Probabilities of Exceedance (PE) of these two variables.

The methodology to be adopted in the present study is shown schematically in Fig.1.1. The first step in the modelling process would be to compute the water requirements of crops grown in the command area. In this study, the decision support tool CROPWAT, developed the Food and Agricultural Organization (FAO) of the UN is proposed to be used. Crop water requirements will be calculated at five different PE levels explained above and the results will be obtained in both monthly and 10 day periods.

A mathematical groundwater flow simulation model for the study area would be developed using the finite difference technique. This model would be simplified by a novel approach of area reduction as a means of reducing computational burden and the simplified model would then be linked to the monthly conjunctive use optimization model, so as to form an LSO model. This LSO model would be solved by a real coded GA. The outputs from this model (i.e. the available water resources in monthly time steps) would then be used as inputs for the intra-seasonal allocation model, in which an LP algorithm would be used to allocate the available water resources among the different crops grown in the command area in decadal periods.

An efficient computer code for an evolutionary search algorithm based on AIS is also proposed to be formulated in this study. This algorithm would be applied in both the first stage and the second stage optimization models discussed above. The performances of AIS would be evaluated in comparison to the results obtained from GA as well as the LP algorithm.
Fig. 1.1. Schematic diagram showing the methodology applied in the present study.
1.5 ASSUMPTIONS

Like any other conjunctive irrigation management study, this study too has limitations. Certain simplifying assumptions are made to avoid the complexities in system representation and to reduce computational complexities. Some of these assumptions are:

1) It is assumed that the cropping pattern suggested by the Brahmaputra Board (1996) would be followed in the command area.

2) It is assumed that the rainfall in the command area and inflow into the reservoir would follow a similar probability of exceedance pattern.

3) The soil type in the command area is assumed to be homogeneous except in the rice growing area.

4) The aquifer is also assumed to be homogeneous and in water table condition throughout the study area.

5) It is assumed that the aquifer boundary conditions along the river Pagladiya would not change much after completion of the dam.

1.6 ORGANIZATION OF THE DISSERTATION REPORT

Keeping in view the desired objectives of this work, the research report is organized in eight chapters as illustrated below:

**Chapter 2**

In this chapter, the relevant literature of conjunctive irrigation planning and management, are discussed briefly. The review of literature includes the various optimization techniques applied for deriving optimal conjunctive use policy decisions. Research reports related to development of groundwater flow models and their
applications, coupling of flow models with optimization models etc. are also reviewed in this chapter.

Chapter 3

The Pagladiya river system, the reservoir and the command area are discussed in this chapter. The meteorology of the study area, crops and cropping pattern and the computation of crop water requirement in the command area are also described in this chapter.

Chapter 4

This chapter discusses, in details, the development of a transient, two dimensional groundwater flow simulation model for the command area of the PDP, using the finite difference technique. The conceptual model, the mathematical model, the solution method for the mathematical model, model validation and calibration procedures are discussed in order.

Chapter 5

In this chapter, two irrigation management models are described. The first stage model is a monthly conjunctive use optimization model which applies GA as the solution method. A detailed description of GA as an efficient search technique and the methodology for problem formulation using GA are presented in succession. In the second stage, an LP problem of intra-seasonal irrigation allocation is described in a detailed fashion.

Chapter 6

The application of the developed conjunctive use models in the study area is discussed in this chapter. The efficacies of the search methods used for optimization are also analyzed. The results are presented in appropriate places in tabular or graphical forms.
Chapter 7

This chapter deals with a discussion on development of a computer code for an evolutionary optimization algorithm based on AIS. It also deals with the application of the developed algorithm in the optimization models discussed in chapter 5 and the evaluation of the performance of AIS in comparison to the other search methods applied.

Chapter 8

Based on the results of computations carried out and observations made, suitable conclusions are drawn in this chapter. And finally, some suggestions for future work in the relevant fields are provided.