UNIVERSITY OF SOUTHERN QUEENSLAND

OPTIMAL WATER ALLOCATION USING A MULTI-OBJECTIVE EVOLUTIONARY ALGORITHM

A Thesis submitted by

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ABSTRACT

Agriculture water management in Bangladesh has become a subject of increasing attention due to population growth. Therefore, it is necessary that we optimize water use in order to increase the agricultural production with the increasing needs of the population as well as to fulfill the need for a sound economy of the country as a whole.

The research engages with the optimum allocation of water in the agricultural sector of Bangladesh. We model the problem using multi-objective constrained optimization problem. The objectives in this problem are to maximize net return and minimizing deficit in environmental flow. A Non-Dominating Sorting Genetic Algorithm, NSGA-II, is used to solve the problem in this research to find the optimum result.

The research indicates that the crops which are produced more and are more profitable in trade should be cultivated more as recommended by the model. The model predictions indicate that rainfall impacts on net return and environmental flow deficit more than water inflow under the scenarios in the Muhuri Irrigation Project (MIP) considered.

CERTIFICATION OF THESIS

This Thesis is entirely the work of G M Wali Ullah except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal Supervisor: Dr Trevor Langlands

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Student and supervisors signatures of endorsement are held at the University.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

Abbreviation	Term	Page
MIP	Muhuri Irrigation Project	2
NR	Net Return	6
EFD	Environmental Flow Deficit	6
MOP	Multi-objective Optimization Problem	7
EA	Evolutionary Algorithm	11
VEGA	Vector Evaluated Genetic Algorithm	12
LOGA	Lexicographic Ordering Genetic Algorithm	12
MOGA	Multiple Objective Genetic Algorithm	12
MODE	Multi-objective Differential Evolution	12
NSGA	Non-dominated Sorting Genetic Algorithm	12
NSGA-II	Non-dominating Sorting Genetic Algorithm-II	13
GA	Genetic Algorithm	13
IGNP	Indira Ghandi Nahal Pariyonaja	13
VIS	Vaal-Harts Irrigation Scheme	14
BWDB	Bangladesh Water Development Board	15
T. Aus	Transplated Aus Rice	19
T.Aman	Transplanted Aman Rice	19

Chapter 1

Introduction and Literature Review

Background

The scarcity of water is one of the significant issues in agricultural sector in Bangladesh. Although Bangladesh is low-lying, crisscrossed with numerous rivers and featured by heavy rainfalls, the country suffers from seasonal scarcity of water, especially during winter. The agriculture sector is the highest user of water in Bangladesh. About 88 percent of the total water is being used in this sector (Food and Agriculture Organization of the United Nations, 2017). Irrigated agriculture has been increasing since the 1960s due to the introduction of high-yielding varieties of crops and modern irrigation systems (Hossain, 2009).

Bangladesh has four main seasons in a year: pre-monsoon, monsoon, post-monsoon, and winter. Of the total rainfall, about 71% occurs in the monsoon season, 27% occurs in the pre-monsoon and post-monsoon season, and 2% occurs in the winter season (Md.Mizanur Rahman Khan Chowdhury, 2017). Still, pre and post-monsoon rainfall is sometimes rare. That is why Bangladesh faces two extreme water-related events each year namely flood and drought (Reddy et al., 2003). To produce required crops in the periods of dry and unreliable rainfall, the country needs to increase water-use efficiency and the conservation of water.

Bangladesh is also a small country with a large population. Its total landmass is $144,170\,\mathrm{km}^2$ and its population is approximately 168 million people. Approximately 37.2% of this population live in urban areas with the rest, 62.8%, living in village areas. Since Bangladeshi villages are still agricultural-based people, they are reliant on agriculture and agricultural productivity to live and lead their lives (Food and Agriculture Organization of the United Nations, 2017).

1.1 Focus of the Research

This research engages with an agricultural project, known as the Muhuri Irrigation Project (MIP). This project is located in Feni, a south-eastern district in Bangladesh, around the confluence of Feni, Muhuri and Kalidaskhali rivers in the coastal belt of the Bay of Bengal (BD Explorer, 2017).

The location is shown below within Bangladesh in Figure 1.1 and separately in Figure 1.2.

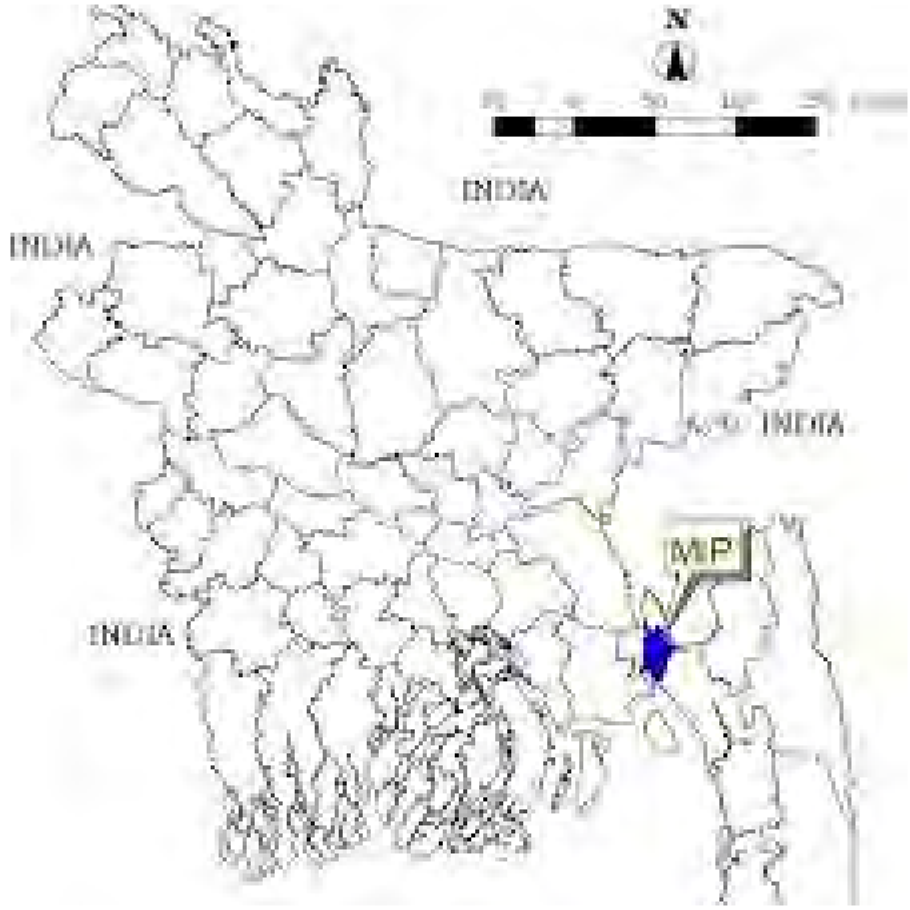


Figure 1.1: Muhuri irrigation project (MIP) location (BD Explorer, 2017).

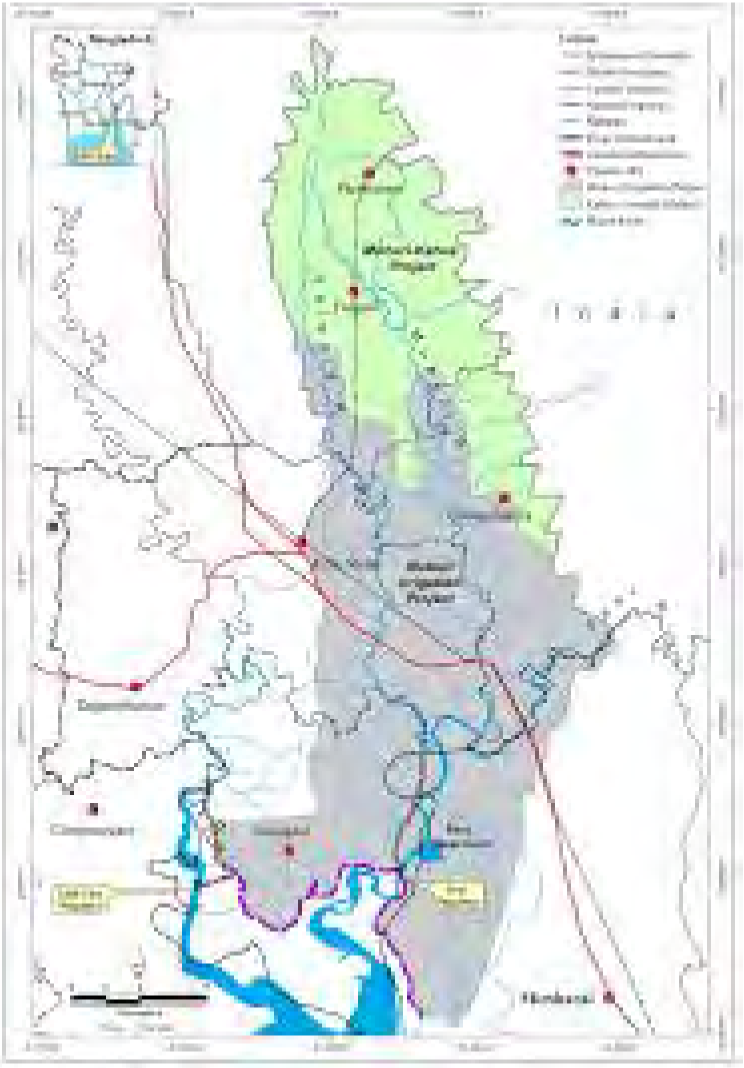


Figure 1.2: Muhuri irrigation project (BD Explorer, 2017).

The MIP is one of the important irrigation projects in Bangladesh as shown in a Figure 1.3, consisting a closure dam and a 20-vent regulator. Construction began in 1978 and was completed in 1986, at a cost of $40 million, to provide irrigation facilities and to check the inflow of saline water into the river from the Bay of Bengal. It helps the farmers to grow various kinds of crops in dry season over the river bank of Muhuri. It is also a large water vessel to produce many kinds of local fish. It comprises of 40,000 ha areas, divided into a 28,600 ha that are cultivable areas and a 14,050 ha are irrigable areas (Asian Development Bank, 2013). Every year the area of MIP is increasing. However, it may not contribute to the cultivation of crops during dry periods optimally. Due to lack of proper water supply system, poor drainage, and unplanned cropping intensities, the project proves to be less productive and beneficial especially during drought and dry times in the year.

Although the MIP is significant for agriculture in Bangladesh, it has not been drawn much attention as a research field either inside or outside Bangladesh. Therefore, the present research identifies research area that is never considered before and appears both interesting and engaging. It has a potential to contribute to the understanding of the water allocation problem in MIP and finding a solution to the problem and thus can have an impact on the agricultural production in that locality.

Figure 1.3: Vent regulator in Muhuri Irrigation Project, Feni, Bangladesh (BD Explorer, 2017).

1.2 Thesis Objectives

A significant portion of research and application in this field of optimization has focused on single objective optimization, whereas most of the natural world problems involve multi-objectives which are conflicting in nature (Olofintoye et al., 2013, Lewis and Randall, 2017). This research focuses on the water allocation problem in Bangladesh which will be modelled using a multi-objective optimization problem. The purpose of this research is to explore the economics of optimal water allocation for irrigation in the MIP of Bangladesh.

The main objectives of the study are to maximize net return and minimize deficit in environmental flow, by adjusting irrigation water when seasonal water availability is limited. It uses the Lewis and Randall (2017) model which will be discussed in more detail in Chapter 2. The model has the objectives of maximizing net return (NR) and minimizing deficit in environmental flow (EFD) which are given in Equations (1.1) and (1.2).

The first objective can be written as

$$\begin{aligned} \max NR &= \sum_{c=1}^{C} TCI_c\, X_c - C_p \sum_{m=1}^{M} P_m - \sum_{c=1}^{C} Vcost_c\, X_c \\ &- C_w \sum_{m=1}^{M} \left(\left(\sum_{c=1}^{C} WREQ_{c,m}\, X_c \right) - P_m \right) \end{aligned} \tag{1.1}$$

where TCI_c is the total crop income of crop c per ha, X_c is the area of crop c (ha), C_p is the cost of groundwater pumping and delivery per unit volume, P_m is the volume of ground water pumped in month m, $Vcost_c$ is the variable cost (such as fertilizer and pesticides applications) per hectare other than water cost for crop c. Also in Equation (1.1) the parameters C_w is the total cost of water per unit volume and $WREQ_{c,m}$ is the water requirement for crop c in month m. C is the total number of types of crops to be planted and M is the total number of months in the planning period.

The first term of the objective function, in Equation (1.1) is the total revenue and the second term is the expenditure related to the groundwater pumping and delivery cost. The third term is the variable cost such as fertilizer, pesticides, seeds and other costs. Finally, the last term consists of two parts one is $\sum_{c=1}^{C} WREQ_{c,m} X_c$ which is the total water requirement for all crops in month m and other one is P_m is the volume of ground water pumped in month m. The difference between water requirement and ground water pumped for month m is called $Allocation(m)$ which comes from the rain after the release of environmental flow. This is also related to the expenditure about the cost of water excess to the groundwater pumping and delivery cost. The difference between the revenue and all expenditures gives the net return.

The second objective is related to the environmental flow. Environmental flows are the quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and the goods and services they provide to people (Mahmood et al., 2020).

The second objective is

$$\min EFD = \sum_{m=1}^{M} \max[(Tenv\_f(m) - Env\_f(m)), 0] \tag{1.2}$$

where $Tenv\_f(m)$ is the target environmental flow for month m and $Env\_f(m)$ is the environmental flow for month m.

The only terms in the right hand side of the Equation (1.2) are included only for those months where the environmental flow is less than the target, otherwise zero is used instead.

1.3 Multi-objective optimization

Optimization is an attempt to maximize a system's desirable properties while simultaneously minimizing its undesirable characteristics (Storn and Price, 1997). *Multi-objective Optimization Problems* (MOPs) (or vector optimization) refers to the class of optimization problems with more than one objective function to be optimized systematically and simultaneously over a given feasible region. It is not easy to optimize all such objective functions together and to find a unique solution in real-life problems. Let us consider the following *Multi-objective Optimization Problem* (MOP)

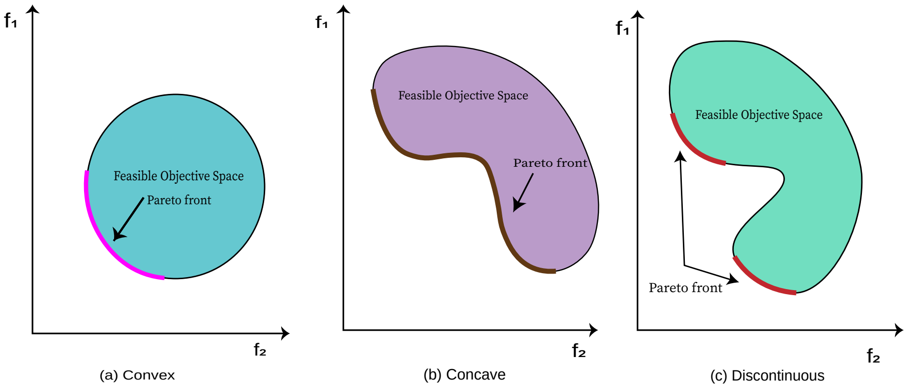
$$\begin{aligned} &\min \boldsymbol{f}(\boldsymbol{x}) \\ \text{s.t.}\ \ &g_j(\boldsymbol{x}) \leq 0, \quad j = 1, 2, ..., m \end{aligned} \tag{1.3}$$

where $\boldsymbol{f}(\boldsymbol{x}) := [f_1(\boldsymbol{x}), ..., f_l(\boldsymbol{x})]$ is a vector of l objective functions and $\boldsymbol{x} \in \mathbb{R}^n$. The objective functions and the constraints are real valued functions i.e. $f_i : \mathbb{R}^n \to \mathbb{R}$, $i = 1, ..., l$, and $g_j : \mathbb{R}^n \to \mathbb{R}$, $j = 1, ..., m$, are *continuously differentiable* functions. Please note that genetic algorithm used in this thesis does not require differentiability.

MOPs are essential for our real life, because they provide a model for the case in which we have to take into account the *trade-off* of several conflicting objectives. Several problems in water management, industry, engineering, economy, and many other fields involve the optimization of several conflicting objectives simultaneously. Agriculture is still the greatest water user of all over the world. When irrigation is constrained by limited water availability, a maximum crop yield is not achievable. With deficit irrigation, the plants are consciously under-supplied with water and a reduced crop yield is accepted as the penalty. Thus, good water management practices in irrigation aim to improve water use efficiency, without sacrificing crop productivity.

It is very difficult to find a solution that is best in respect to all the objectives rather there are equally good solutions. Points satisfying a *trade-off* among conflicting objective functions are referred to as *Pareto points* (Miettinen, 2012) or *efficient points* (Yu, 2013). The set consisting of the images of these points in the objective function space is called the *Pareto front*. Three examples of a *Pareto front* are shown in Figure 1.4.

A solution is called *Pareto optimal* if none of the objective functions can be



(a) Convex

(b) Concave

(c) Discontinuous

Figure 1.4: Example of different shapes of feasible objective space (a) Convex, (b) Concave and (c) Discontinuous.

improved in value without degrading some of the other objective values. From the mathematical perspective, every *Pareto optimal* solution is equally acceptable as the solution to the MOP. However, for practical reasons ultimately only one solution is chosen. To choose one desirable solution out of the set of *Pareto optimal* solutions involves a decision maker. A person who plays the role of the decision maker has insights into the problem and is able to express preference relations between the different solutions. But first options must be provided to the decision maker.

The fundamental concepts related to MOPs will be discussed next. If all objective and constraint functions are linear, then (1.3) is called a *linear multi-objective optimization problem*. If at least one of the objective or constraint functions are nonlinear, then (1.3) becomes a *nonlinear multi-objective optimization problem*. When all functions are convex then (1.3) is called a *convex multi-objective optimization problem* as shown Figure 1.4(a). When at least one of the functions involved is non-convex, the problem is a *non-convex multi-objective optimization problem* as shown Figure 1.4(b). When objective functions are not continuous, the Pareto front is *discontinuous* as shown Figure 1.4(c).

The solutions of (1.3) are called *efficient points* or *Pareto points* or *nondominated* solutions. A point $\bar{\boldsymbol{x}}$ is said to be an *efficient point* or *nondominated* solution to problem (1.3) if two conditions are met:

1. The solution $\bar{\boldsymbol{x}}$ is no worse than $\bar{\boldsymbol{y}}$ in any objectives, that is $f_j(\bar{\boldsymbol{x}}) \ntrianglerighteq f_j(\bar{\boldsymbol{y}})$, for $j \in 1, ..., l$, where l is the number of objectives.
2. The solution $\bar{\boldsymbol{x}}$ is slightly better than $\bar{\boldsymbol{y}}$ in at least one of the objectives, $f_j(\bar{\boldsymbol{x}}) \triangleleft f_j(\bar{\boldsymbol{y}})$ for at least one $j \in 1, ..., l$, where l is the number of objectives.

If both conditions above are satisfied then $\bar{\boldsymbol{x}}$ dominates $\bar{\boldsymbol{y}}$ and is written as $\bar{\boldsymbol{x}} \preceq \bar{\boldsymbol{y}}$. If one of the two conditions are not met then $\bar{\boldsymbol{x}}$ does not dominates $\bar{\boldsymbol{y}}$. A point $\bar{\boldsymbol{x}}$ is said to be *weak efficient* to problem (1.3) if there is no $\bar{\boldsymbol{y}} \in \boldsymbol{X}$ such that $\boldsymbol{f}(\bar{\boldsymbol{y}}) < \boldsymbol{f}(\bar{\boldsymbol{x}})$. The set of *weak efficient* solutions is a superset of the set of *efficient* solutions.

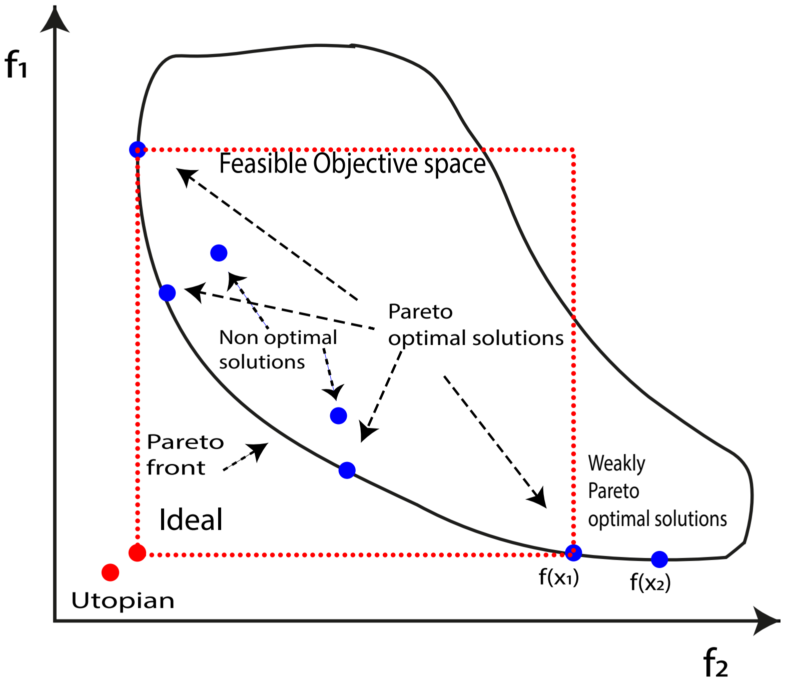


Figure 1.5: Different points of two-objective optimization problem, where both objectives are to be minimized.

In order to solve a MOP, it is required that the ranges for all the objective functions in the objective space be known. The lower bound for individual objective function $f_i(\bar{\boldsymbol{x}})$ is obtained by minimizing the function f_i individually.

If $\bar{x}_{f_i}$ is a minimizer of the problem (1.3), then $z_i = f(\bar{x}_{f_i})$, $i = 1, ..., l$, are the components of the vector of *individual minima.* When all these lower bounds are combined together to form one vector then the vector is called the *ideal vector.* The *ideal vector* contains the individual minima of each objective function as shown in Figure 1.5.

Clearly, if an *ideal vector* is feasible for problem (1.3), then it is a solution of MOP. In general, an ideal vector is not feasible and a reference vector is considered which is strictly better than the *ideal vector* is called a *utopia vector* as shown Figure 1.5. A *utopia vector* $\boldsymbol{u} \in \mathbb{R}^n$ associated with problem (1.3) is defined as $u_i = z_i - \epsilon_i$ where $\epsilon_i > 0$ for all $i = 1, ..., l.$ and z_i is an *ideal vector.*

In the context of the thesis f_1 represents the negative net return (NR) and f_2 represents by minimizing the deficit in environmental flow (EFD) in the MOP for the water allocation problem. For solving our conflicting MOP we converted all objective functions to the minimization form and all the constraints are converted to the form $h(\bar{\boldsymbol{x}}) \leqslant 0$. Hence we minimize the negative net return or in essence the net cost as the first objective function.

1.4 Solution techniques

Numerous optimization techniques have been employed in recent decades to deal with optimal water allocation in agriculture such as Dauer and Krueger (1980), Xevi and Khan (2005), Lalehzari et al. (2015), Pastori et al. (2015), Lewis and Randall (2017), Ikudayisi et al. (2018) and so on. All techniques are generally classified into two categories; (1) classical methods and (2) evolutionary algorithms.

In classical methods, all objective functions are converted into a single or a family of single objective optimization problems using some parameters. Then the resulting single-objective problem is solved by standard optimization methods and software. Examples of some classical methods are the weighted sum method (Gass and Saaty, 1955), the ϵ-constraint method (Chankong and Haimes, 2008), the Pascoletti–Serafini scalarization method (Pascoletti and Serafini, 1984), the Normal Boundary Intersection method (Das and Dennis, 1998) and the feasible-value-constraint method (Burachik et al., 2017). In classical method, a single point solution is found for every iteration. Also, these methods may not work effectively when some of the objectives are noisy or have a discontinuous variable space. The problem is that the classical methods are very much sensitive to the parameters used (Srinivas and Deb, 1994).

Evolutionary Algorithms (EAs) are population-based well renowned meta heuristic optimization algorithms that use biology-inspired mechanisms like mutation, crossover, natural selection, survival of the fittest in order to refine a set of candidate solutions iteratively (Weise, 2009). The classical methods and the evolutionary methods are different from each other. In classical method the optimal solution is found using direct calculation. By contrast, in evolutionary method the optimal solution is searched from a randomly generated population of possible solutions (Azamathulla et al., 2008).

This research uses EAs for solving MOPs. EAs are particularly desirable for solving MOPs for two reasons. Firstly, they deal simultaneously with a set of possible solutions (the so-called population) which allows one to find an entire set of Pareto optimal solutions in a single run of the algorithm, instead of having to perform a series of separate runs as in the case of the traditional mathematical programming techniques. Secondly, evolutionary algorithms are less susceptible to the shape or continuity of the Pareto front, whereas these two issues are a real concern for mathematical programming techniques (Bhargava, 2013). Moreover, In this research total number of variables is 22. It is difficult to calculate the optimum value using direct method. That is why an evolutionary algorithm is used in this research.

There exist numerous evolutionary algorithms which ensure that, under certain conditions, the solution obtained is a *Pareto optimal point.* Among them the most common evolutionary algorithms are the well-known *Vector Evaluated Genetic Algorithm* (VEGA) (Schaffer, 1985), the *Lexicographic Ordering Genetic Algorithm* (Fourman, 1985), the *Multiple Objective Genetic Algorithm* (MOGA) (Holland, 1975), the Multi-objective Differential Evolution (MODE) (Storn and Price, 1997), and the *Non-dominated Sorting Genetic Algorithm* (NSGA) (Deb et al., 2000).

The first multi-objective evolutionary algorithm, called the *Vector Evaluated Genetic Algorithm* (VEGA) was proposed by Schaffer (1985). This algorithm emphasizes solutions which are good for individual objective functions but it is very difficult to produce *Pareto optimal* solutions in the case of a non-convex objective function space (Coello et al., 2007).

In the *Lexicographic Ordering Genetic Algorithm* (LOGA), the Decision Maker (DM) is asked to rank the objectives in order of importance. The optimum solution is then obtained by minimizing the objective functions in sequence, starting with the most important one and moving forward according to the assigned order of importance of the objectives. It is suitable only when the importance of each objective (in comparison to the others) is clearly known (Coello et al., 2007).

Multi-Objective Genetic Algorithm (MOGA) is an evolutionary algorithm that can solve both constrained and unconstrained optimization problem which was introduced by Holland (1975). This method is efficient and relatively easy to implement but its performance is highly dependent on an appropriate selection of the sharing factor (Coello et al., 2007).

Multi-objective Differential Evolution Algorithm (MODEA) is a type of evolutionary algorithm originally proposed by Storn and Price (1997) for optimization problems over a continuous domain but same parameters may not guarantee the global optimum solution and takes more computation time (Babu and Anbarasu, 2005).

The Non-dominating Sorting Genetic Algorithm-II (NSGA-II) is an improved version of the Non-dominating Sorting Genetic Algorithm (NSGA) proposed by Deb, Agrawal, Pratap, and Meyarivan (2000). It starts with building a population of rival individuals and then ranks and sorts according to its non-domination level. After that it creates a new offspring pool by using evolutionary operators, and finally combines the parent and offspring before splitting the new combined pool into fronts. In comparison with the previous version, the NSGA-II has less computational complexity, considers elitism, systematically preserves the diversity of *Pareto optimal* solutions, and adaptively handles the problem constraints (Haghighi and Asl, 2014).

The NSGA-II has been successfully used in the wide range of engineering problems such as long-term groundwater monitoring (Reed et al., 2007), optimization of economic/emission load dispatch for hybrid generating systems (Wafa and Ahmed, 2013), controlling the wind energy systems (Zamanifar et al., 2014) and analysis of water distribution networks (Zeng et al., 2010).

1.5 Applications of different methods for water allocation in irrigation

Recently, a significant amount of research done regarding water management optimization. Among such works are, the work by Wardlaw and Bhaktikul (2004), Xevi and Khan (2005), Lalehzari et al. (2015), Lewis and Randall (2017), and Ikudayisi et al. (2018).

A Genetic Algorithm (GA) was developed by Wardlaw and Bhaktikul (2004) to solve an irrigation water scheduling problem. The objective of the study is to optimize the utilization of water resources in irrigation systems operating on a rotational basis. This algorithm was applied to the Pugal branch canal in the Indira Ghandi Nahal Pariyonaja (IGNP) irrigation system located in North West India. Considering zero-one and rotational approaches they developed a scheduling approach which combines both canal delivery scheduling with in-field soil moisture requirements.

A multi-criteria decision-making framework was developed by Xevi and Khan (2005) to solve water allocation problems with conflicts objectives in irrigation. A multi-objective problem was described in this research which consisted of three objective functions: maximizing net return, minimizing variable cost, and minimizing total supplementary ground water pumping requirements. This model was applied to the Irrigation Area at Berembed weir on the Murrumbidgee River, Australia. To solve the MOP the authors used a weighted version of goal programming model where all objective functions are converted into a single objective function.

Lalehzari et al. (2015) proposed a multi-objective programming model on water allocation to agricultural areas from three different sources of water: rainfall, river, and ground water by using a NSGA-II to obtain a Pareto front. This study contains two maximization objectives: (1) net benefit and (2) relative water use efficiency. The irrigation scheduling was evaluated in the experimental field located at Baghmalek plain, Khuzestan province, Iran. The study suggested that NSGA-II improves precision in irrigation scheduling (Lalehzari et al., 2015).

Lewis and Randall (2017) conducted a study which is largely an extension of that presented in Xevi and Khan, 2005. Here they combined all three objectives into a single objective and then added a new objective function to minimize deficits in the downstream release of water for environmental flows. An evolutionary computational techniques and pareto optimization concepts have been applied for solving this problem. From the analysis, it is concluded that using crop selection their result are extraordinary than that of Xevi and Khan (2005) result.

In a study conducted by Ikudayisi et al. (2018), a multi-objective optimization of optimum irrigation water allocation and crop distribution was solved. The adopted technique in this study was an evolutionary algorithm called combined Pareto multi-objective differential evolution algorithm. The algorithm combines methods of Pareto ranking and Pareto dominance selections to implement a novel selection scheme at each generation. Using a combined Pareto multi-objective differential evolution algorithm this paper optimizes irrigation water allocation and crop distribution under limited water availability while planting three different crops on a 100 hectares of farmland at the Vaal-Harts Irrigation Scheme (VIS) in South Africa. The objectives of the model were formulated to maximize total net benefit of crops while minimizing irrigation water use.

Zeinali et al. (2020) used a multi-objective optimization to improve the performance of a dynamic coupled model for obtaining optimal allocation of surface water and groundwater in irrigation. The objective functions of this study were maximizing the demand site coverage and minimizing the groundwater drawdown in the Balarood Dam, Iran. The goal in this study is to obtain an optimal conjunctive allocation by using the non-dominated sorting genetic algorithm II (NSGA-II). Application of this method in the study area enhance the demand supply reliability and contribute to reducing the groundwater drawdown at the end of the operational period (Zeinali et al., 2020).

Adama et al. (2020) developed a water allocation model using Genetic Algorithm to equitably allocation available water to the various sectors in Kano River Irrigation Scheme in Nigeria. The results of this research showed that the decision making tool for effective water allocation as the water allocation model yielded an optimal as well as equitable water release with a 96.44% demand met. The model is robust and relatively easy to apply and can be employed by farm managers to achieve equity and optimal use of the available water resource (Adama et al., 2020).

Boah and Twum (2020) presented a state of the art review of water quality optimization models and techniques from early 1970s to date. In this research they categorized all models/techniques into two types and then discussed about the different types. The result of this research showed that more effort will need to be given to the application of interior-point methods of mathematical optimization to water quality management (Boah and Twum, 2020).

In this research, we model the problem using multi-objective constrained optimization problem. The objectives in this problem are to maximize net return and minimizing deficit in environmental flow. A Non-Dominating Sorting Genetic Algorithm, NSGA-II, is used to solve the nonlinear constraint problem to find the optimum result. This model was applied to data sourced from Bangladesh. This to the author's knowledge has not been done before.

1.6 Overview of the Thesis

The thesis focuses on the optimal water allocation in the small irrigation system known as the Muhuri Irrigation Project in Bangladesh. This thesis is organized into five chapters including this chapter.

Chapter 1 contains the general introduction and literature review to the study. It describes water scarcity as the main issue affecting the irrigation sector of Bangladesh in dry season. It also gives a review of some existing evolutionary optimization algorithms in water allocation problem.

Chapter 2 provides a detail description of the model components. It also describes about data that are collected from Mr.Oli Afaz Chowdhury, Sub-Divisional Engineer, Hathazari O& M Sub-Division, Bangladesh Water Development Board (BWDB), Chattogram.

In Chapter 3 a novel evolutionary multi-objective optimization algorithm called Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is describe to solve constrained and real world irrigation water use and crop yield problem.

Chapter 4 presents the results and discussion of the model findings.

The final chapter summaries the main findings and conclusion of the study and gives some limitations and identifies the areas of future research.

Chapter 2

Data Collection and Model Definition

Introduction

This chapter provides the details of data collection and the model used. The data used in this study come from different sources including from the Bangladesh Water Development Board (BWDB), previous studies and research findings, literature review and specific assumptions. This chapter also provides details of model.

2.1 Data Description

2.1.1 Salient Features of Study Area

Muhuri Irrigation Project (MIP) is located in Feni, a south-eastern district in Bangladesh. Actually it is a reservoir project created by the three rivers (1) the Feni river, (2) the Muhuri river, and (3) the Kalidas-Pahalia river as shown in Figure 1.3 in the previous chapter. The creation of this artificial reservoir body, linked with a network of 245 irrigation canals along with 3.411 km closure dam and 40 vent (each vent is 3.65m x 3.65m) regulator stops the intrusion of sea water into the MIP area. It has been built to seasonally hold the river's water for local agricultural irrigation. The dam closes in early winter creating a large lake, and the sluice gate is opened before monsoon to release its water. During winter and spring, this lake, in addition to holding agricultural water, is used for fish cultivation. The project area covers six Upazilas; Feni sadar, Sonagazi, Fulgazi Chagalnaiya, Parsuram and Mirsarai. Mirsarai upazila lies in the Chittagong district the other 5 Upazilas lie in Feni district. The gross project area measures about 40,000 ha, the cultivated area is 28,600 and the irrigable area is 14,050 ha (BD Explorer, 2017).

2.1.2 Rainfall and Evapotranspiration Data

Bangladesh is low-lying, crisscrossed country with an area of approximately $144,170\,\mathrm{km}^2$. In climatic point of view Bangladesh has four main seasons in a year: (i) the dry winter season from December to February, (ii) the pre-monsoon hot summer season from March to May, (iii) the rainy monsoon season from June to September, and (iv) the post-monsoon autumn season which lasts from October to November. Summer in Bangladesh is very humid as wind blow from the southern hemisphere creating a lot of moisture in the atmosphere, eventually depositing heavy amounts of precipitation. Whereas winds from the Northern hemisphere are very dry and in winter it starts to blow towards the warm southern oceans. The annual average rainfall in the MIP area is 2447mm (Mainuddin et al., 2014).

Table 2.1 shows the Monthly rainfall data in millimetre (mm) for the period of July, 2015 to June, 2019 in the MIP area. This data was collected from the Bangladesh Water Development Board (BWDB), Feni, Bangladesh.

Table 2.1: Rainfall (in mm) data in Muhuri Irrigation Area.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019	0	115	0	68	200	100-	-	-	-	-	-	-
2018	0	0	0	320	490	660	375	190	92	128	0	0
2017	0	0	78	735	180	850	819	455	510	270	23	225
2016	0	0	0	70	384	425	800	420	95	400	0	0
2015	-	-	-	-	-	-	1555	706	666	685	0	0

The rainfall received in a given period at the MIP is highly variable from one month to another. The variability depends on the type of climate and the period. From Table 2.1 we see that the significant amount of rainfall is observed in the MIP area from April to October. From November to March we find a little rainfall. The dashes “ – ” in Table 2.1 represents missing or unavailable data from the Muhuri Irrigation Area.

Evapotranspiration reaches its maximum level in April and May when temperature, sunshine and wind are all at, or close to, their maximum levels for the year. Monthly evapotranspiration data was collected from the Asian Development Bank (2013) and is given in Table 2.2.

Table 2.2: Evapotranspiration (in mm) data in Muhuri Irrigation Area.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Feni	72	89	130	143	145	115	113	117	110	106	81	68

In Xevi and Khan (2005) article we have seen that, the researchers have collected wide range of data according to the three seasons: (i) Dry, (ii) Average, and (iii) Wet. However, the data in the present research is not as complete as in Xevi and Khan (2005) article. Due to limited scope of the thesis and the unfavorable situation in collecting data via email, a sufficient data could not be collected. Despite this, we have used the data which has been collected supplemented with the data from literature.

2.1.3 Economic data for crops

A wide range of crops are grown in the MIP. They are broadly classified into two groups: Kharif crops and Rabi crops.

Kharif crops are grown in the summer season and harvested in late summer or in early winter. Kharif crops are mostly rainfed and partially irrigated. Rabi crops are grown in dry season and harvested in the spring or early summer. During this time, there is very little rainfall in this area (Mainuddin et al., 2014). So they are mostly irrigated. This thesis considered ten crops these are Transplated Aus Rice (T.Aus), Transplanted Aman Rice (T.Aman), Boro Rice, Wheat, Potato, Oilseeds, Pulses, Sugercane, Winter Vegetables, and

Summer Vegetables.

Crops production (T/ha) and crop market price (AUD) data in Table 2.3 was collected from the Deputy Chief Extension Officer, BWDB, Feni, Bangladesh.

Table 2.3: Economic data for crops in Muhuri Irrigation Area (1 AUD = 60 Taka).

Crops	Production (T/Ha)	Market Price(AUD) per ton
T. Aus	3.2	331
T. Aman	4.25	365
Boro Rice	5.85	331
Wheat	2.8	206
Potato	23	248
Oilseeds	1.1	537
Pulses	1.56	557
Sugercane	50	4965
Winter Vegetables	16.5	435
Summer Vegetables	14.85	383

In Table 2.4 the expected variable costs of pumping fuel, labor, drip tubing, and pesticide were calculated from operation and maintenance specifications and production requirements. Some data have been adapted from Xevi and Khan (2005). Based on the similarities of production cost between Bangladesh and Australia some data has been assumed.

Table 2.4: Expected variable cost for different crops in Muhuri Irrigation Area (1 AUD = 60 Taka).

Crops	Cost (AUD)/Ha
T. Aus	665
T. Aman	363
Boro Rice	277
Wheat	339
Potato	860
Oilseeds	487
Pulses	803
Sugercane	167
Winter Vegetables	436
Summer Vegetables	385

2.1.4 Crop coefficient

The crop coefficient (K_c) is the ratio of the crop evapotranspiration (ET_c) to the reference crop evapotranspiration (ET_o)

$$K_c = \frac{ET_c}{ET_o}. \tag{2.1}$$

Evapotranspiration (ET) is a combination of the water evaporated from the soil surface and transpired through the plant. The reference crop evapotranspiration (ET_o) is a measurement of the water use for that reference crop. To calculate reference crop evapotranspiration (ET_o) grass is used as the reference crop. However other crops may not use the same amount of water as grass due to changes in rooting depth, crop growth stages, and plant physiology.

Table 2.5: Crop coefficient (K_c) (Mainuddin et al., 2014).

Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T. Aus	0.2	0.2	0.2	1.05	1.2	1.2	0.9	0.2	0.2	0.2	0.2	0.2
T. Aman	0.2	0.2	0.2	0.2	0.2	0.2	1.2	1.2	0.9	0.2	0.2	0.2
Boro Rice	1.2	0.9	0.9	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1.05	1.2
Wheat	1.15	1.15	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4
Potato	0.8	0.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.6	1.15	1.15
Oilseeds	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.35	1.05
Pulses	1.05	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4
Sugercane	0.4	0.4	0.2	0.2	0.2	0.2	1.15	1.15	0.9	0.9	0.6	0.6
Winter Vegetable	0.9	0.9	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.6	1.1
Summer Vegetable	0.2	0.2	0.2	0.6	1.1	0.9	0.9	0.2	0.2	0.2	0.2	0.2

The crop coefficient (K_c) takes into account the crop type and crop development to adjust the (ET_o) for that specific crop. There may be several crop coefficients used for a single crop throughout an irrigation season depending on the crop's stage of development. In this research, crop coefficient data in

Table 2.5 has been taken from Mainuddin et al. (2014).

2.1.5 Water Inflow

Major rivers within the project area are the Feni, Kalidas-Pahalia, and Muhuri rivers, in addition, there are many Khals located in the area. Other rivers outside the project area such as Titas, Gumti, Dakatia and Meghna act as the main drainage collectors. Surface water irrigation is from the three rivers supported by storage in the rivers, drains and reservoir in the backwater from Feni Regulator. In Table 2.6 monthly water inflows from the three rivers was collected from the Asian Development Bank (2013).

Table 2.6: Monthly Water Inflow in cubic meter per second (Asian Development Bank, 2013).

River	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Feni	13.2	9.2	7.4	11.6	15.5	31.9	42.1	69.7	39.2	31.4	18.5	14.9
Muhuri	2.1	1.4	1.6	1.6	3.4	16.5	16.7	22.2	14.2	11.9	7.5	3.3
Kalidash Pahalia	1.2	0.8	1.0	1.0	2.0	9.9	10.0	13.3	8.5	7.1	4.5	2.0
Total	16.5	11.4	10.0	14.1	21.1	58.3	68.8	105.2	61.9	50.4	30.5	20.1

2.2 Model Description

2.2.1 Model formulation

The irrigation water use optimization problem in this study was conducted for a planting season at MIP. Ten different crops, namely Transplated Aus Rice (T.Aus), Transplanted Aman Rice (T.Aman), Boro Rice, Wheat, Potato, Oilseeds, Pulses, Sugercane, Winter Vegetales and Summer Vegetables, are to be planted potentially on the piece of land. Formulation of the constrained multi-objective mathematical optimization problem is provided in the following sections. The model solution was conducted for a reduced number of crops and months. These results are not presented as they did provide a meaningful solution to the full problem.

2.2.2 Decision variables and objectives

As mentioned in Chapter 1 the main aim of the study is to find the corresponding optimal crop mix and planting areas per crop while maximizing net return (NR) whilst minimizing irrigation water and minimizing deficit in environmental flow (EFD). The decision variables are X_c and $Env\_f(m)$ where X_c is the area of crop c to be planted in hectare and $Env\_f(m)$ is the environmental flow for month m. The Lewis and Randall (2017) model is adopted and improved for this research project.

Lewis & Raindall presented a model-based system for water management. Their project site is Murrumbidgee Irrigation Area in Australia. The have collected their data from that site and optimized water through crop selection across dry, average and wet years. The first objective of their model is to maximize Net Revenue (NR) (as introduced in Chapter 1)

$$\begin{aligned} \max NR &= \sum_{c=1}^{C} TCI_c\, X_c - C_p \sum_{m=1}^{M} P_m - \sum_{c=1}^{C} Vcost_c\, X_c \\ &- C_w \sum_{m=1}^{M} \left(\left(\sum_{c=1}^{C} WREQ_{c,m}\, X_c \right) - P_m \right) \end{aligned} \tag{2.2}$$

where TCI_c is the total crop income of crop c, X_c is the area of crop c (ha), C_p is the cost of groundwater pumping and delivery per unit volume, P_m is the volume of ground water pumped in month m, $Vcost_c$ is the variable cost (such as fertilizer and pesticides applications) per hectare other than water cost for crop c. Also in Equation (2.2) the parameters C_w is the total cost of water per unit volume and $WREQ_{c,m}$ is the water requirement for crop c in month m. C is the total number of types of crops to be planted and M is the total number of months in the planning period.

The first term of the objective function in Equation (2.2) is the total revenue and the second term is the expenditure related to the groundwater pumping and delivery cost. The third term is the expenditure which comprises of the variable cost such as fertilizer, pesticides, seeds and other costs. Finally, the last term is also related to the expenditure, is the cost of surface water available for irrigation of crops in month m. The difference between the revenue and all expenditures gives the net return.

The second objective is to maintain sufficient downstream flows for environmental reasons. This objective is set with a view to maintain a balance between the use of water and life of the nature in the MIP. Because if the focus is given only on irrigation but not on the environment around it the bio-diversity will be hampered. Still the objective focuses on how to sustain bio-diversity with minimum use of water.

$$\min EFD = \sum_{m=1}^{M} \max[(Tenv\_f(m) - Env\_f(m)), 0] \tag{2.3}$$

where $Tenv\_f(m)$ is the target environmental flow for month m and $Env\_f(m)$ is the environmental flow for month m.

The only terms in the summation of the Equation (2.3) that are included are only for those months where the environmental flow is less than the target, otherwise zero is used instead. The environmental flow, $Env\_f(m)$ is the quantity, quality and timing of water that are necessary to sustain the ecosystem.

2.2.3 Water requirement

The crop water requirements per month, $WREQ_{c,m}$, is the excess of evapotranspiration with the growth duration in months over rainfall.

$$WREQ_{c,m} = k_{c,m}\, ET_m - Rain_m \tag{2.4}$$

where $k_{c,m}$ is the crop coefficient for crop c in month m, ET_m is the evapotranspiration for month m and $Rain_m$ is the rainfall, in millimetres, for month m.

2.2.4 Problem constraints

There are a number of physical and environmental constraints imposed on the model which are given in the following.

The first constraint is the pumping water constraint.

$$\sum_{c=1}^{C} P_{c,m} \leq Pump_m \tag{2.5}$$

where $Pump_m$ is the allowable pumping in the irrigated areas for month m.

This constraint ensures the volume of ground water pumped from the irrigation area in any month does not exceed the allowable pumping for that month.

The second constraint is maximum area constraint.

$$\sum_{c=1}^{C} X_c \leqslant T_{Area} \tag{2.6}$$

where T_{Area} is the total cropping area available. This constraint limits the total crop area planted to be less than or equal to the total area available.

The third constraint is minimum area constraint.

$$X_c(minimum\_area - X_c) \leq 0, \tag{2.7}$$

This constraint limits the amount of the crop planted to be of at least a minimum size or zero. This means that if a crop has a minimum plantable area, the corresponding crop area, X_c, must be greater than this minimum area if the crop is to be planted.

The next constraint relates to the amount of groundwater pumping. The groundwater pumping required can be derived from the crop water requirements and the surface water available for irrigation of the crop in month m and is given by

$$P_m = \left(\sum_{c=1}^{C} WREQ_{c,m} X_c \right) - Allocation(m) \tag{2.8}$$

where P_m is the groundwater pumped in month m, X_c is the area of crop c to be planted in hectare and $Allocation(m)$ is the amount of surface water available for irrigation of crops in month m.

The last constraint is water allocation constraint

$$Allocation(m) = Inflow(m) - Env\_f(m) \tag{2.9}$$

where $Allocation(m)$ is the amount of surface water available for irrigation of crops in month m and $Inflow(m)$ is the amount of surface (river) water available in month m. After the release of environmental flows from the surface water available, this constraint is given by the surface water available for irrigation of crops in month m.

2.3 Summary

This chapter presents the model description and data. The research is based on Lewis and Randall water management model for solving multi-objective optimization using evolutionary computation. This research mainly depends on the secondary data. However, the secondary data used in this research is limited because of problem of correspondence with the MIP authority and the Bangladesh Water Development Board (BWDB). Time constraints and lack of information in the collected data set (see data set at Appendix A) has meant we have supplemented the model with data from literature. The next chapter will discuss how the model will be solved.

Chapter 3

The Solution Algorithm

Introduction

The multi-objective optimization method, Non-dominated Sorting Genetic Algorithm-II (NSGA-II) Deb, Agrawal, Pratap, and Meyarivan (2000), has been improved and adopted to solve water allocation from three sources (surface water, groundwater, and precipitation) to different growth stages of a cropping pattern by using modified MatLab code first developed Baskar (2015). The non-dominated sorting principle and crowding distance criterion will be applied to find the best solution of two objective functions simultaneously.

Genetic algorithms (GAs) are adaptive meta heuristic search algorithms which classified as an evolutionary computing algorithms, which use techniques inspired by natural evolution (Hassanat et al., 2019). GA is the most promising algorithm to find quick solution. There are many potential genetic algorithms such as Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Simulated Annealing (SA) Tabu Search (TS), Differential Evolution (DE), Non-dominated Sorting Genetic Algorithm-II (NSGA-II). The study uses NSGA-II. A comparison of the other algorithms with the NSGA-II to find the best solution will be a topic for my future research.

3.1 The Non-dominated Sorting Genetic Algorithm -II (NSGA-II)

The NSGA-II is a multi-objective genetic algorithm developed by Deb, Agrawal, Pratap, and Meyarivan (2000) see Appendix B . It is an extension and improvement of NSGA, which was proposed earlier by Srinivas and Deb (1994). It is one of the most popular elitist multi-objective optimization algorithms.

An elite preserving operator favors the elites of a population by giving them an opportunity to be directly carried over to the next generation. Elitism can be implemented to different degrees in an multi-oblective evolutionary algorithm. The presence of elitism should improve the performance of a multi-objective evolutionary algorithms (Bhargava, 2013).

In the structure of NSGA-II, in addition to the genetic operators of crossover and mutation, there are two specialized multi-objective operators and mechanisms namely non-dominated sorting and crowding distance that are used and are defined in the following section.

3.1.1 Non-dominated Sorting

The idea behind the non-dominated sorting procedure is that a ranking selection method is used to emphasize good points. Before the selection is performed, the population is ranked on the basis of an individual's non-domination described in Section 1.4, Chapter 1. The fast non-dominated sorting algorithm is described as below (Deb et al., 2000).

- **Step 1 :** For each individual p and q in main population P $\{p,q \in P\}$ do the following:
    - Initialize a set $S_p = \phi$ which contains all the individual that are being dominated by p.
    - Initialize a set $n_p = \phi$ which contains the number of individuals that dominate p.
    - If p dominates q then include q in S_p.
    - If p is dominated by q then increment n_p.

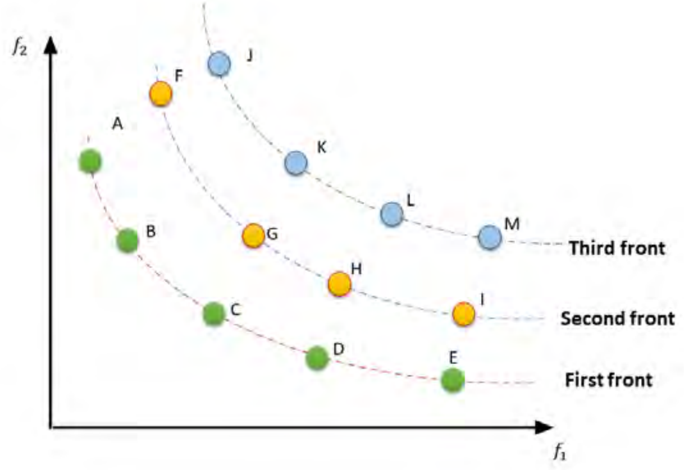


Figure 3.1: Non-dominated sorting procedure (reproduced from Wang et al. (2015)).

  - If no solution dominates p then p is the a member of the first front. In Figure 3.1, populations A, B, C, D, E are the members of the first front.

- **Step 2 :** Front one is then permanently neglected.
- **Step 3 :** Then among the remaining members the second rank is assigned to the second fronts who don't dominate the others and these members are then permanently ignored. In Figure 3.1 populations F, G, H, I are the members of the second front.
- **Step 4 :**This process continues until all of the members based on Figure 3.1 are assigned to the different fronts.

3.1.2 Crowding Distance

Once the non-dominated sort is complete the crowding distance is assigned. Crowding distance helps to get an estimate of the density of population surrounding of a particular solution in the population in Figure 3.2. If the distance between populations is short and the indicated density is high, the reproduction probability is low. if the distance is long and the indicated density is low, reproduction probability is high. Since the individuals are selected based on rank and crowding distance, all the individuals in the population are assigned a crowding distance value. Crowding distance is assigned front-wise and comparing the crowding distance between two individuals in different fronts is meaningless. The crowding distance, $cd(x)$ of a solution i, in Figure 3.2 is the average side-length of the Cuboid (shown with a dashed box). The following formula is used to calculate the crowding distance of each point in the population (Konak et al., 2006).

$$cd_k(x_{[i,k]}) = \frac{f_k(x_{[i+1,k]}) - f_k(x_{[i-1,k]})}{f_k^{max} - f_k^{min}} \tag{3.1}$$

where $cd_k(x_{[i,k]})$ is the crowding distance of the objective function k in the solution i. f_k^{max} and f_k^{min} are respectively the maximum and minimum values of the objective function k in the population. $f_k(x_{[i+l,k]})$ is the value of the objective function k in the solution $i + l$ and $f_k(x_{[i-l,k]})$ is the value of the objective function k in the solution $i - l$.

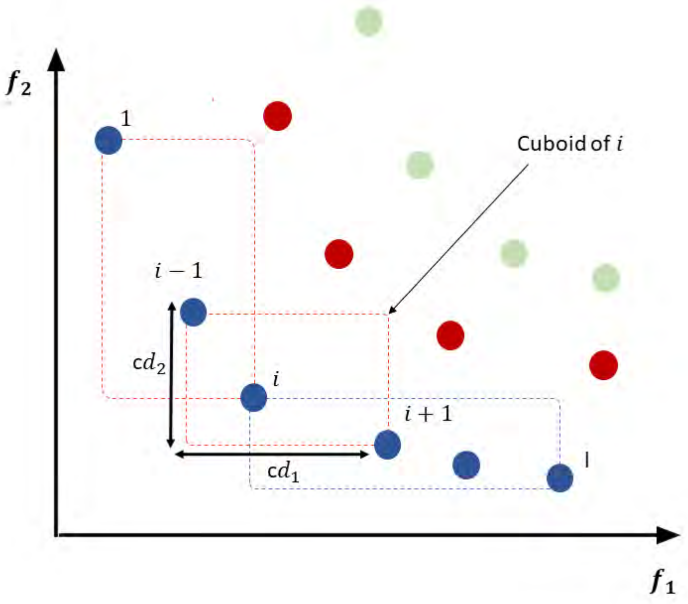


Figure 3.2: The crowding distance calculation.

The following steps are used to calculate the crowding distance;

- **Step 1 :** Rank the population and identify non-dominated fronts F_1 (Fists front), F_2 (Second front), ..., F_R (Last front) as shown in Figure

3.1. For each front $j = 1, 2, ..., R$ repeat Step 2 and 3.

- **Step 2 :** For each objective function k, sort the solutions in F_j in the ascending order. Let $l = |F_j|$ and $x_{[i,k]}$, represent the ith solution in the sorted list with respect to the objective function k. For each objective function, the boundary solutions having the minimum and maximum function values are assigned a huge distance value, i.e., infinity. So

$$cd_k(x_{[1,k]}) = \infty \tag{3.2}$$

and

$$cd_k(x_{[l,k]}) = \infty \tag{3.3}$$

whilst for $i = 2, 3, ..., l-1$ assign

$$cd_k(x_{[i,k]}) = \frac{f_k(x_{[i+1,k]}) - f_k(x_{[i-1,k]})}{f_k^{max} - f_k^{min}}. \tag{3.4}$$

- **Step 3 :** To find the total crowding distance, $cd(x)$ of a solution i, sum the solution's crowding distances with respect to each objective, $k = 1, 2, ..., r$ i.e.

$$cd(x) = \sum_{k=1}^{r} cd_k(x). \tag{3.5}$$

As a consequence, every chromosome in the population will have two attributes, including the non-domination rank and crowding distance. Hence, a crowded comparison operator is applied to the selection process so that it is guided at the various stages of the algorithm toward a uniformly spread-out Pareto front. In the NSGA-II the crowded comparison operator is so applied to the population that between two solutions with different non-domination rank, the solution with lower rank is selected. However, if both solutions have the same rank, the one with higher crowded distance is preferred

3.2 Crowded Comparison Operator

The NSGA-II uses a fixed population size of N. In generation t, the offspring population Q_t in the red area of the Figure 3.3 of size N is first created by using the usual genetic operator from the parent population P_t in the blue area of the Figure 3.3. After combining, these two populations form a new population $P_t \cup Q_t$ of size $2N$. By using non-dominated sorting technique all of the populations are allocate one of the fronts F_1 (blue), F_2 (green), ..., F_R fronts. For all of the front members, the crowding distances are calculated. Since the overall population size of $P_t \cup Q_t$ is $2N$, therefore all fronts cannot be accommodated in the N slots available for the new population. Here the operator randomly selects between two solutions with different non-domination ranks giving preference to the solution with the lower rank. Otherwise, if the solutions have the same non-domination rank, the solution with a higher crowding distance is the winner as shown in Figure 3.3 (Abiri et al., 2017, Deb et al., 2000).

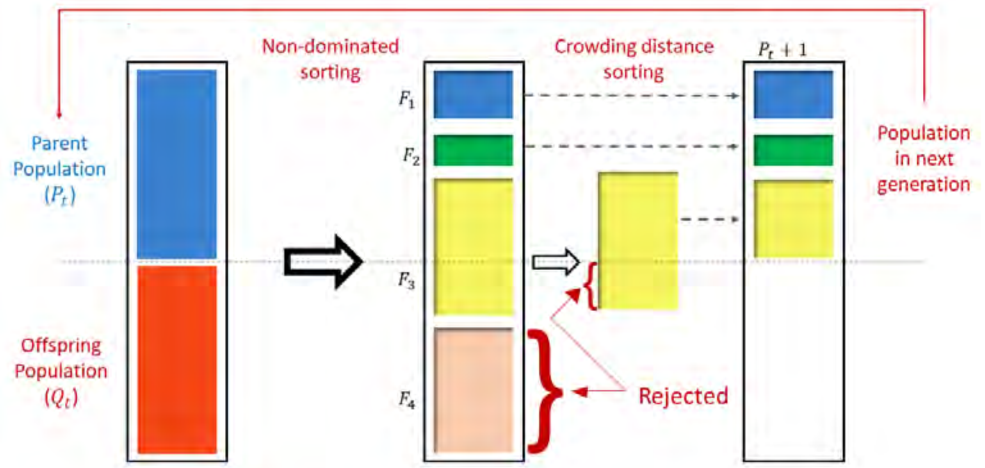


Figure 3.3: The operation of NSGA - II algorithm (reproduced from Abiri et al. (2017)).

3.3 The Main Loop

The implementation of the NSGA-II in this study uses the following steps as shown in Figure 3.4 (Goel, 2011).

- **Step 1 :** In Genetic Algorithm (GA) terminology, a solution vector $\boldsymbol{x} \in \boldsymbol{X}$ is called an individual or a chromosome. Chromosomes are made of discrete units called genes. Normally, a chromosome corresponds to a unique solution $\boldsymbol{x}$ in the solution space. GA operate with a collection of chromosomes, called a population. The population is normally randomly initialized. The initial population (points) P_0 of size N is generated randomly based on the problem range.
- **Step 2 :** For the given population (points) P_0 of size N, the objective functions are evaluated at each population (points) to determine the fitness value.
- **Step 3 :** All non-dominated population (points) receive a rank of one. Then the rank of one are temporarily removed from consideration, and the population (points) that are non-dominated relative to the remaining group are given a rank of two. This process is repeated until all population (points) are ranked.
- **Step 4 :** Select parent population (points) with the lowest rank having the highest fitness value. That is, fitness is inversely proportional to the rank.
- **Step 5 :** Apply crossover to generate new offspring. Crossover is the most significant phase in a evolutionary algorithms. Offspring are created by exchanging the genes of parents among themselves until the crossover point is reached. The parents are selected among existing chromosomes in the population with preference towards fitness so that offspring is expected to inherit good genes which make the parent fitter.
- **Step 6 :** The next operation, which also used to introduce variations into the population (points), is mutation. Apply mutation with a low probability to maintain diversity within the population (points) and prevent premature convergence.

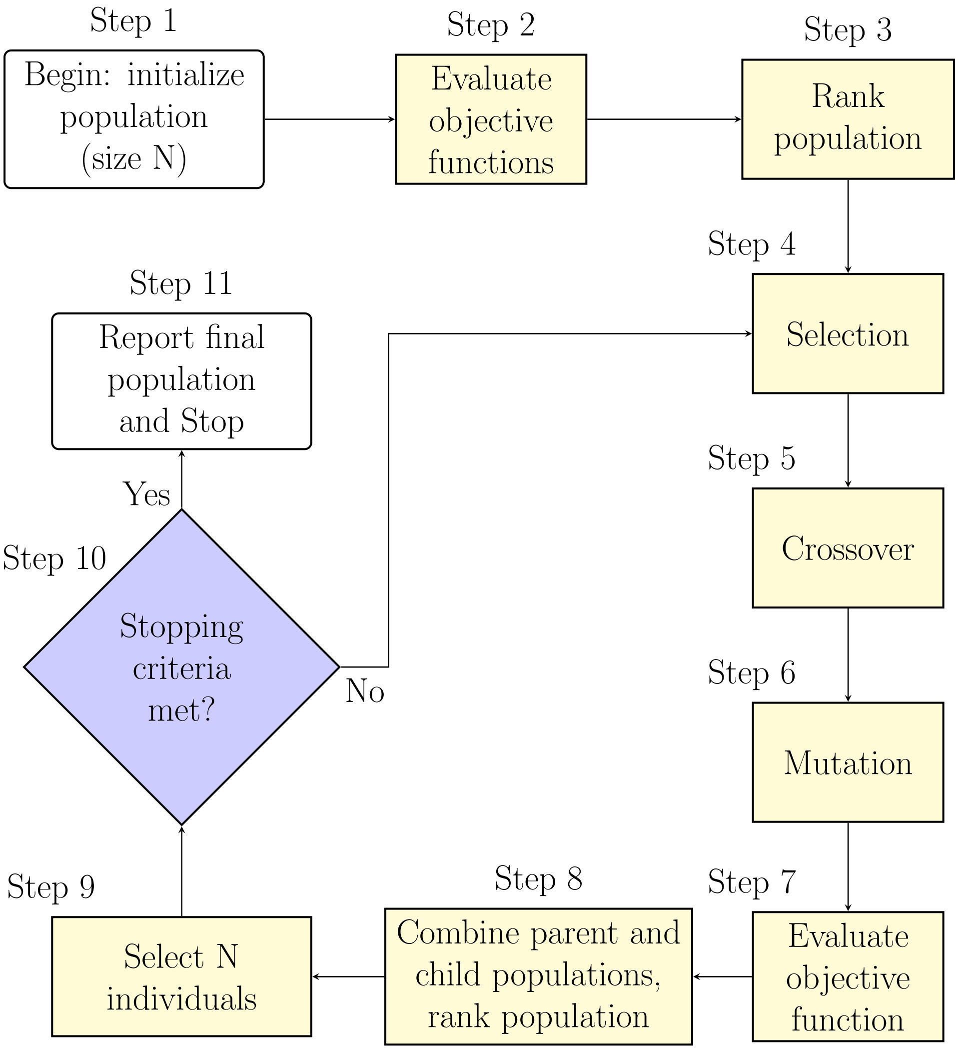


Figure 3.4: Flow Chart.

- **Step 7 :** For the new offspring population (points) Q_t of size N, the objective functions are evaluated at each offspring population (points) to determine the fitness value.

- **Step 8 :** After evaluating the fitness values of Q_t, for every generation t, combine Q_t into an intermediate population P_t of size $2N$; implement the fast non-dominated sorting to divide this combined population into different ranks; calculate crowding distances of the population to get an estimate of the density of solution surrounding a particular solution in the population.

- **Step 9 :** Select a new parent population P_{t+1} of size N from $P_t \cup Q_t$ using a binary tournament selection and crowded comparison operator.

- **Step 10 :** The algorithms terminates if one of the following termination conditions is satisfied when

  - there has been no improvement in the population for X iterations,

  or

  - it has reached an absolute number of generations,

  or

  - the objective function value has reached a certain pre-defined value,

  or

  otherwise repeat Steps 4 to 8 until the stop criterion is satisfied.

- **Step 11 :** Output the final results of the simulations.

3.4 Summary

In this chapter we have discussed the NSGA-II algorithm for solving optimal water allocation problem in the context of MIP, Bangladesh. In particular we have discussed the main steps of the NSGA-II, how the crowding distance is calculated, and the non-dominated sorting principle. We will focus on result and analysis in the next chapter.

Chapter 4

Results and Discussion

Introduction

The results obtained from the model are presented in this chapter. The NSGA-II optimization method was used to compute the environmental flow for twelve months and the cropping pattern for ten crops (T. Aus, T. Aman, Boro Rice, Wheat, Potato, Oilseeds, Pulses, Sugercane, Winter Vegetables, and Summer Vegetables) with data gathered from all weather conditions. MatLab software developed by Baskar (2015) was modified to implement the NSGA-II optimization method used to solve the MOP in Section 2.2, Chapter 2.

4.1 Model solution and experimental setup

The mathematical model equations of the objective functions and the constraints listed in Section 2.2, Chapter 2 for the constrained multi-objective optimization problem in this study were solved using NSGA-II.

The number of variables set in this study is total number of crops, X_c which consists ten crops and the environmental flow, $Env\_f(m)$ for twelve months. The indices used for the ten crops and months are given the Tables 4.1 and 4.2 respectively. The lower bound of all the variables is zero. The upper bound of the cultivable area for each crop is $70,000$ ha and the environmental flow for each month is set to 300 GL. The minimum area is 1000 ha. The target environmental flow, $Tenv\_f(m)$ is set to 100 GL for each month.

Table 4.1: Crops index, c, corresponding to X_c.

c	Crop
1	Transplanted Aus Rice (T. Aus)
2	Transplanted Aman Rice (T. Aman)
3	Boro Rice
4	Wheat
5	Potato
6	Oilseeds
7	Pulses
8	Sugercane
9	Winter Vegetable
10	Summer Vegetable

Table 4.2: Month index, m, corresponding to $Env\_f(m)$.

m	Month
1	January
2	February
3	March
4	April
5	May
6	June
7	July
8	August
9	September
10	October
11	November
12	December

The population size is a sensitive issue in GA; if the size of the population (search space) is small, this means little search space is available, and therefore it is possible to reach an unwanted local optimum. Although, if the population size is very large, the area of search is increased, but the computational load becomes high (Roeva et al., 2015). Therefore, the size of the population must be reasonable. In each computation run the population size of the algorithm in this study is set at 100.

Crossover rate (probability) is the number of times a crossover occurs for chromosomes in one generation, i.e., the chance that two chromosomes exchange some of their parts, 100% crossover rate means that all offspring are made by crossover. If it is 0%, then the complete new generation of individuals is to be exactly copied from the older population, except those resulted from the mutation process. Crossover rate is in the range of [0, 1] (De Jong and Spears, 1992). The crossover rate in this study is set at 0.2.

Mutation takes place after crossover is done. Mutation rate (probability) determines how many chromosomes should be mutated in one generation. Mutation rate is in the range of [0, 1] (Lynch, 2010). In our study the mutation scaling factor is set at 1.

Number of generations refers to the number of cycles before the termination. It depends on the problem type and complexity. In this case the NSGA-II algorithm is iterated for 500 generations.

For evolutionary algorithms like GA, there are eight kinds of stopping criteria (Mathworks, 2020):

1. **Generations (iterations):** When the generation (iterations) reaches to this predefined value, it stops and provides the best solution in the last generation (iterations).
2. **Time limit:** The algorithm stops after running for an amount of time in seconds equal to Time limit.
3. **Fitness limit:** The algorithm stops when the value of the fitness function for the best point in the current population is less than or equal to Fitness limit.
4. **Stall generations:** The algorithm stops when the average relative change in the fitness function value over Stall generations is less than Function tolerance.
5. **Stall time limit:** The algorithm stops if there is no improvement in the objective function during an interval of time in seconds equal to Stall time limit.
6. **Stall test:** The stall condition is either average change or geometric weighted. For geometric weighted, the weighting function is $\frac{1}{2^n}$, where n is the number of generations prior to the current. Both stall conditions apply to the relative change in the fitness function over Stall generations.
7. **Function tolerance:** The algorithm runs until the average relative change in the fitness function value over Stall generations is less than Function tolerance.
8. **Constraint tolerance:** The Constraint tolerance is not used as stopping criterion. It is used to determine the feasibility with respect to

nonlinear constraints. Also, $max(sqrt(eps), ConstraintTolerance)$ determines feasibility with respect to linear constraints.

In this research maximum number of iterations is set for stopping criteria. Here 300, 600 and 1000 iterations are set for maximum number of iterations to compare the result. Further investigation of the effect of stopping criteria to be considered in future research.

4.2 Results and Discussion for Base Level

The multi-objective optimization problem of Equations 2.2 and 2.3 in Chapter 2 for maximizing net return (NR) and minimizing deficit in environmental flow (EFD) in the MIP in Bangladesh was solved using the parameters mentioned in Section 4.1 by the NSGA-II method. Results for different iterations and comparison are discussed next.

4.2.1 Result for 300 iterations

A first, test run has been done using 300 iterations. Here we use average rainfall data which is called base level rainfall calculated from the Table 2.1, Chapter 2, and is repeated in Table 4.3. Also we use total water inflow data which is called base level collected from Table 2.6, Chapter 2, and is given in Table 4.4 below.

Table 4.3: Rainfall data (in mm) in Muhuri Irrigation Area.

Jan	Feb	Mar	Apr	May	Jun
0	28.27	19.5	298.25	313.5	508.75

Jul	Aug	Sep	Oct	Nov	Dec
887.25	442.75	340.75	370.75	5.75	56.25

Table 4.4: Total water inflow in cubic meter.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
16.5	11.4	10.0	14.1	21.1	58.3	68.8	105.2	61.9	50.4	30.5	20.1

The Pareto optimal objective values obtained using 300 iterations are shown in Figure 4.1 and Table 4.5 shows the result. This figure presents the Pareto front obtained by NSGA-II which represents 34 non-dominated solutions for net revenue in units of 10 million Australia dollars and environmental flow deficit in units of 100 GL.

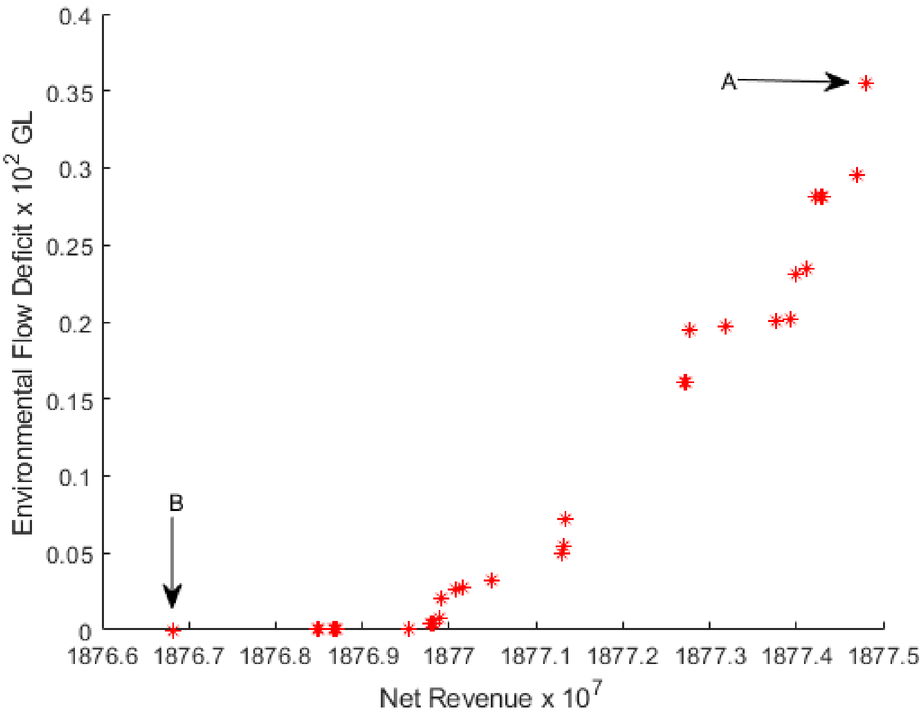


Figure 4.1: Pareto optimal solution sets for 300 iterations.

Table 4.5: Summary for 300 iterations.

Name	net return (NR)	environmental flow deficit (EFD)
Mean	1877.12×10^7AUD	10.01 GL
Standard deviation	0.23	0.12
Maximum output	1877.48×10^7 AUD	35.53 GL
Minimum output	1876.68×10^7 AUD	0.00 GL
Number of solutions	34	
Computational time	706.59 min	

In Table 4.5 a summary is given which shows the standard deviation for the NR and the EFD are 0.23 and 0.12 respectively. The maximum and minimum results for the NR are 1877.48×10^7 AUD and 1876.68×10^7 AUD respectively. The difference between these two results is 0.8×10^7 AUD. The maximum result, minimum result and the difference between these two results for the EFD are 35.53 GL, 0.00 GL and 35.53 GL respectively.

The solution of MOPs results is a set of non-dominated solutions which are Pareto optimal solutions. No solution in this set can be considered better than any other in the absence of decision maker choice. However, it is important that the decision maker chooses only one solution for final implementation. In this study, the NSGA-II algorithm gives the optimal solutions to the crop using optimal water allocation at MIP, Bangladesh. In a single simulation, NSGA-II finds quality Pareto solutions that provide trade-off between the conflicting objectives of the optimization problem.

From a analysis of all the 34 solutions (Table C.1 in Appendix C) as presented in Figure 4.1, solution 1 (A in Figure 4.1) is the best in terms of net return (NR) but worst in terms of environmental flow deficit (EFD). Whilst solution 34 (B in Figure 4.1) is the best in EFD but worst in NR. The 1st solution (A) as shown in Table C.1 in Appendix C, has the highest total net return of AUD 1877.48×10^7 with 35.53 GL EFD generated. Whereas solution 34 (B) has the lowest 0 GL EFD with AUD 1876.68×10^7 NR.

4.2.1.1 Crop Area

The cropping pattern of the 1st solution (A in Figure 4.1) of Table C.1 in Appendix C is given in Figure 4.2. Here the horizontal axis shows the different crops and the area of land measured by hectare (ha) each is given in the vertical axis.

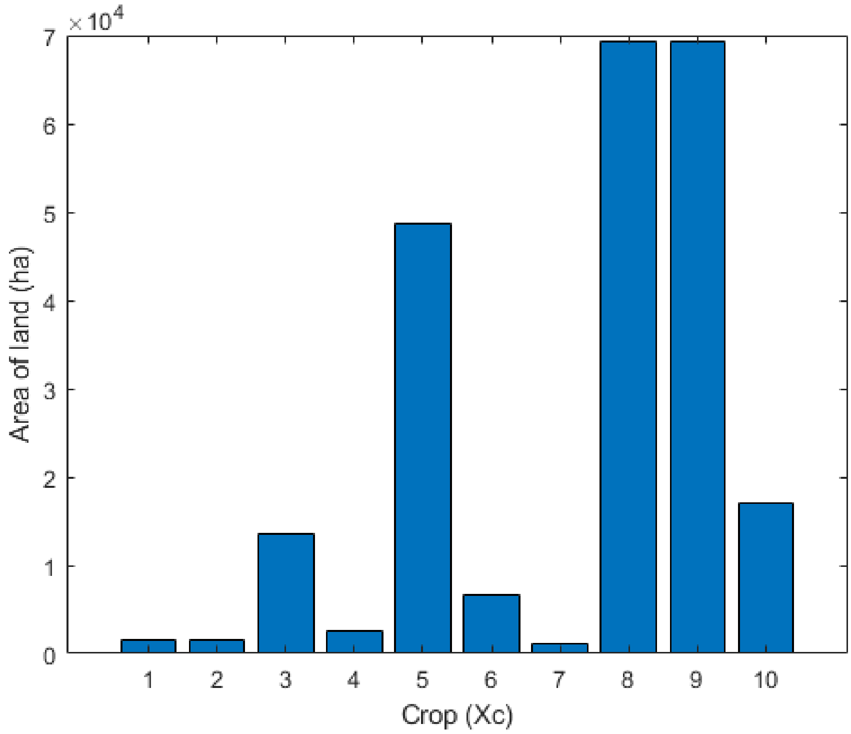


Figure 4.2: Different planting areas for the ten crops of the 1st solution in the non-dominated solutions using NSGA-II for 300 iterations.

This solution suggests that 1 (T. Aus), 2 (T. Aman), 3 (Boro Rice), 4 (Wheat), 5 (Potato), 6 (Oilseeds), 7 (Pulses), 8 (Sugarcane), 9 (Winter Vegetables), and 10 (Summer Vegetables) should be planted in 1452.18 (ha), 1516.63 (ha), 13504.46 (ha), 2555.28 (ha), 48610.52 (ha), 6567.29 (ha), 1072.37 (ha), 69228.00 (ha),69227.79 (ha) and 16982.25 (ha) areas of land respectively.

When the crop mixes of the solutions are inspected in Figure 4.2, we see that the maximum areas, 69228.00 (ha) and 69227.79 (ha), are devoted to growing Sugarcane and Winter Vegetables. The reason becomes clear as both crops are highly profitable with a yield per hectare of 50 tonnes and 16.5 tonnes delivering a gross return of AUD 4965 and AUD 435 per hectare respectively.

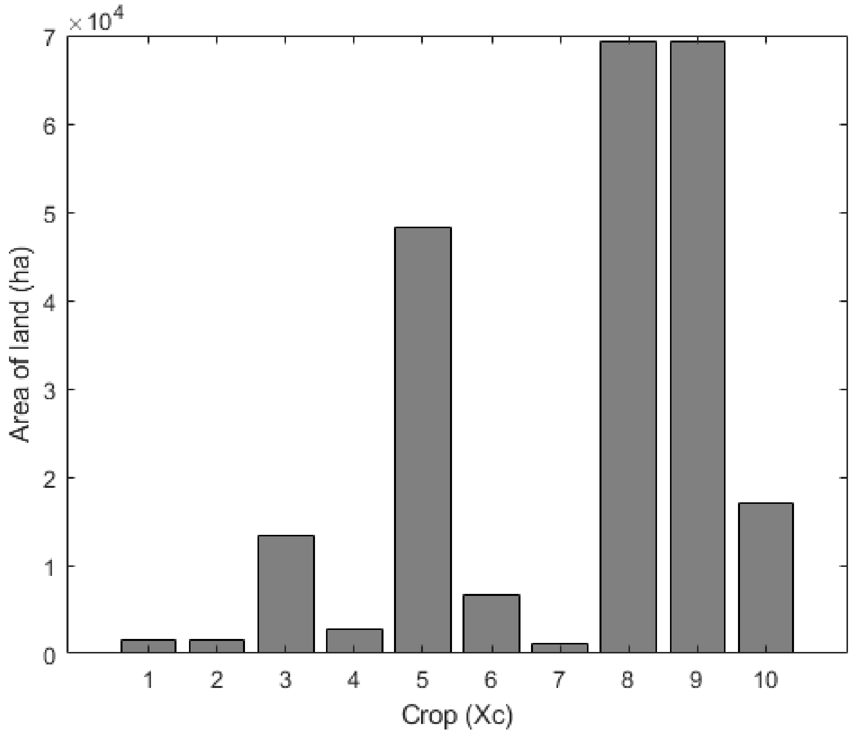


Figure 4.3: Different planting areas for the ten crops of the 34th solution in the non-dominated solutions using NSGA-II for 300 iterations.

The 34th solution as shown in Table C.2 in Appendix C, has the lowest total net return of AUD 1876.68 × 10^7 with zero GL deficit in environmental flow. The cropping pattern of the 34th solution of Table C.2 in Appendix C is given in Figure 4.3. This solution suggests that 1 (T. Aus), 2 (T. Aman), 3 (Boro Rice), 4 (Whea)t, 5 (Potato), 6 (Oilseeds), 7 (Pulses), 8 (Sugarcane), 9 (Winter Vegetables), and 10 (Summer Vegetables) should be planted in 1453.53 (ha), 1529.59 (ha), 13451.38, (ha), 2854.91 (ha), 48197.63 (ha), 6631.99 (ha), 1072.15 (ha), 69227.99 (ha), 69227.88 (ha) and 17026.76 (ha) areas of land respectively.

In Figure 4.3 we see almost same scenario as like Figure 4.2 except a few differences. According to the Table C.1 the 1st solution presents the planting area of Wheat, Potato, and Summer Vegetables are 2555.28 (ha), 48610.52 (ha), and 16982.25 (ha) respectively. But in the 34th solution of the Table C.2, a slightly different scenario is seen for planting these three crops. Here 2854.91 (ha), 48197.63 (ha),and and 17026.76 (ha) areas of land are devoting to these crops.

4.2.1.2 Environmental Flow

The environmental flow in GL of the 1st solution of Table C.1 in Appendix C is given in Figure 4.4.

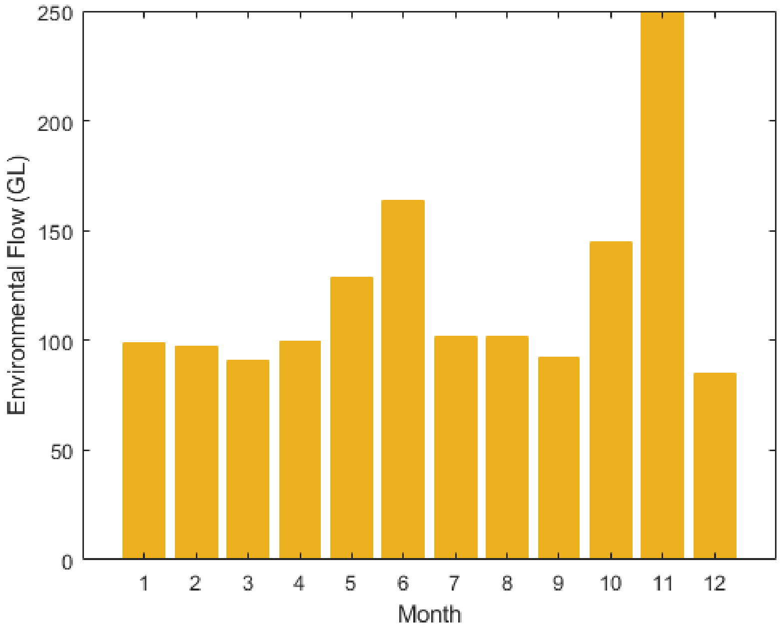


Figure 4.4: Environmental flow for a year of the 1st solution in the non-dominated solutions using NSGA-II for 300 iterations.

As is observed from the Figure 4.4, highest amount of water i.e. approximately 250 GL is required for environmental flow in the month of 11 (November). The second and third highest amount of water are needed for the months of 6 (June) and 10 (October) and their amount are approximately 164 GL and 145 GL respectively. Approximately 129 GL water is required for the month of 5 (May). Finally, in the remaining months the environmental flow almost same and near to 100 GL.

The environmental flow in GL of the 34th solution of Table C.2 in Appendix C is given in Figure 4.5.

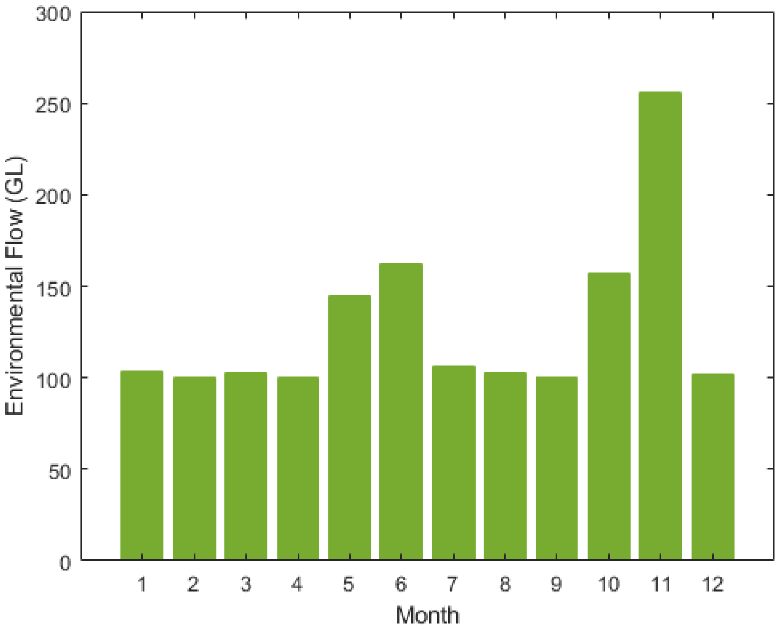


Figure 4.5: Environmental flow for a year of the 34th in the non-dominated solutions using NSGA-II for 300 iterations.

In Figure 4.5, we see a slight difference of environmental flow with the comparison of Figure 4.4 in the MIP, Bangladesh. In 11 (November), approximately 256 GL of water is needed for the environmental flow which is the highest amount of water among the other months. Approximately 162 GL and 157 GL are required for the months of 6 (June) and 10 (October) respectively. Approximately 145 Gl of water is needed for the month of 5 (May). Finally, rest of the months of the year the environmental flow almost same and approximately to 100 GL.

4.2.2 Comparison between the 1st and the 34th solutions

If a decision maker gives the priority to the net return, then solution 1 (A in Figure 4.1) in Tables C.1 and C.3 in Appendix C shown in Figures 4.2 and 4.4 are the best solution. This solution will bring the highest net return but the decision maker compromises the second objective. If an individual gives priority to the the second objective i.e. minimum environmental flow deficit, then solution 34 (B in Figure 4.1) in Table C.2 in Appendix C shown in Figures 4.3 and 4.5 are the best solution. In this situation that individual might compromise to the first objective. The difference between the highest and the lowest net return and environmental flow deficit is approximately AUD 8 million and 35.53 GL respectively.

When we compare the cropping pattern of both solutions, a big difference is observed for the crop Potato. Solution 1 suggests to cultivate approximately 48611 ha for Potato shown in Figure 4.2 whereas solution 34 suggests approximately 48198 ha shown in Figure 4.3 and the difference is 413 ha. The second highest difference is observed for the crop Wheat and the difference between solution 1 and solution 34 is 299 ha.

For the crops Boro Rice, Oilseeds and Summer Vegetables, the difference between solution 1 and solution 34 is nearly 50 ha. Other crops cultivable area almost same in both solutions.

Likewise, the cropping pattern, we see the difference between solution 1 and solution 34 for environmental flow. The highest difference is observed in the month of December. In December, approximately 85 GL water is needed for the environmental flow in solution 1 shown in Figure 4.4 and approximately 102 GL for solution 34 shown in Figure 4.5. In May and October, the environmental flow difference between solution 1 and solution 34 are 16 GL and 13 GL respectively. Other months of the year almost same in both solutions.

Here two solutions i.e. solution 1 and solution 34 are discussed. A decision maker may choose solution 1 or 34 or any other solutions from solution 1 to 34 in Tables C.1,,C.2, C.3, and C.4 in Appendix C depending on their preference.

4.2.3 Result for 600 iterations

A computation has been made using 600 iterations. The Pareto optimal objective values obtained are shown in Figure 4.6 and Table 4.6 shows the result. This figure presents the Pareto front obtained by NSGA-II which represents 15 non-dominated solutions for net revenue in units of 10 million Australia dollars and environmental flow deficit in units of 100 GL.

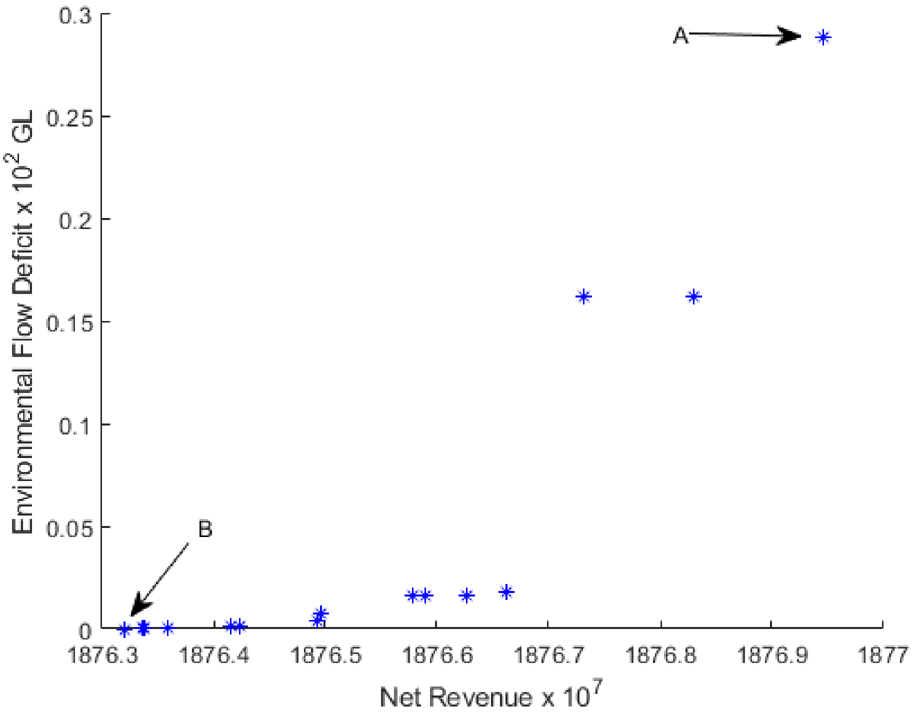


Figure 4.6: Pareto optimal solution sets for 600 iterations.

Table 4.6: Summary for 600 iterations.

Name	net return (NR)	environmental flow deficit (EFD)
Number of solutions	34	34
Mean	1876.54×10^7AUD	4.62 GL
Standard deviation	0.19	0.09
Maximum output	1876.95×10^7 AUD	28.79 GL
Minimum output	1876.32×10^7 AUD	0.00 GL
Number of solutions	15	
Computational time	1324.17 min	

Table 4.6 gives a summary of the result of a Pareto front for 600 iterations which shows the standard deviation for the NR and the EFD are 0.19 and 0.09 respectively. The maximum and minimum results for the NR are 1876.95×10^7 AUD and 1876.32×10^7 AUD respectively. The difference between these two results is 0.63×10^7 AUD. The maximum result, minimum result and the difference between these two results for the EFD are 28.79 GL, 0.00 GL and 28.79 GL respectively. These standard deviation result are smaller than 300 iteration case in Table 4.5.

4.2.3.1 Crop Area

When we analyse of all 15 solutions as presented in Figure 4.6, the 1st solution (solution A in Figure 4.6) in context of the net return, given in Table C.5 in Appendix C, has the highest total net return of AUD 1876.95×10^7 with a 28.79 GL deficit in environmental flow generated from planting the ten crops. The cropping pattern of this solution is given in Figure 4.7.

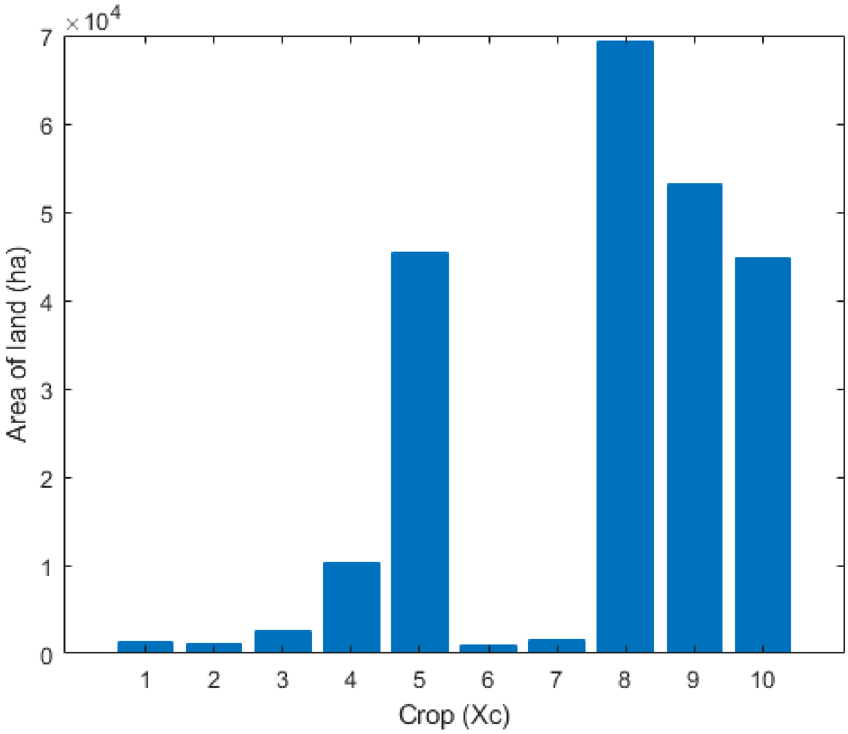


Figure 4.7: Different planting areas for the ten crops of the 1st solution in the non-dominated solutions using NSGA-II for 600 iterations.

This solution suggests that 1 (T. Aus), 2 (T. Aman), 3 (Boro Rice), 4 (Wheat, 5 (Potato), 6 (Oilseeds), 7 (Pulses), 8 (Sugarcane), 9 (Winter Vegetables), and 10 (Summer Vegetables) should be planted in 1359.34 (ha), 1187.93 (ha), 2636.32 (ha), 10391.06 (ha), 45403.72 (ha), 1011.75 (ha), 1552.23 (ha), 69228.00 (ha), 53076.28 (ha) and 44897.37 (ha) areas of land respective.

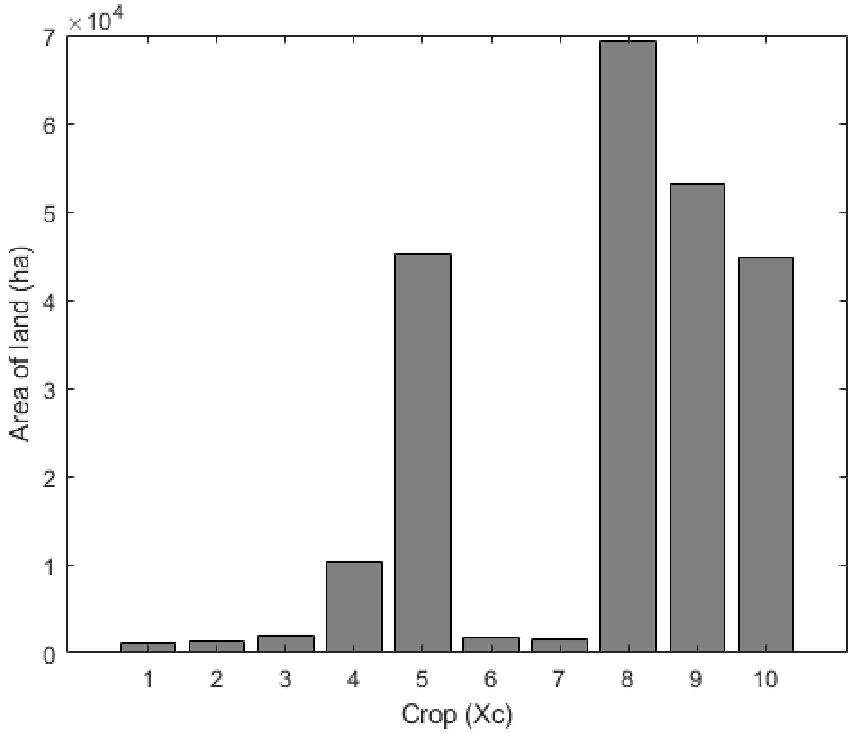


Figure 4.8: Different planting areas for the ten crops of the 15th solution in the non-dominated solutions using NSGA-II for 600 iterations.

The 15th solution (solution B in Figure 4.6) given in Table C.5 in Appendix C, has the lowest EFD of 0 GL with AUD 1876.32 × 10^7 NR. The cropping pattern of the 15th solution of Table C.5 in Appendix C is given in Figure 4.8.

This solution suggests that 1 (T. Aus), 2 (T. Aman), 3 (Boro Rice), 4 (Wheat, 5 (Potato), 6 (Oilseeds), 7 (Pulses), 8 (Sugarcane), 9 (Winter Vegetables), and 10 (Summer Vegetables) should be planted in 1192.14 (ha), 1330.56 (ha), 1913.86 (ha), 10375.42 (ha), 45214.20 (ha), 1772.70 (ha), 1561.83 (ha), 69227.91 (ha), 53252.31 (ha) and 44852.63 (ha) areas of land respective.

When we compare Figures 4.7 and 4.8, a significant difference is shown for two crops namely 3 (Boro Rice) and 4 (Wheat). In the 1st solution (Table C.5 in Appendix C), 2636.32 (ha) area is cultivated for 3 (Boro Rice) whereas in the 15th solution this figure is decreased to 1913.86 (ha). On the other hand, 1011.75 (ha) area is cultivated for 4 (Wheat) in solution 1 and this figure is increased to 1772.70 (ha) in solution 15. The least difference between solution 1 and solution 15 for the crops T. Aus, T. Aman, and Potato exists on Table C.6 in Appendix C. Other crops are almost same in both solutions.

4.2.3.2 Environmental Flow

The environmental flow in GL of the 1st (A in Figure 4.6) and 15th (B in Figure 4.6) solutions (see Table C.6 in Appendix C) are given in Figures 4.9 and 4.10 respectively.

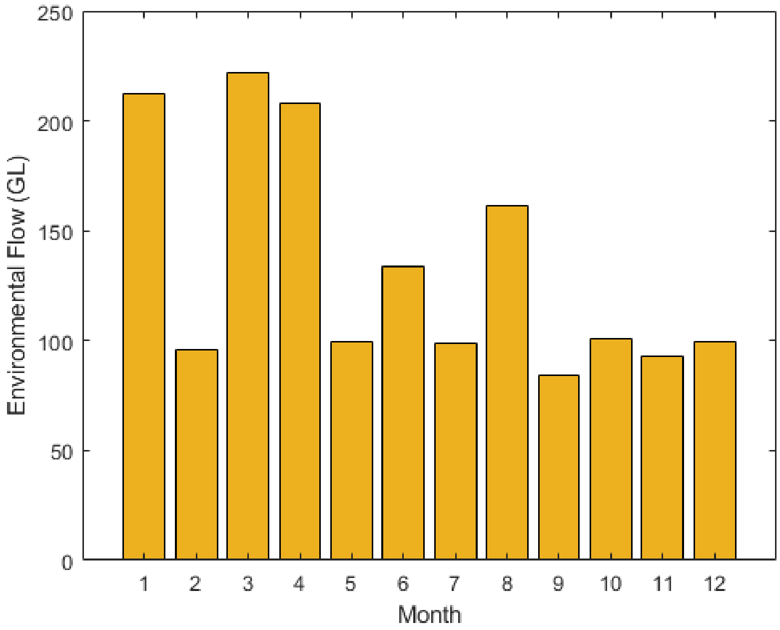


Figure 4.9: Environmental flow for a year of the 1st solution in the non-dominated solutions using NSGA-II for 600 iterations.

According to the Figures 4.9 and 4.10, we see that the highest environmental flow difference in both solutions is 18 GL in the month of 9 (September). The environmental flow difference in 1 (January), 2 (February), 3 (March), and 11 (November) are 13 GL, 10 GL, 13 GL, and 14 GL respectively. There is no significant difference of environmental flow between these two figures in the rest of the months.

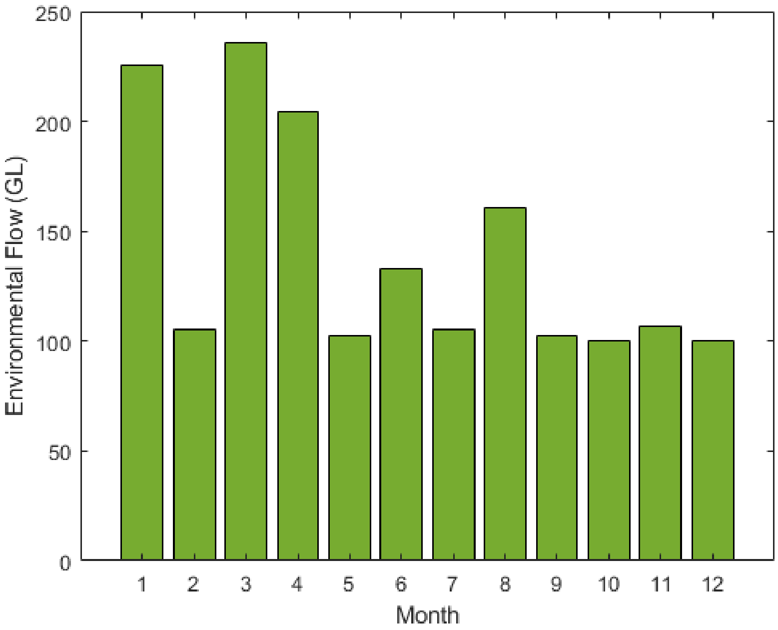


Figure 4.10: Environmental flow for a year of the 15th solution in the non-dominated solutions using NSGA-II for 600 iterations.

4.2.4 Comparison between the 1st and the 15th solution

Like the comparison is given in Section 4.2.2, if a decision maker gives the priority to the net return, then solution A in Figure 4.6 (solution 1 in Table C.5 in Appendix C) is the best solution. This solution will bring the highest net return but the decision maker might compromise to the second objective. If an individual gives priority to the the second objective i.e. minimum environmental flow deficit, then solution B in Figure 4.6 (solution 15 in Table C.5 in Appendix C) is the best solution. In this situation that individual might compromise to the first objective. The difference between the highest and the lowest net return and environmental flow deficit is approximately AUD 6 million and 28.79 GL respectively. In this comparison, an individual is free to choose any solution from 1 (A) to 15 (B) in Table C.5 in Appendix C according to his priority.

4.2.5 Result for 1000 iterations

The computational experiments were repeated, maintaining the same targets for environmental flow and using 100 trial solutions and 1000 iterations. The

Pareto optimal objective values obtained are shown in Figure 4.11 and Table 4.7 shows the result. This figure presents the Pareto front obtained by NSGA-II which represents 20 non-dominated solutions for net revenue in units of 10 million Australia dollar and environmental flow deficit in units of 100 GL.

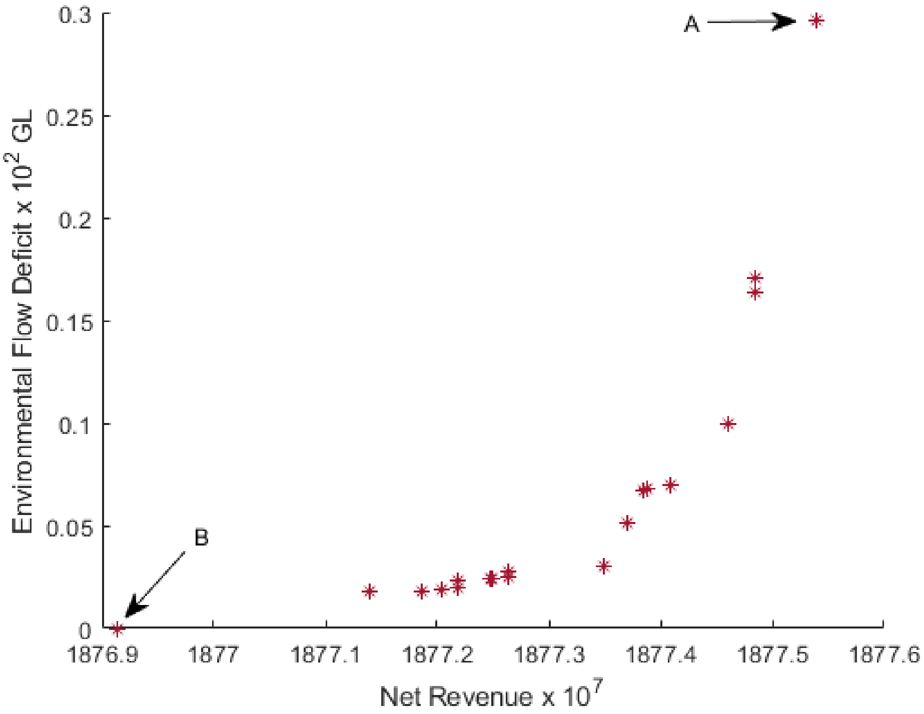


Figure 4.11: Pareto optimal solution sets for 1000 iterations.

Table 4.7: Summary for 1000 iterations.

Name	net return (NR)	environmental flow deficit (EFD)
Mean	1877.30×10^7AUD	6.19 GL
Standard deviation	0.15	0.07
Maximum output	1877.54×10^7 AUD	29.57 GL
Minimum output	1876.91×10^7 AUD	0.00 GL
Number of solutions	20	
Computational time	2610.44 min	

In Table 4.7 a summary is given for 1000 iterations which shows the standard deviation for the NR and the EFD are 0.15 and 0.07 respectively. The maximum and minimum results for the NR are 1877.54×10^7 AUD and 1876.91×10^7 AUD respectively. The difference between these two results is 0.63×10^7 AUD. The maximum result, minimum result and the difference between these two results for the EFD are 29.57 GL, 0.00 GL and 29.57 GL respectively. These standard deviation results are again smaller than 600 iteration case in Table 4.6.

4.2.5.1 Crop Area

From the analysis of all the 20 solutions as presented in Figure 4.11, 1st solution (A in Figure 4.11 also given Table C.7 in Appendix C), has the highest total net benefit of AUD 1877.54 × 10^7 with a 29.57 GL deficit in environmental flow generated from planting the ten crops as shown in Figure 4.12.

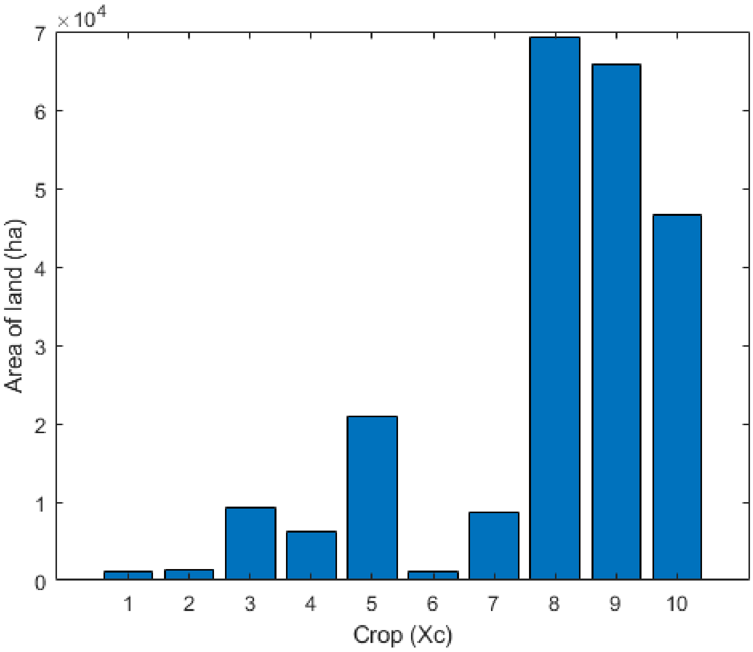


Figure 4.12: Different planting areas for the ten crops of the 1st solution in the non-dominated solutions using NSGA-II for 1000 iterations.

This solution suggests that 1 (T. Aus), 2 (T. Aman), 3 (Boro Rice), 4 (Wheat, 5 (Potato), 6 (Oilseeds), 7 (Pulses), 8 (Sugarcane), 9 (Winter Vegetables), and 10 (Summer Vegetables) should be planted in 1261.46 (ha), 1382.83 (ha), 9240.16 (ha), 5995.73 (ha), 20937.04 (ha), 1343.26 (ha), 8744.62 (ha), 69227.86 (ha), 65708.28 (ha) and 46573.34 (ha) areas of land respectively.

The 20th solution (B in Figure 4.11 also given in Table C.7 in Appendix C), has the lowest EFD of 0 GL with AUD 1876.91×10^7 NR. The cropping pattern of the 20th solution (Table C.5 in Appendix C) is given in Figure 4.13.

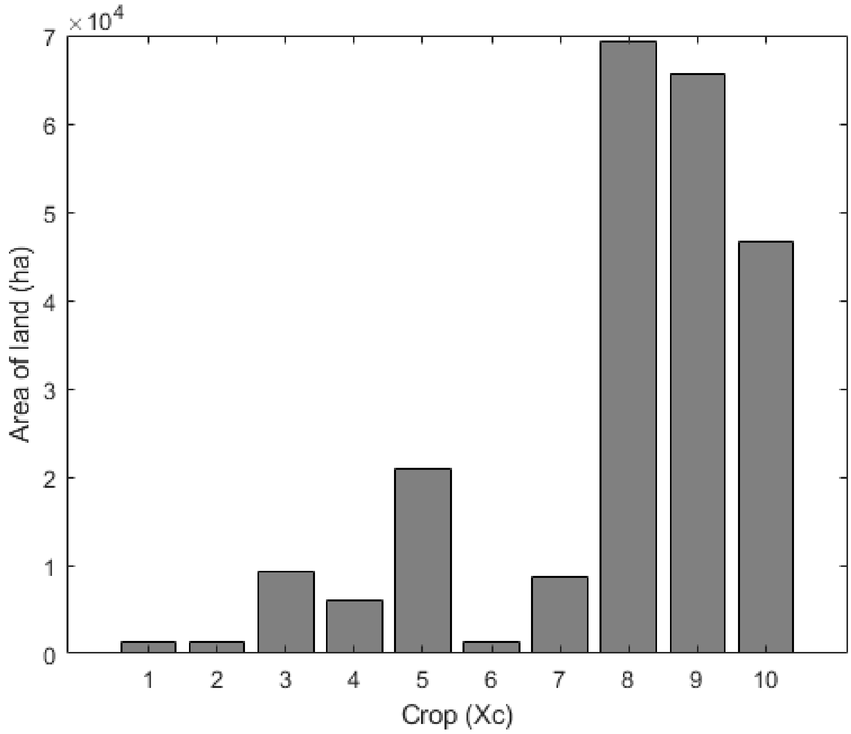


Figure 4.13: Different planting areas for the ten crops of the 20th solution in the non-dominated solutions using NSGA-II for 1000 iterations.

This solution suggests that 1 (T. Aus), 2 (T. Aman), 3 (Boro Rice), 4 (Wheat, 5 (Potato), 6 (Oilseeds), 7 (Pulses), 8 (Sugarcane), 9 (Winter Vegetables), and 10 (Summer Vegetables) should be planted in 1261.46 (ha), 1382.83 (ha), 9240.16 (ha), 5995.73 (ha), 20937.04 (ha), 1343.26 (ha), 8744.62 (ha), 69227.86 (ha), 65708.28 (ha) and 46573.34 (ha) areas of land respective.

From Figures 4.12 and 4.13, we see a substantial difference between solution 1 and solution 20 on cultivating the crops 4 (Wheat) and 1 (T. Aus). In solution 1, approximately 6250 ha and 1067 areas of land are devoted for cultivating 4 (Wheat) and 1 (T. Aus) respectively. On the other hand in solution 20, these areas are approximately 5996 ha and 1261 ha. For the crops 3 (Boro Rice), 6 (Oilseeds), and 9 (Winter Vegetable) the difference between solutions 1 and 20 is nearly 140 ha. The cultivable areas for other crops are almost same.

4.2.5.2 Environmental Flow

The environmental flow of the 1st (A) and 20th (B) solutions in context of the net return (Table C.8 in Appendix C) are given in Figures 4.14 and 4.15 respectively.

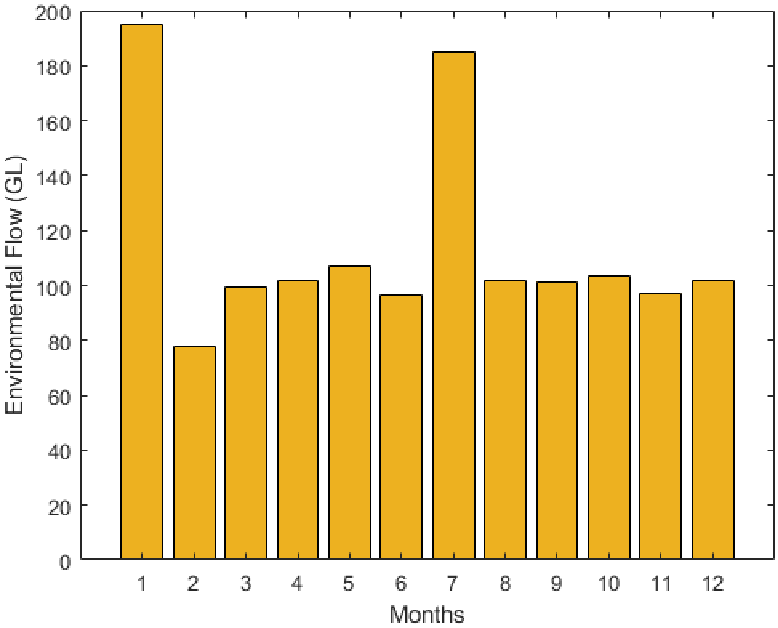


Figure 4.14: Environmental flow for a year in the non-dominated solutions using NSGA-II for 1000 iterations.

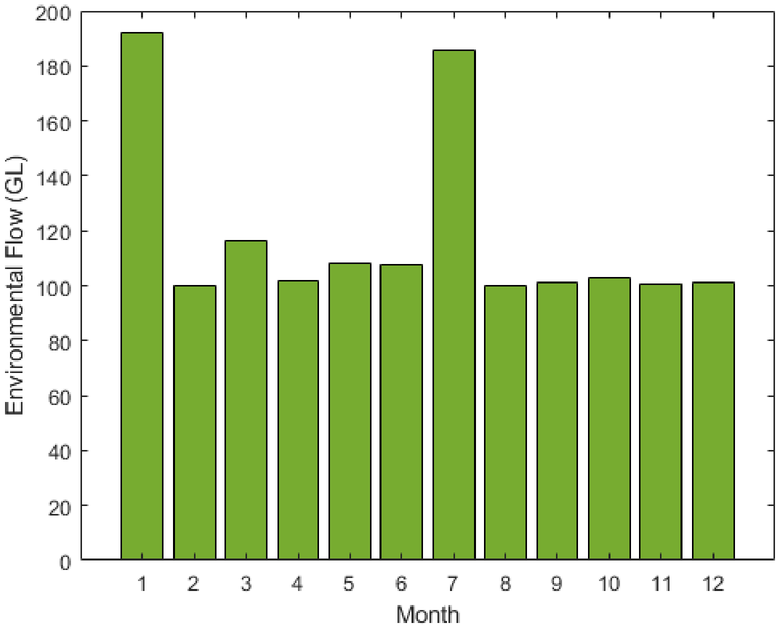


Figure 4.15: Environmental flow for a year in the non-dominated solutions using NSGA-II for 1000 iterations.

As is observed from the Figures 4.14 and 4.15, the environmental flow for the months of 1(January) and 7 (July) are higher than all other months. In Figure 4.14, the environmental flow for 1 (January) and 7 (July) are approximately 195 GL and 185 GL respectively. These results come to about 192 GL and 186 GL in Figure 4.15. Among the remaining months, except for 2 (February) and 3 (March) the environmental flows are approximately the same and this value is nearly 100 GL. However, the highest difference is observed between two solutions in 2 (February) and amounting approximately 33 GL. The environmental flow for the month of 3 (March) in solution 1 is approximately 100 GL and in solution 20 is about 116 GL.

4.2.6 Comparison between the 1st and the 20th solution

Here the comparison is between the solution A and B in Figure 4.11. If a decision maker gives the priority to the net return, then solution 1 (A in Figure 4.11 also Table C.7 in Appendix C) is the best solution. If an individual gives priority to the the second objective i.e. minimum environmental flow deficit, then solution 20th (B in Figure 4.11 also Table C.7 in Appendix C) is the best solution. The difference between the highest and the lowest net return and environmental flow deficit is approximately AUD 6.2 million and 29.57 GL respectively. Here we also see that the decision maker has the same scope to choose any solution from 1(A) to 20 (B) in Table C.7 in Appendix C depending on their priority.

A simulation run of the algorithm for 1500 iterations was attempted. Unfortunately, the algorithm failed complete processing due to insufficient memory being available. The simulations in this thesis was conducted on a Windows 10 laptop with 8 GB RAM running a 1.60 GHz Intel(R) Core (TM) i5-8250U CPU.

4.2.7 Comparison between 300, 600, and 1000 iterations cases

The results for three Pareto front curves are plotted together in Figure 4.16. Means and standard deviations for the first and the second objectives are given in Tables 4.8 and 4.9 respectively. According to the Figure 4.16 the Pareto curve for 1000 iterations is smooth, but the Pareto curves for 300 and 600 iterations are not smooth as like as the others. These three Pareto fronts suggest that the Pareto curve of 1000 iterations is better convergent than the others.

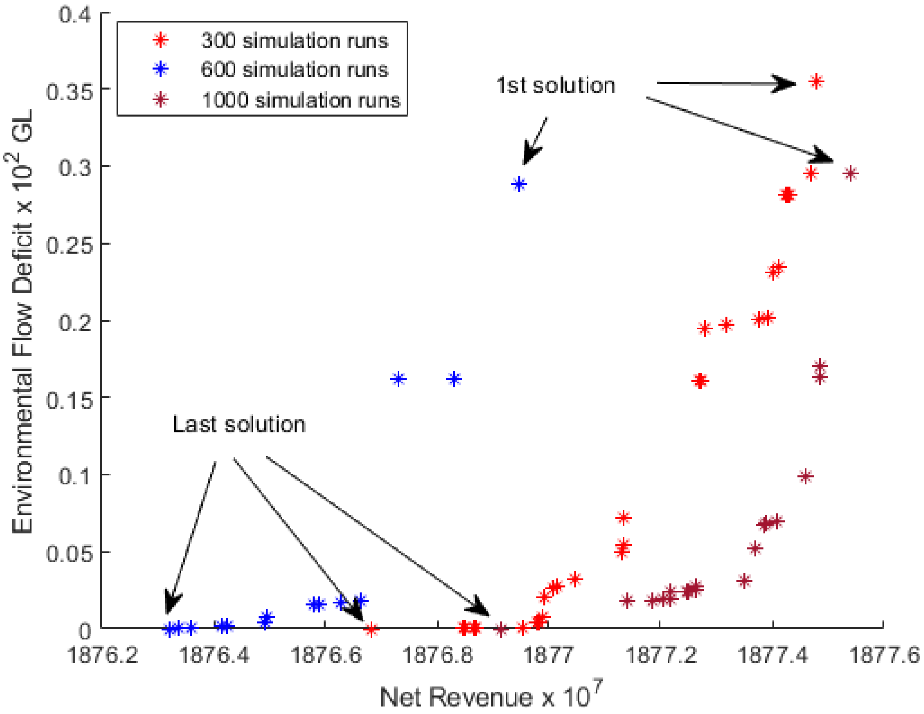


Figure 4.16: Comparison of the Pareto optimal solution sets of different number of runs scenarios.

Tables 4.8 and 4.9 show a comparison results of the mean and the standard deviation of first and second objectives for 300, 600, and 1000 iterations.

Table 4.8: Comparison between the means and the standard deviations for the first objective in different number of iterations.

Name	300 iterations	600 iterations	1000 iterations
Mean	1877.12×10^7AUD	1876.54×10^7AUD	1877.30×10^7AUD
SD	0.23	0.19	0.15

Table 4.9: Comparison between the means and the standard deviations for the second objective in different number of iterations.

Name	300 iterations	600 iterations	1000 iterations
Mean	10.01 GL	4.62 GL	6.19 GL
SD	0.12	0.09	0.07

According to the Tables 4.8 and 4.9, when the number of iterations is increased, the standard deviation decreases, and the result becomes more robust.

Difference of NR and EFD for the 1st solution in context of net return of different number of iterations are given in Table 4.10.

Table 4.10: Comparison between two objective functions in different number of iterations for the 1st ranked solution.

Objective functions	300 iterations	600 iterations	1000 iterations
NR	18774797761.40	18769459470.8940	18775397073.16
EFD	35.53	28.79	29.57

From the Tables 4.10 we see that the highest net return comes from 1000 iterations and amount is AUD 18775397073.16. However, for the second objective the lowest result comes from 600 iterations and amount is 28.79 GL.

Difference of NR and EFD for the last solution in context of net return of different number of iterations are given in Table 4.11.

Table 4.11: Comparison between two objective functions in different number of iterations for the last ranked solution.

Objective functions	300 iterations	600 iterations	1000 iterations
NR	18766823891.0216	18763200712.6931	18769130197.81
EFD	0.00	0.00	0.00

According to the Table 4.11, we see the same scenario as like Table 4.10 for net return. But the second objective is zero for all three cases.

Among all three iterations, 1000 iterations gives the better result for the first objective and 600 iterations gives the better result for second objective.

4.2.7.1 Comparison between crops pattern for 300, 600, and 1000 iterations cases

The comparison between crops pattern for 1st solutions in context of net return for 300, 600, and 1000 iterations is given in the Figure 4.17.

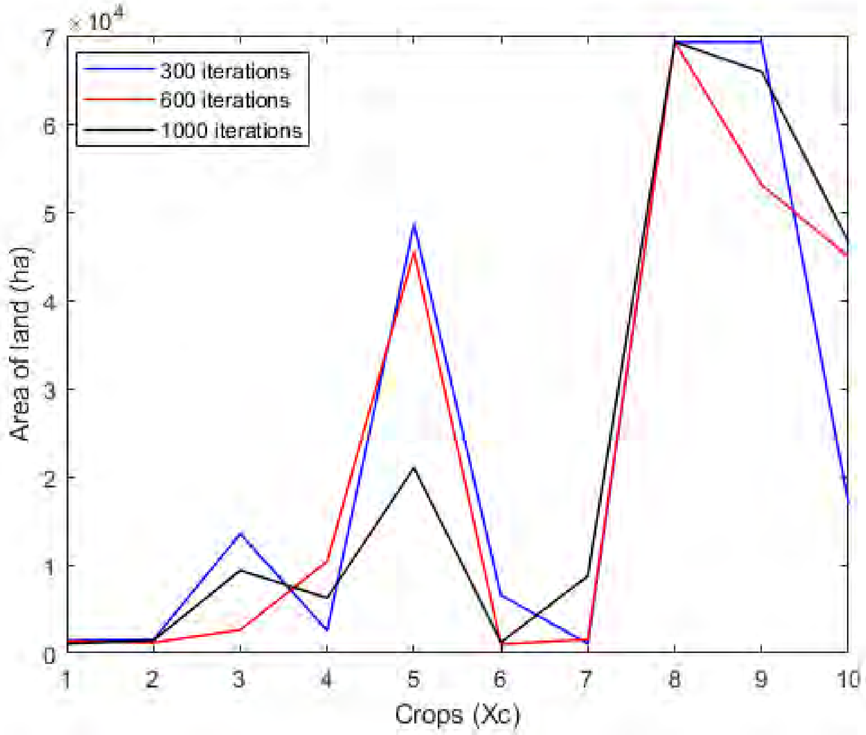


Figure 4.17: comparison between crops pattern for 1st solutions in context of net return for 300, 600, and 1000 iterations.

According to the illustration, area of land for cultivating (1) T. Aus, (2) T. Aman, and (9) Winter Vegetables are same for all three iterations. However, the biggest difference is observed for the crops of Potato and Summer Vegetables. Approximately 48611 ha and 45404 ha areas are suggesting to cultivate Potato in 300 and 600 simulation respectively. Whereas 1000 simulation suggests to cultivate approximately 20997 ha. But opposite scenario is seen for cultivating Summer Vegetables. These amount are approximately 46563 ha, 44897 ha, and 16982 ha for 1000, 600, and 300 simulations respectively. Almost the same scenario is found for the other crops with a little variation. The 1000 simulation solution has the best NR compare other cases but this could because it has converged fully.

The comparison between crops pattern for last solutions in context of net return for 300, 600, and 1000 iterations is given in the Figure 4.18.

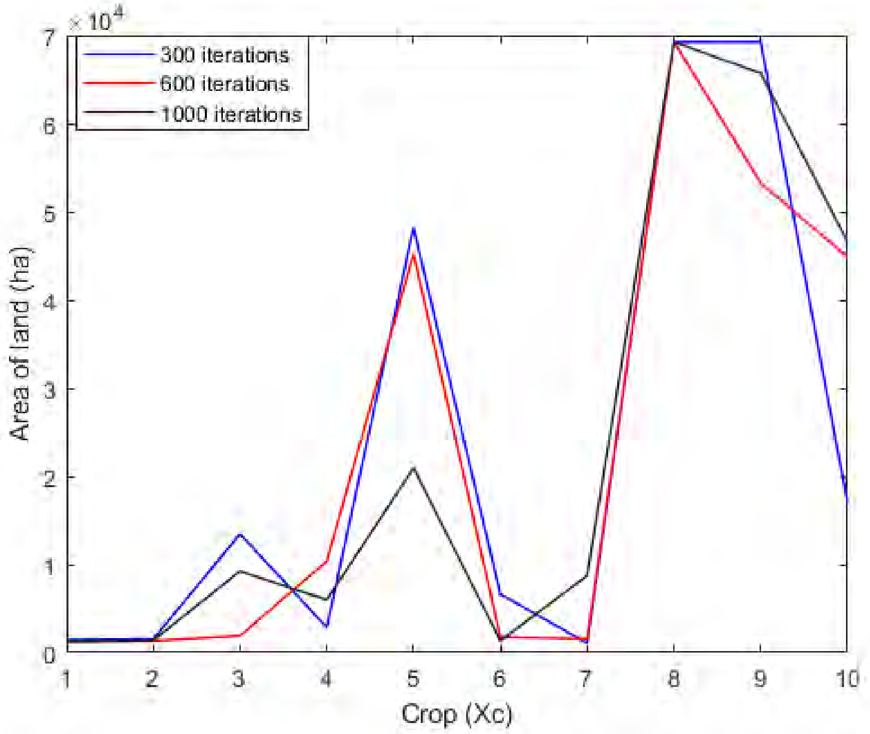


Figure 4.18: comparison between crops pattern for last solutions in context of net return for 300, 600, and 1000 iterations.

Similar to Figure 4.17, we see the same scenario with slight differences in Figure 4.18. Here, approximately 48198 ha and 45214 ha are suggesting to cultivate Potato in 300 and 600 iterations respectively. But in 1000 iterations this area is nearly 20937 ha.

For Summer Vegetables, this figure is suggesting to cultivate approximately 46573 ha, 44853 ha, and 17027 ha areas for 1000, 600, and 300 iterations respectively. is more profitable.

4.2.7.2 Comparison between environmental flow for 300, 600, and 1000 iterations

The comparison between environmental flow for 1st solutions in context of net return for 300, 600, and 1000 iterations is given in the Figure 4.19.

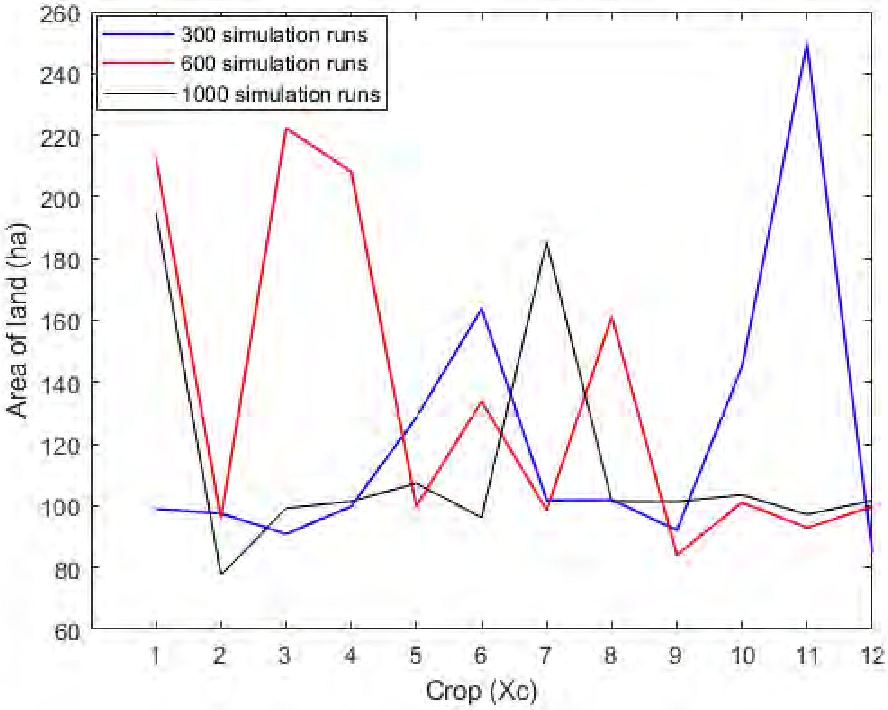


Figure 4.19: comparison between environmental flow for 1st solutions in context of net return for 300, 600, and 1000 iterations.

As is observed from the Figure 4.19, the highest environmental flow required, in the case of 300 iterations is for the month of 11 (November) and the amount is about 250 GL for 300 iterations. But in the 600 and 1000 iterations cases this amount decreased to approximately 93 GL and 97 GL. Opposite scenario is seen for the month of January. In January, about 99 GL water is required for the environmental flow for 300 iterations. This amount increased to approximately 195 GL and 212 GL for 1000 and 600 simulations runs. Surprisingly, in March and April nearly 222 GL and 208 GL water are required for the environmental flow for 600 iterations. On the other hand in these two months nearly 100 GL is needed for 300 and 1000 iterations. However, from May to August the differences are smaller but still vary for the three cases. Total approximately 1455 GL, 1610 GL, and 1368 GL water are required for the whole year for 300, 600, and 1000 simulations respectively. These three simulations show that the result come from 1000 simulations is better than the other two.

The comparison between environmental flow for last solutions in context of net return for 300, 600, and 1000 iterations is given in the Figure 4.20.

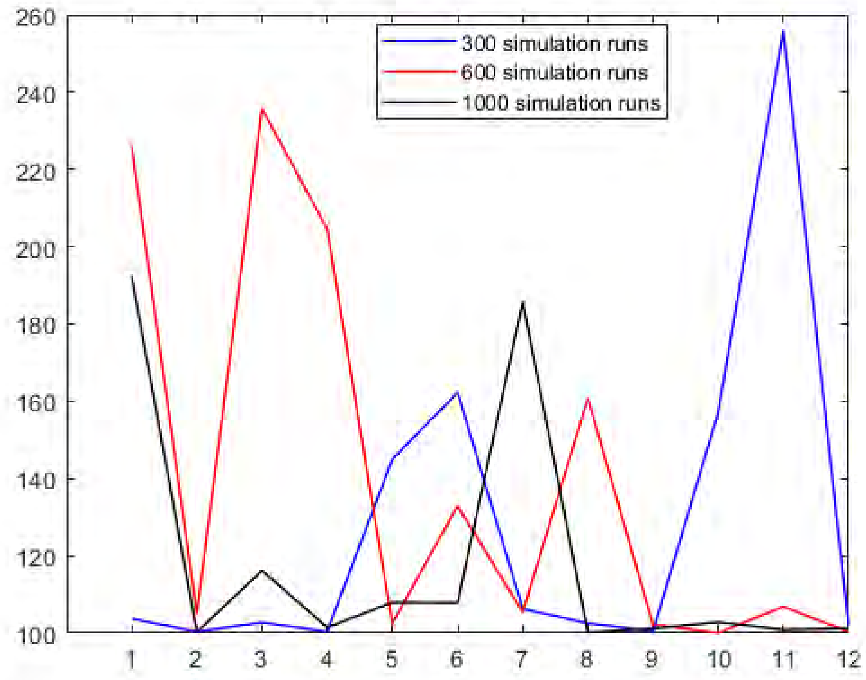


Figure 4.20: comparison between crops pattern for last solutions in context of net return for 300, 600, and 1000 iterations.

Almost same scenario is seen in Figure 4.20 with a little variation. Total approximately 1539 GL, 1682 GL, and 1418 GL water are required for the whole year for 300, 600, and 1000 simulations respectively.

After getting this difference in results we have run the program for 2000 simulation. Unfortunately, after eight straight days of running, the program was abruptly stopped, the reason being the computer storage was full.

4.3 Effect of rainfall

The results for five Pareto front curves when rainfall is varied by 10% and 20% less and by 10% and 20% more from the base level using 300 iterations is shown in Figure 4.21. The corresponding related data used is given in Table 4.12.

Table 4.12: Rainfall data in mm.

Base level rainfall	Jan	Feb	Mar	Apr	May	Jun
	0.00	28.27	19.5	298.25	313.50	508.75
	Jul	Aug	Sep	Oct	Nov	Dec
	887.25	442.75	340.75	370.75	5.75	56.25
10% less rainfall	Jan	Feb	Mar	Apr	May	Jun
	0.00	25.44	17.55	268.43	282.15	457.88
	Jul	Aug	Sep	Oct	Nov	Dec
	798.53	398.48	306.68	333.68	5.18	50.63
10% more rainfall	Jan	Feb	Mar	Apr	May	Jun
	0.00	31.1	21.45	328.07	377.66	559.62
	Jul	Aug	Sep	Oct	Nov	Dec
	975.98	487.03	374.83	407.83	6.33	61.88
20% less rainfall	Jan	Feb	Mar	Apr	May	Jun
	0.00	22.62	15.50	238.60	250.80	407.00
	Jul	Aug	Sep	Oct	Nov	Dec
	709.80	354.20	340.72	296.60	4.60	45.00
20% more rainfall	Jan	Feb	Mar	Apr	May	Jun
	0.00	33.92	23.40	357.90	376.20	610.50
	Jul	Aug	Sep	Oct	Nov	Dec
	1064.70	531.30	408.90	444.90	6.90	67.50

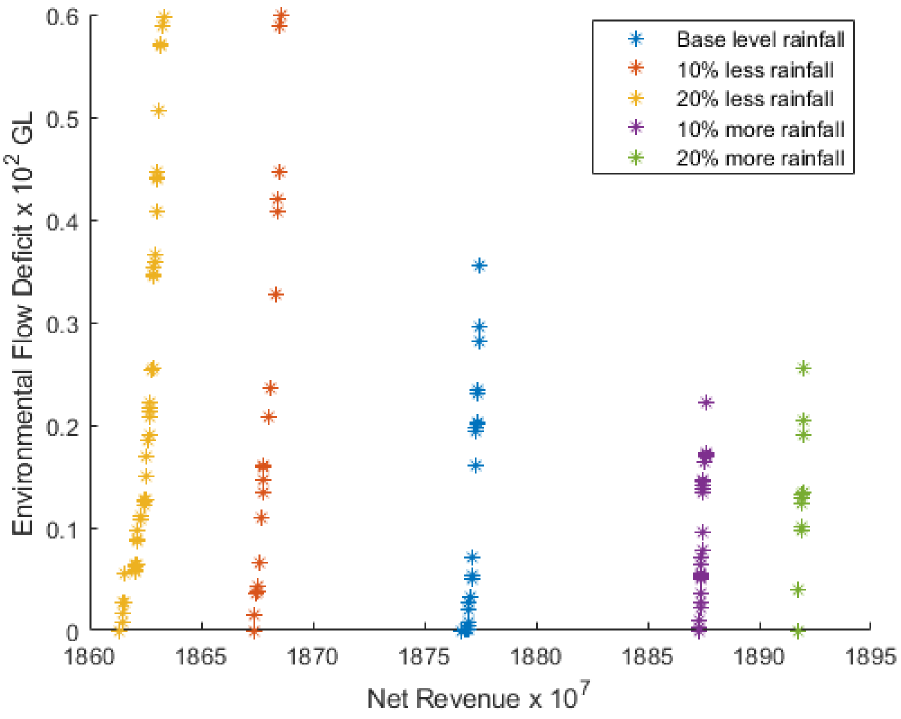


Figure 4.21: Compare Pareto optimal solution sets of different rainfall.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when rainfall is less than 10% from the base level is given in Table 4.13.

Table 4.13: Compare different objective functions value, when rain is less than 10%.

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Objective functions	Base level rain	10% less rain	Absolute difference	Percentage
NR (AUD)	18774797761.40	18685988940.82	-88808820.58	-0.47
EFD (GL)	35.53	59.87	24.34	67.95

The Table 4.13 illustrates that if rainfall is 10% less from the base level NR will decrease 0.47% and EFD will increase 67.95%.

The result of two objective functions for the last solution in context of net return for 300 iterations when rainfall is less than 10% from the base level is given in Table 4.14.

Table 4.14: Compare different objective functions value, when rain is less than 10%.

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Objective functions	Base level rain	10% less rain	Absolute difference	Percentage
NR (AUD)	18766823891.02	18673563546.99	-93260344.03	-0.50
EFD (GL)	0.00	0.00	0.00	0.00

The Table 4.14 presents that if rainfall is 10% less from the base level NR will decrease 0.50% but there is no effect on EFD.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when rainfall is more than 10% from the base level is given in Table 4.15.

Table 4.15: Compare different objective functions value, when rain is more than 10%.

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Objective functions	Base level rain	10% more rain	Absolute difference	Percentage
NR	18774797761.40	18876308314.66	101510553.26	0.54
EFD	35.53	22.16	-24.14	-37.63

The Table 4.15 presents that if rainfall is 10% more than from the base level NR will increase 0.54% and EFD will decrease 37.63%.

The result of two objective functions for the last solution in context of net return for 300 iterations when rainfall is more than 10% from the base level is given in Table 4.16.

Table 4.16: Compare different objective functions value, when rain is more than 10%.

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Objective functions	Base level rain	10% more rain	Absolute difference	Percentage
NR	18774797761.40	18873152942.53	98355181.13	0.52
EFD	0.00	0.00	0.00	0.00

The Table 4.16 provides that if rainfall is 10% more than from the base level NR will increase 0.52% but there is no effect on EFD for the last solution.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when rainfall is less than 20% from the base level is given in Table 4.17.

Table 4.17: Compare different objective functions value, when rain is less than 20%.

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Objective functions	Base level rain	20% less rain	Absolute difference	Percentage
NR	18774797761.40	18633144666.23	-141,653,095.16	-0.76
EFD	35.53	59.68	24.14	67.95

The Table 4.17 presents that if rainfall is 20% less from the base level NR will decrease 0.74% and EFD will increase 67.95%.

The result of two objective functions for the last solution in context of net return for 300 iterations when rainfall is less 20% from the base level is given in Table 4.18.

Table 4.18: Compare different objective functions value, when rain is less than 20%.

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Objective functions	Base level rain	20% less rain	Absolute difference	Percentage
NR	18774797761.40	18613406027.31	-161391734.09	-0.86
EFD	0.00	00.00	0.00	0.00

The Table 4.18 provides that if rainfall is 20% less from the base level NR will decrease 0.86% but there is no effect on EFD for the last solution.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when rainfall is more than 20% from the base level is given in Table 4.19.

Table 4.19: Compare different objective functions value, when rain is more than 20%.

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Objective functions	Base level rain	20% more rain	Absolute difference	Percentage
NR	18774797761.40	18920005078.14	145207316.74	0.77
EFD	35.53	25.52	-10.01	-28.17

The Table 4.19 illustrates that if rainfall is 20% more than from the base level NR will increase 0.77% and EFD will decrease 28.27%.

The result of two objective functions for the last solution in context of net return for 300 iterations when rainfall is more than 20% from the base level is given in Table 4.20.

Table 4.20: Compare different objective functions value, when rain is more than 20%.

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Objective functions	Base level rain	20% more rain	Difference	Percentage
NR	18774797761.40	18917167845.36	142370083.96	0.76
EFD	0.00	00.00	0.00	0.00

The Table 4.20 shows that if rainfall is 20% more than from the base level NR will increase 0.76% but there is no effect on EFD for the last solution.

4.3.0.1 Comparison of crops pattern for different rainfall

The comparison of crops pattern for 1st solutions in context of net return for different rainfall using 300 iterations is given in the Figure 4.22.

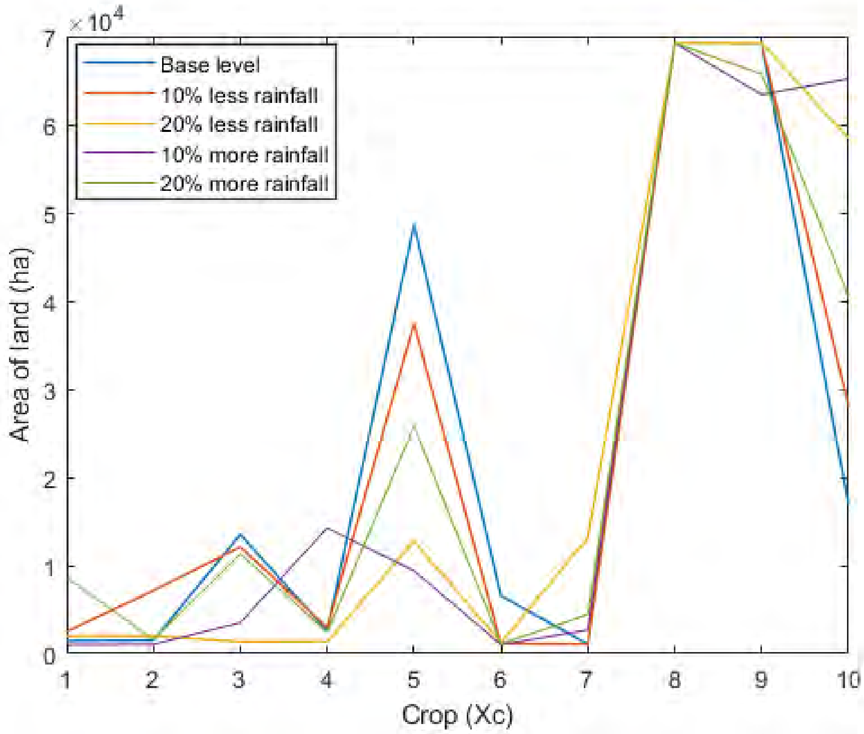

Figure 4.22: comparison of crops pattern for different rainfall.

According to the Figure 4.22, the area of land for cultivating 8 (Sugercane) is same for all five conditions and amount is approximately 69228 ha. However a biggest difference is observed for the crops of 5 (Potato) and 10 (Summer Vegetables). In base level rainfall, we see the highest amount of land is devoted for cultivating the crop 5 (Potato) but opposite scenario is seen for the crop 10 (Summer Vegetables). When rainfall decreases or increases, the cultivation of crop 5 (Potato) always decreases but opposite matter is happened for the crop 10 (Sugercane). For other crops the differences are smaller but still vary.

4.3.0.2 Comparison between environmental flow for different rainfall

The comparison between environmental flow for 1st solutions in context of net return for different rainfall using 300 iterations is given in the Figure 4.23.

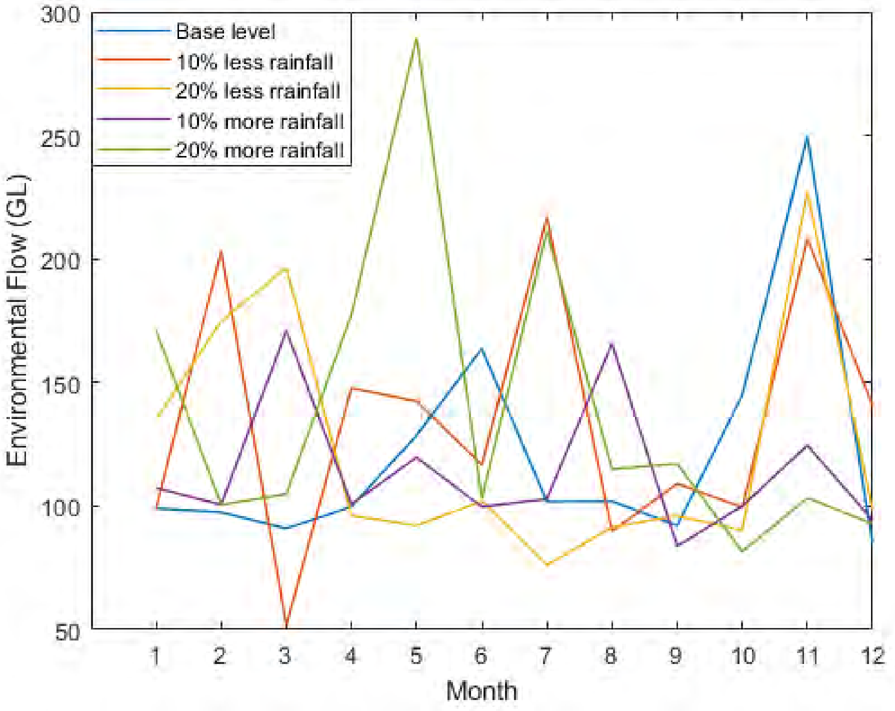

Figure 4.23: comparison between environmental flow for different rainfall.

As is observed from the Figure 4.23, when rainfall is 20% more than from the base level the highest environmental flow is required for the month of 5 (May) and amount is approximately 290 GL. On the other hand the lowest environmental flow is needed for the month of 3 (March) when rainfall is 10% less from the base level and amount is about 50 GL.

In the light of above discussion, It can be argued that, if it rains more, the profit will be more and the cost of irrigation and water supply for environmental flow will decrease.

4.4 Effect of water inflow

The results for five Pareto front curves when water inflow is less and more by 10% and less and more by 20% (Table 4.21) from the base level using 300 iterations is shown in Figure 4.24.

Table 4.21: water inflow data in cubic meter.

Base level water inflow	Jan	Feb	Mar	Apr	May	Jun
	16.50	11.40	10.00	14.10	21.10	58.30
	Jul	Aug	Sep	Oct	Nov	Dec
	68.80	105.20	61.90	50.40	30.50	20.10
10% less water inflow	Jan	Feb	Mar	Apr	May	Jun
	14.85	10.26	9.00	12.69	18.99	52.47
	Jul	Aug	Sep	Oct	Nov	Dec
	61.92	94.68	55.71	45.36	27.45	18.09
10% more water inflow	Jan	Feb	Mar	Apr	May	Jun
	18.15	12.54	11.00	15.51	23.21	64.13
	Jul	Aug	Sep	Oct	Nov	Dec
	75.68	115.72	68.09	55.44	33.55	22.11
20% less water inflow	Jan	Feb	Mar	Apr	May	Jun
	13.20	9.12	8.00	11.28	16.88	46.64
	Jul	Aug	Sep	Oct	Nov	Dec
	55.04	84.16	49.52	40.32	24.40	16.08
20% more water inflow	Jan	Feb	Mar	Apr	May	Jun
	19.80	13.68	12.00	16.92	25.32	69.96
	Jul	Aug	Sep	Oct	Nov	Dec
	82.56	126.24	74.28	60.48	36.60	24.12

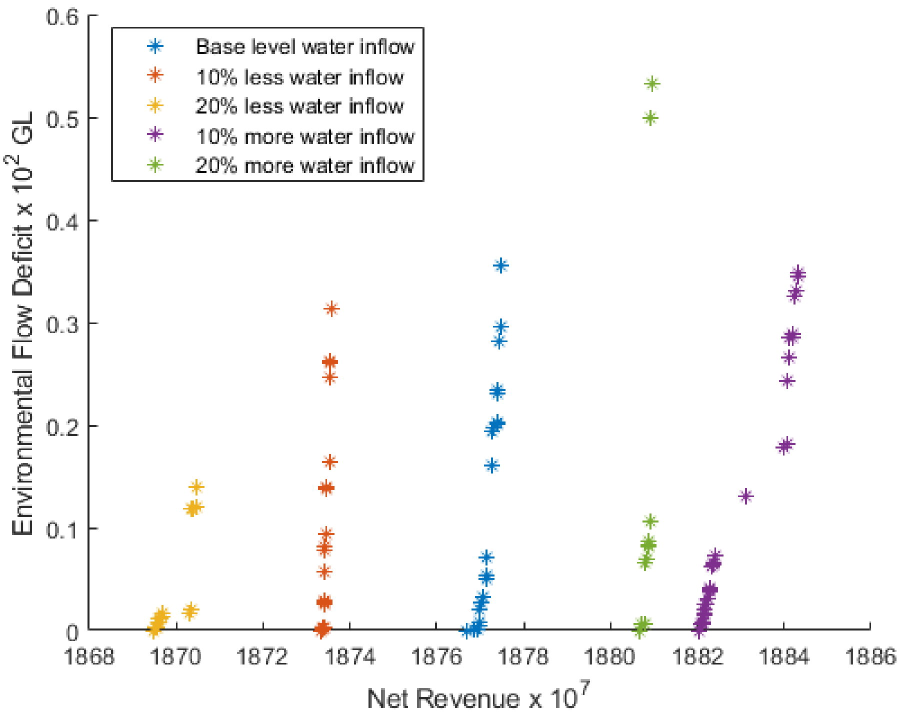

Figure 4.24: Compare Pareto optimal solution sets of different water inflow.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when water inflow is 10% less from the base level is given in Table 4.22.

Table 4.22: Compare different objective functions value, when water inflow is less than 10%.

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Objective functions	Base level water inflow	10% less water inflow	Absolute difference	Percentage
NR	18774797761.40	18735938923.84	-38858837.55	-0.21
EFD	35.53	31.37	-4.16	-11.71

According to the Table 4.22 when water inflow is 10% less from the base level, we see that both NR and EFD will decrease 0.21% and 11.71% respectively.

The result of two objective functions for the last solution in context of net return for 300 iterations when water inflow is 10% less from the base level is given in Table 4.23.

Table 4.23: Compare different objective functions value, when water inflow is less than 10%.

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Objective functions	Base level water inflow	10% less water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18733362569.74	-41435191.66	0.22
EFD (GL)	0.00	0.00	0.00	0.00

Table 4.23 provides that if rainfall is 10% less from the base level NR will decrease 0.22% but there is no effect on EFD for the last solution.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when water inflow is more than 10% from the base level is given in Table 4.24.

Table 4.24: Compare different objective functions value, when water inflow is more than 10%.

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Objective functions	Base level water inflow	10% more water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18843119828.23	68322066.83	0.36
EFD (GL)	35.53	34.86	-0.67	-2.81

The Table 4.24 illustrates that if water inflow is 10% more than from the base level NR will increase 0.36% and EFD will decrease 2.81%.

The result of two objective functions for the last solution in context of net return for 300 iterations when water inflow is more than 10% from the base level is given in Table 4.25.

Table 4.25: Compare different objective functions value, when water inflow is more than 10%.

Objective functions	Base level water inflow	10% more water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18820543489.65	45745728.25	0.24
EFD (GL)	0.00	0.00	0.00	0.00

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The Table 4.25 provides that if water inflow is 10% more than from the base level NR will increase 0.24% but there is no effect on EFD for the last solution.

The result of two objective functions for the 1st solution in context of net return for 300 iterations when water inflow is 20% less from the base level is given in Table 4.26.

Table 4.26: Compare different objective functions value, when water inflow is less than 20%.

Objective functions	Base level water inflow	20% less water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18704648123.26	-70149638.14	-0.37
EFD (GL)	35.53	13.98	-21.56	-60.66

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Table 4.26 shows that if the water inflow is 20% less from the data level, there is a slight decrease in NR but significant change in EFT amounting 60.66%.

The result of two objective functions for the last solution in context of net return for 300 iterations when water inflow is 20% less from the base level is given in Table 4.27.

Table 4.27: Compare different objective functions value, when water inflow is less than 20%.

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Objective functions	Base level water inflow	20% less water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18694884071.77	-79913689.63	-0.43
EFD (GL)	0.00	0.00	0.00	0.00

The Table 4.27 provides that if water inflow is 20% more than from the base level NR will decrease 0.43% but there is no effect on EFD for the last solution.

The result of two objective functions for the first solution in context of net return for 300 iterations when water inflow is more than 20% from the base level is given in Table 4.28.

Table 4.28: Compare different objective functions value, when water inflow is more than 20%.

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Objective functions	Base level water inflow	20% more water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18809554007.80	34756246.4	5.32×10^{-9}
EFD (GL)	35.53	53.18	17.65	2.81

The Table 4.28 presents that if water inflow is 20% more than from the base level, there is very little impact on NR and a slight change in EFD.

The result of two objective functions for the last solution in context of net return for 300 iterations when water inflow is more than 20% from the base level is given in Table 4.29.

Table 4.29: Compare different objective functions value, when water inflow is more than 20%.

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Objective functions	Base level water inflow	20% more water inflow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18806582997.01	31785235.61	0.17
EFD (GL)	0.00	0.00	0.00	0.00

The Table 4.29 provides that if water inflow is 20% more than from the base level NR will increase 0.17% but there is no effect on EFD for the last solution.

4.4.1 Comparison of crops pattern for different water inflow

The comparison of crops pattern for 1st solutions in context of net return for different water inflow using 300 iterations is given in the Figure 4.25.

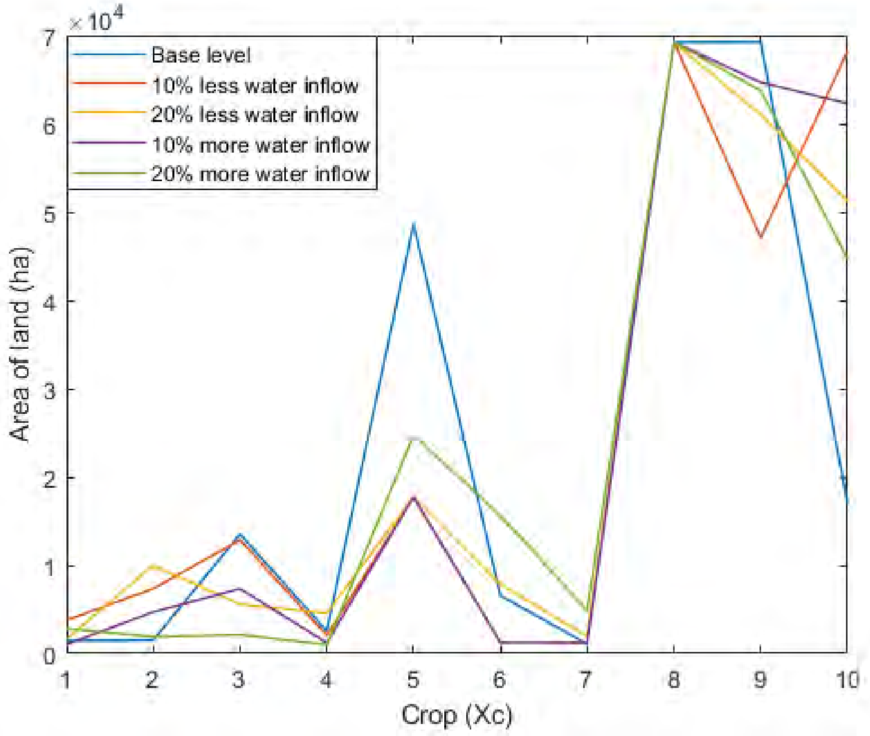

Figure 4.25: comparison of crops pattern for different water inflow.

Similar in Figure 4.22, we see the same scenario with slight differences in Figure 4.25. For different water inflow level conditions the crop 8 (Sugarcane) are cultivating almost same area of land. But for crops 5 (Potato) and 10 (Summer Vegetables), we see the opposite scenario. For all other crops, there is a slight variation.

4.4.2 Comparison between environmental flow for different water inflow

The comparison between environmental flow for 1st solutions in context of net return for different water inflow using 300 iterations is given in the Figure 4.26.

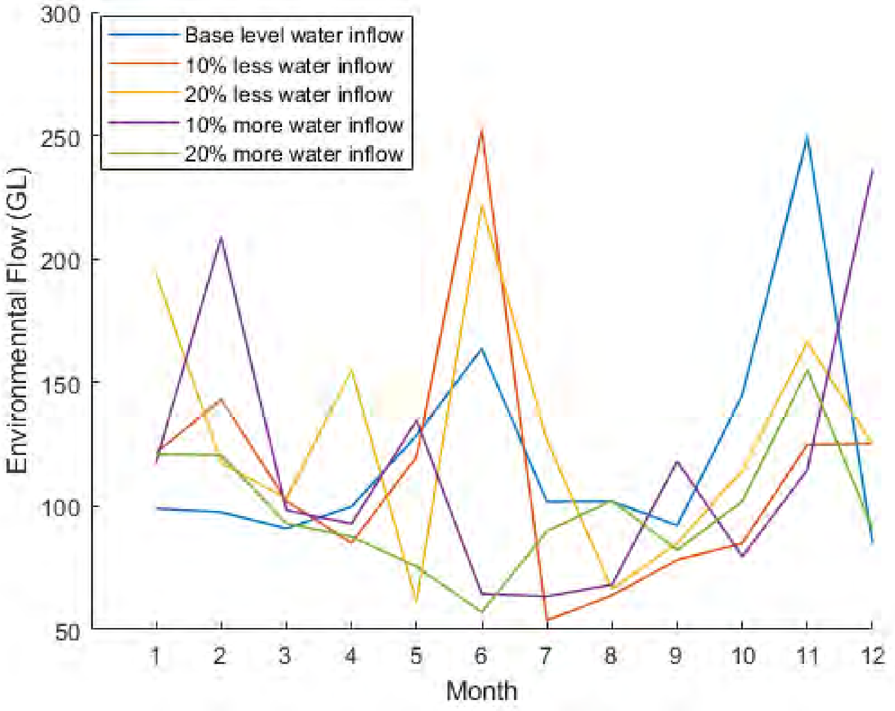

Figure 4.26: comparison between environmental flow for different water inflow.

According to the Figure 4.26, the highest environmental flow is required for less than 10% water inflow from the base level in the month of 6 (June). Same scenario is seen for base level water inflow in the month of 11 (November). For the case of 10% more water inflow, we see more than 200 GL water is required for environmental flow in the months of 2 (February) and 12 (December).

From the tables and figures we conclude that, more water inflow brings more profit.

4.5 Result for cyclic target environmental flow

The computational experiments were run, maintaining the cyclic target environmental flow which is given in Table 4.30 and using 100 trial solutions for 300 iterations. This data has been assumed from Xevi and Khan (2005).

Table 4.30: Cyclic target environmental flow in GL.

Jan	Feb	Mar	Apr	May	Jun
125	115	100	90	75	60

Jul	Aug	Sep	Oct	Nov	Dec
50	65	85	100	120	125

Using cyclic target environmental flow which is given in Table 4.30 the Pareto optimal objective values obtained are shown in Figure 4.27.

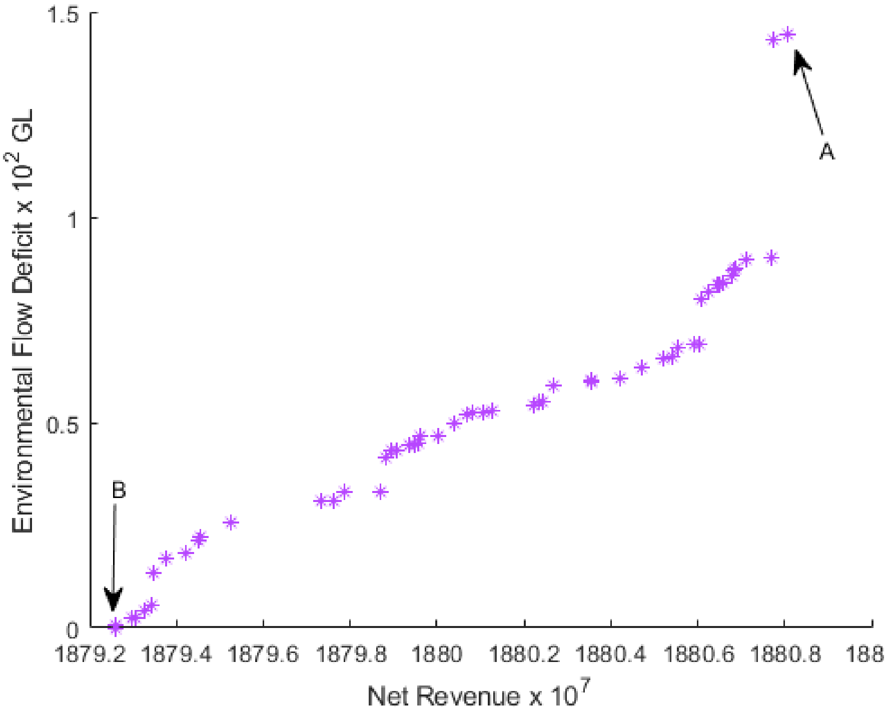

Figure 4.27: Pareto optimal solution sets for cyclic target environmental flow.

This figure presents the Pareto front obtained by NSGA-II which represents 56 non-dominated solutions for net revenue in units of 10 million Australia dollar and environmental flow deficit in units of 100 GL. In Figure 4.27 the highest net revenue is AUD 1880.81 × 10^7 with 144.47 GL deficit in environmental flow and the lowest net revenue is AUD 1879.26 × 10^7 with zero GL deficit in environmental flow.

4.5.1 Comparison between constant and cyclic target environmental flow

The results for two Pareto front curves are plotted together in Figure 4.28.

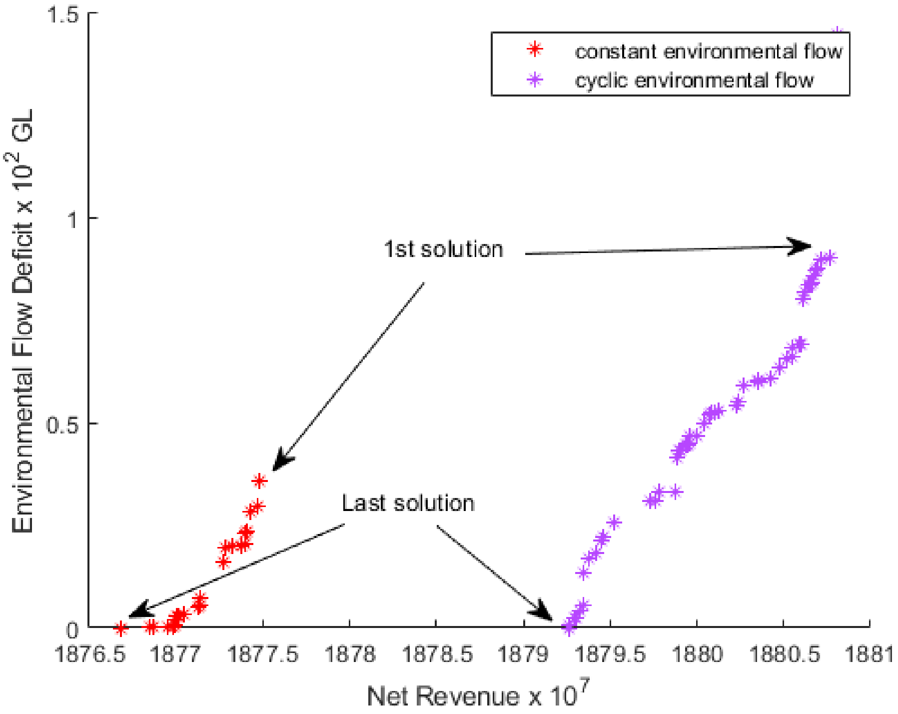

Figure 4.28: Compare Pareto optimal solution sets of constant and cyclic target environmental flow.

As is observed from the Figure 4.28, we see that when we use the cyclic target environmental flow, NR will increase but EFD will decrease. The difference of NR between constant and cyclic target environmental flow is AUD $33,253,531.67$. The difference of EFD between constant and cyclic target environmental flow is 108.94 GL.

Table 4.31 shows the difference of objective functions for 1st solution of constant and cyclic target environmental flow.

Table 4.31: Compare different objective functions value for constant and cyclic target environmental flow.

Objective functions	constant target environmental flow	cyclic target environmental flow	Absolute difference	Percentage
NR (AUD)	18774797761.40	18808051292.67	33253531.27	0.18
EFD (GL)	35.53	144.47	108.94	306.59

If we use cyclic target environmental flow, the result is quite opposite to constant target environmental flow. Table 4.31 provides that NR will increase 0.18% surprisingly EFD will increase 306.59%.

4.6 Summary

In summary, the chapter focuses on four things.Firstly, the chapter shows how multiple simulations have been conducted and what results come from three simulations namely 300, 600, and 1000. Secondly, the chapter displays what is the impact of rainfall on net return and environmental flow deficit. Thirdly, the impact of water inflow is shown. And finally the chapter shows the output of cyclic environmental flow. In this way, the chapter argues that more iterations gives the better result. It also shows that rainfall has a greater impact on NR and EFD than water inflow. However, the result of cyclic target environmental flow is opposite to that constant target environmental flow.

Chapter 5

Conclusion and Recommendations

Introduction

This study sought to explore the economics of optimal water allocation for irrigation in the MIP of Bangladesh. Although Bangladesh is not a country with widespread, year-round water scarcity, it faces severe water shortage during the dry winter season. The main objective of this thesis is to maximize net return and minimize deficit in environmental flow using optimal water management policies.

The first chapter of the thesis discusses the context of this research and present the literature review. It also discusses the focus of the thesis and solution techniques. In chapter two, model and data are described. In chapter three, we have discussed about Non-dominated Sorting Genetic Algorithm-II (NSGA-II) which has been used to solve the multi-objective optimization problem in the present research. The result and discussion chapter 4 shows four things: firstly, the NSGA-II optimization method is described which is used to solve the MOP, applying 300, 600, and 1000 iteration runs; secondly, the chapter shows the calculation of the rainfall effect on net return and environmental flow deficit; thirdly, it focuses on the effect of water inflow on net return and environmental flow deficit; and finally, the chapter compares the net return and environmental flow deficit using cyclic and constant environmental flow.

5.1 Research Outcomes

Based on the above mentioned framework the thesis has several outcomes. The following is the synthesis of those outcomes:

- The thesis supports that the more is the number of iteration runs the better is the result of evolutionary algorithms. The Pareto Curve for more iterations appears to be smoother and better convergent.
- The crop which are produced more and profitable in trade, the model recommends to cultivate them more.
- During dry season there requires more environmental flow to sustain the environment and to cultivate the crops than the rainy season.
- The decrease and increase of net return (NR) and rainfall are directly proportional to each other. However, the relationship between rainfall and environmental flow deficit (EFD) is not proportional. The decrease of rain by 10% contributes to the increase of environmental flow deficit (EFD) but the decrease of rain by 20% does not impact on environmental flow deficit (EFD) in the same way.
- When the water inflow increases, net return (NR) also increases. On the other hand, environmental flow deficit (EFD) decreases with increase when water inflow increases and vice versa.

5.2 Limitations and further research

5.2.1 Limitations

The study has some limitations. Firstly, limited amount of data directly collected from the field. Secondly, some data was taken from literature or assumed as described in Chapter 2. National average data was also used in some parameter estimations, when the local data was not available. Thirdly, the amount of data available was limited. Another limitation is that the Genetic algorithms are non-deterministic methods. Thus, the solutions they provide may vary each run of the algorithm for the same set of model parameters. Genetic algorithm's convergence is also very much dependent on several things such as initial solution, number of iteration, number of population, number of generation, crossover, and mutation rate.

5.2.2 Further research

There is an avenue for further research in this thesis. The avenue is based on the present research to develop a new model to optimize water allocation in context of several irrigation projects in Bangladesh including MIP. The present model I have taken based on the Murrumbidgee Irrigation Area (MIA), in Australia. But following the environmental, social and economic differences between Bangladesh and Australia, a new model can be developed.

In future project I will collect primary data from the project sites. I will then compare other evolutionary algorithms with NSGA-II to find the best solution and the current practices of crop/land use against model predictions. This plan will facilitate a more comprehensive understanding of the land, crop, weather and environment relationships in different irrigation projects in Bangladesh.

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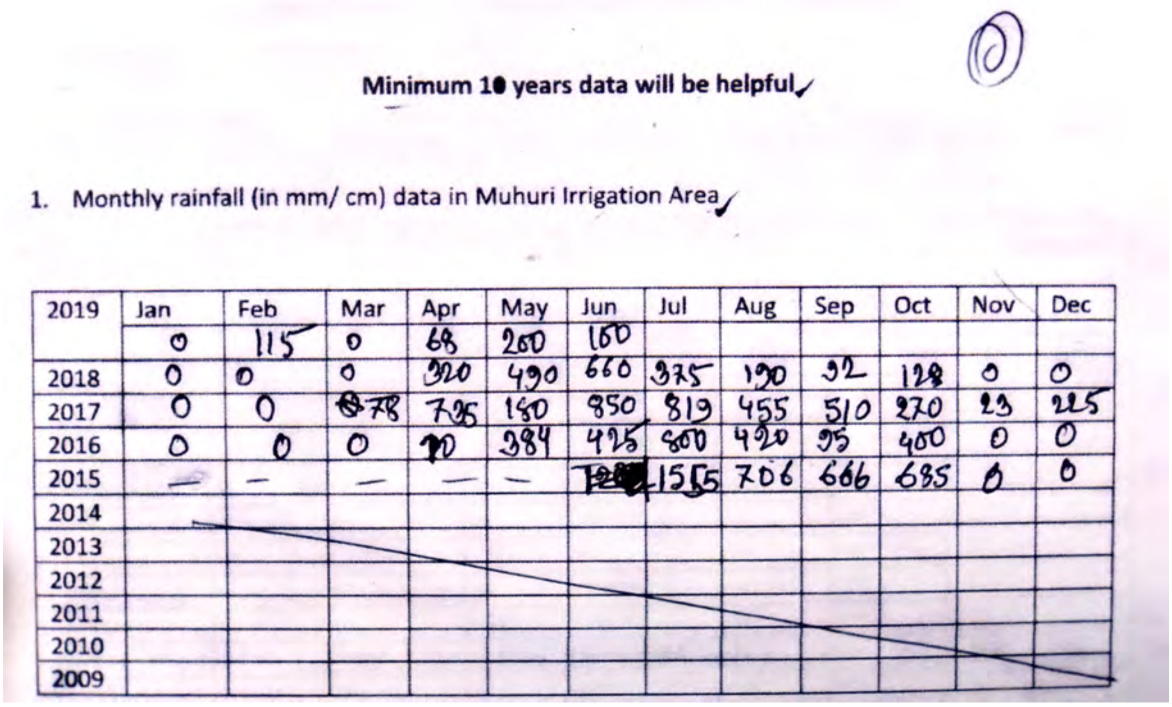
Appendix A

Raw data

This section contains raw data that has been collected from Mr.Oli Afaz Chowdhury, Sub-Divisional Engineer, Hathazari O& M Sub-Division, Bangladesh Water Development Board (BWDB), Chattogram, Bangladesh.

Figure A.1 is monthly rainfall data from June, 2015 to June, 2019 in Muhuri Irrigation Area.



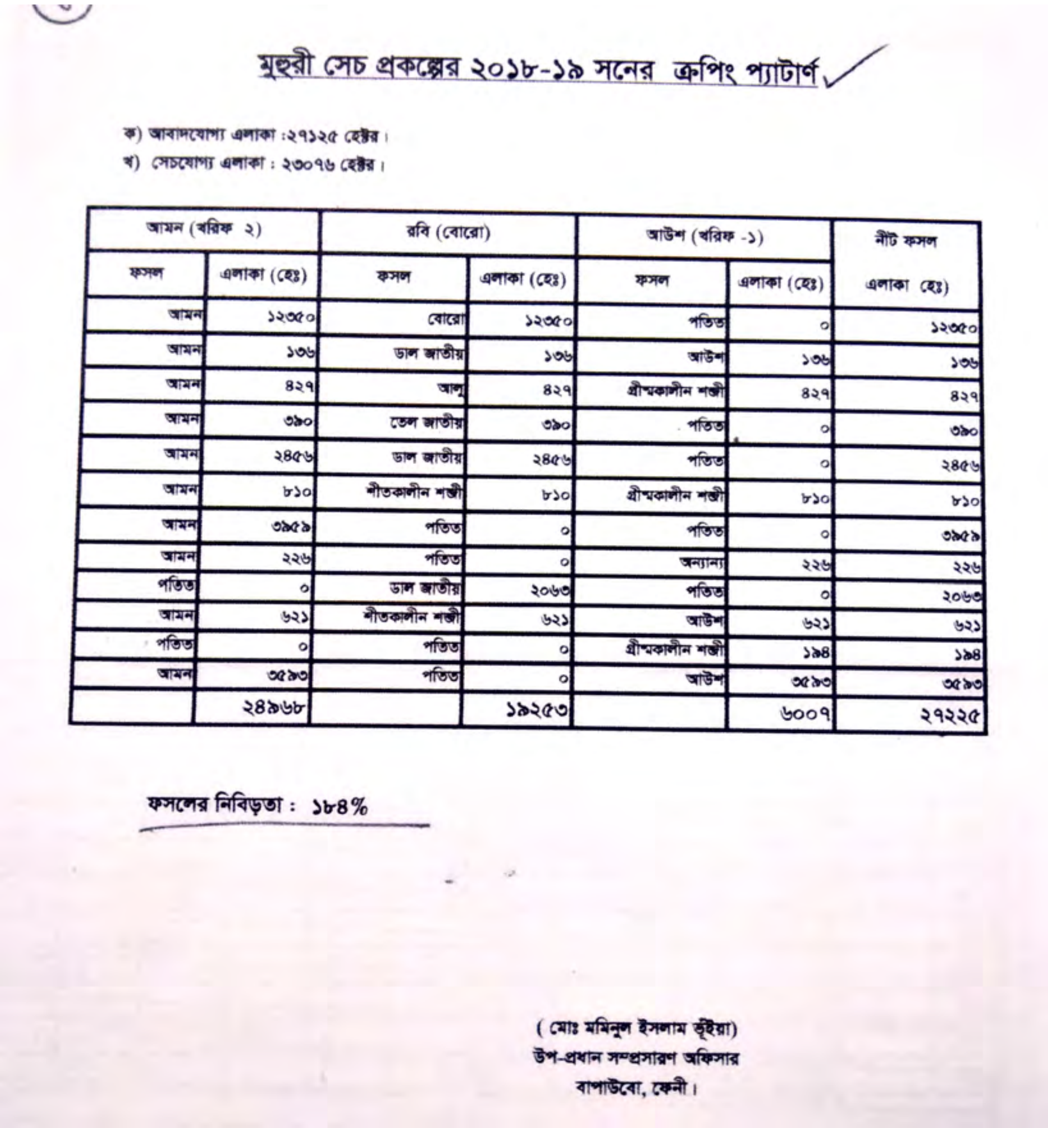
Minimum 10 years data will be helpful✓

1. Monthly rainfall (in mm/ cm) data in Muhuri Irrigation Area✓

2019	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	0	115	0	68	200	160						
2018	0	0	0	320	490	660	375	190	92	128	0	0
2017	0	0	~~0~~ 78	725	180	850	819	455	510	270	23	225
2016	0	0	0	70	384	425	800	420	95	400	0	0
2015	—	—	—	—	—	[illegible]	1555	706	666	685	0	0
2014												
2013												
2012												
2011												
2010												
2009												

Figure A.1: Monthly rainfall (mm) data from June, 2015 to June, 2019 in Muhuri Irrigation Area.

Figure A.2 is the cropping pattern of the Muhuri Irrigation Project in session 2018-2019. Here data is in the Bangla language.



মুহুরী সেচ প্রকল্পের ২০১৮-১৯ সনের ক্রপিং প্যাটার্ণ

ক) আবাদযোগ্য এলাকা :২৭১২৫ হেক্টর।
খ) সেচযোগ্য এলাকা : ২৩০৭৬ হেক্টর।

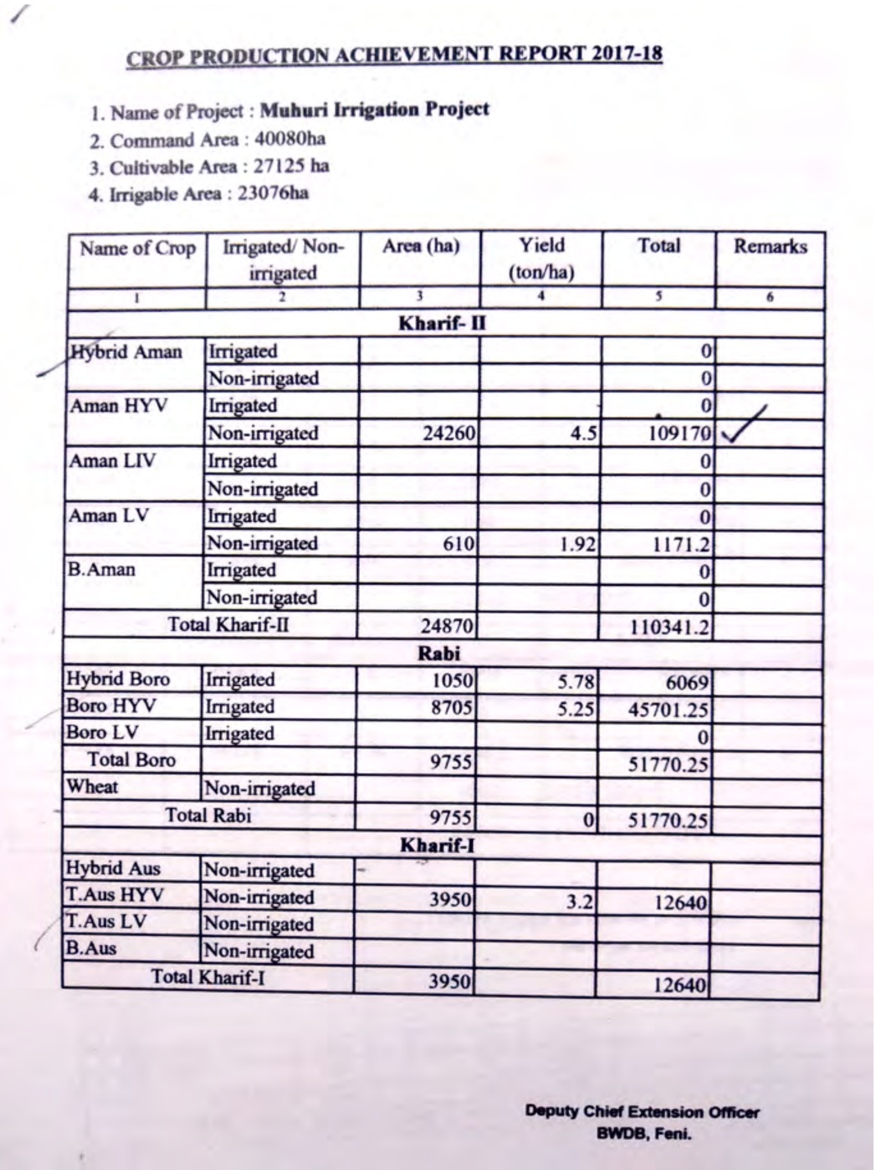
আমন (খরিফ ২)		রবি (বোরো)		আউশ (খরিফ -১)		নীট ফসল এলাকা হেঃ)
ফসল	এলাকা (হেঃ)	ফসল	এলাকা (হেঃ)	ফসল	এলাকা (হেঃ)	
আমন	১২৩৫০	বোরো	১২৩৫০	পতিত	০	১২৩৫০
আমন	১৩৬	ডাল জাতীয়	১৩৬	আউশ	১৩৬	১৩৬
আমন	৪২৭	আলু	৪২৭	গ্রীষ্মকালীন শজ্বী	৪২৭	৪২৭
আমন	৩৯০	তেল জাতীয়	৩৯০	পতিত	০	৩৯০
আমন	২৪৫৬	ডাল জাতীয়	২৪৫৬	পতিত	০	২৪৫৬
আমন	৮১০	শীতকালীন শজ্বী	৮১০	গ্রীষ্মকালীন শজ্বী	৮১০	৮১০
আমন	৩৯৫৯	পতিত	০	পতিত	০	৩৯৫৯
আমন	২২৬	পতিত	০	অন্যান্য	২২৬	২২৬
পতিত	০	ডাল জাতীয়	২০৬৩	পতিত	০	২০৬৩
আমন	৬২১	শীতকালীন শজ্বী	৬২১	আউশ	৬২১	৬২১
পতিত	০	পতিত	০	গ্রীষ্মকালীন শজ্বী	১৯৪	১৯৪
আমন	৩৫৯৩	পতিত	০	আউশ	৩৫৯৩	৩৫৯৩
	২৪৯৬৮		১৯২৫৩		৬০০৭	২৭২২৫

ফসলের নিবিড়তা : ১৮৪%

(মোঃ মমিনুল ইসলাম ভূঁইয়া)
উপ-প্রধান সম্প্রসারণ অফিসার
বাপাউবো, ফেনী।

Figure A.2: Cropping pattern of Muhuri Irrigation Project in session 2018-2019.

Figure A.3 is Crop production achievement report 2017-18 in the Muhuri Irrigation Project.



CROP PRODUCTION ACHIEVEMENT REPORT 2017-18

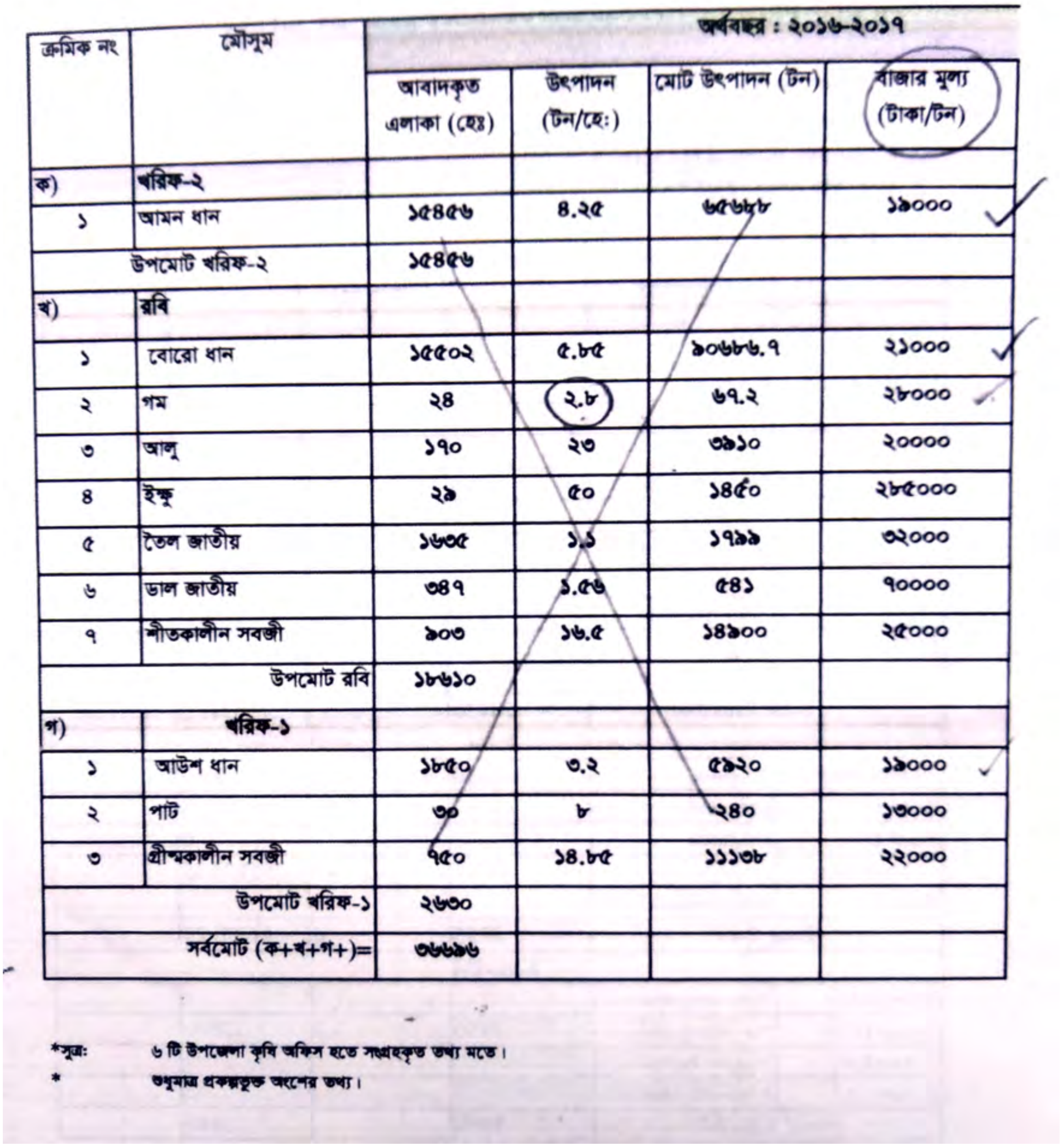
1. Name of Project : **Muhuri Irrigation Project**
2. Command Area : 40080ha
3. Cultivable Area : 27125 ha
4. Irrigable Area : 23076ha

Name of Crop 1	Irrigated/ Non-irrigated 2	Area (ha) 3	Yield (ton/ha) 4	Total 5	Remarks 6
Kharif- II					
Hybrid Aman	Irrigated			0	
	Non-irrigated			0	
Aman HYV	Irrigated			0	
	Non-irrigated	24260	4.5	109170	✓
Aman LIV	Irrigated			0	
	Non-irrigated			0	
Aman LV	Irrigated			0	
	Non-irrigated	610	1.92	1171.2	
B.Aman	Irrigated			0	
	Non-irrigated			0	
Total Kharif-II		24870		110341.2	
Rabi					
Hybrid Boro	Irrigated	1050	5.78	6069	
Boro HYV	Irrigated	8705	5.25	45701.25	
Boro LV	Irrigated			0	
Total Boro		9755		51770.25	
Wheat	Non-irrigated				
Total Rabi		9755	0	51770.25	
Kharif-I					
Hybrid Aus	Non-irrigated				
T.Aus HYV	Non-irrigated	3950	3.2	12640	
T.Aus LV	Non-irrigated				
B.Aus	Non-irrigated				
Total Kharif-I		3950		12640	

Deputy Chief Extension Officer
BWDB, Feni.

Figure A.3: Crop production achievement report 2017-18 in Muhuri Irrigation Area .

Figure A.4 shows the crop production per hectare and market value of different crops in the Muhuri Irrigation Project. Here data is in the Bangla language.



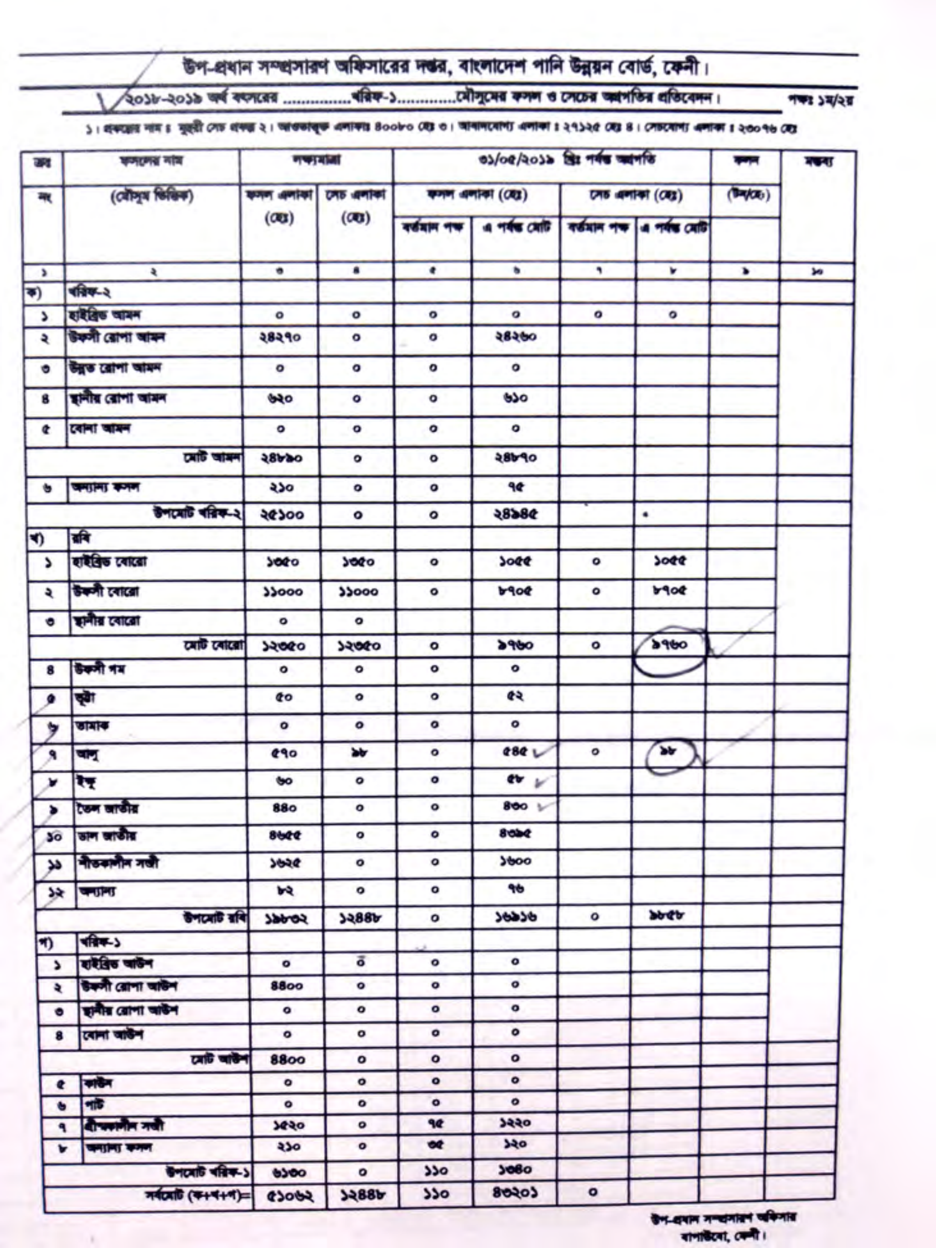
ক্রমিক নং	মৌসুম	অর্থবছর : ২০১৬-২০১৭			
		আবাদকৃত এলাকা (হেঃ)	উৎপাদন (টন/হেঃ)	মোট উৎপাদন (টন)	বাজার মুল্য (টাকা/টন)
ক)	খরিফ-২				
১	আমন ধান	১৫৪৫৬	৪.২৫	৬৫৬৮৮	১৯০০০ ✓
	উপমোট খরিফ-২	১৫৪৫৬			
খ)	রবি				
১	বোরো ধান	১৫৫০২	৫.৮৫	৯০৬৮৬.৭	২১০০০ ✓
২	গম	২৪	২.৮	৬৭.২	২৮০০০ ✓
৩	আলু	১৯০	২৩	৩৯১০	২০০০০
৪	ইক্ষু	২৯	৫০	১৪৫০	২৮৫০০০
৫	তৈল জাতীয়	১৬৩৫	১.১	১৭৯৯	৩২০০০
৬	ডাল জাতীয়	৩৪৭	১.৫৬	৫৪১	৭০০০০
৭	শীতকালীন সবজী	৯০৩	১৬.৫	১৪৯০০	২৫০০০
	উপমোট রবি	১৮৬১০			
গ)	খরিফ-১				
১	আউশ ধান	১৮৫০	৩.২	৫৯২০	১৯০০০ ✓
২	পাট	৩০	৮	২৪০	১৩০০০
৩	গ্রীষ্মকালীন সবজী	৭৫০	১৪.৮৫	১১১৩৮	২২০০০
	উপমোট খরিফ-১	২৬৩০			
	সর্বমোট (ক+খ+গ+)=	৩৬৬৯৬			

*সুত্রঃ ৬ টি উপজেলা কৃষি অফিস হতে সংগ্রহকৃত তথ্য মতে।

* শুধুমাত্র প্রকল্পভূক্ত অংশের তথ্য।

Figure A.4: Crop production and market value of different crops in Muhuri Irrigation Area.

Figure A.5 is seasonal crop and irrigation report of the Muhuri Irrigation Project in session 2018-2019. Here data is in the Bangla language.



উপ-প্রধান সম্প্রসারণ অফিসারের দপ্তর, বাংলাদেশ পানি উন্নয়ন বোর্ড, ফেনী।

২০১৮-২০১৯ অর্থ বৎসরের ....খরিফ-১............মৌসুমের ফসল ও সেচের অগ্রগতির প্রতিবেদন। পক্ষঃ ১ম/২য়

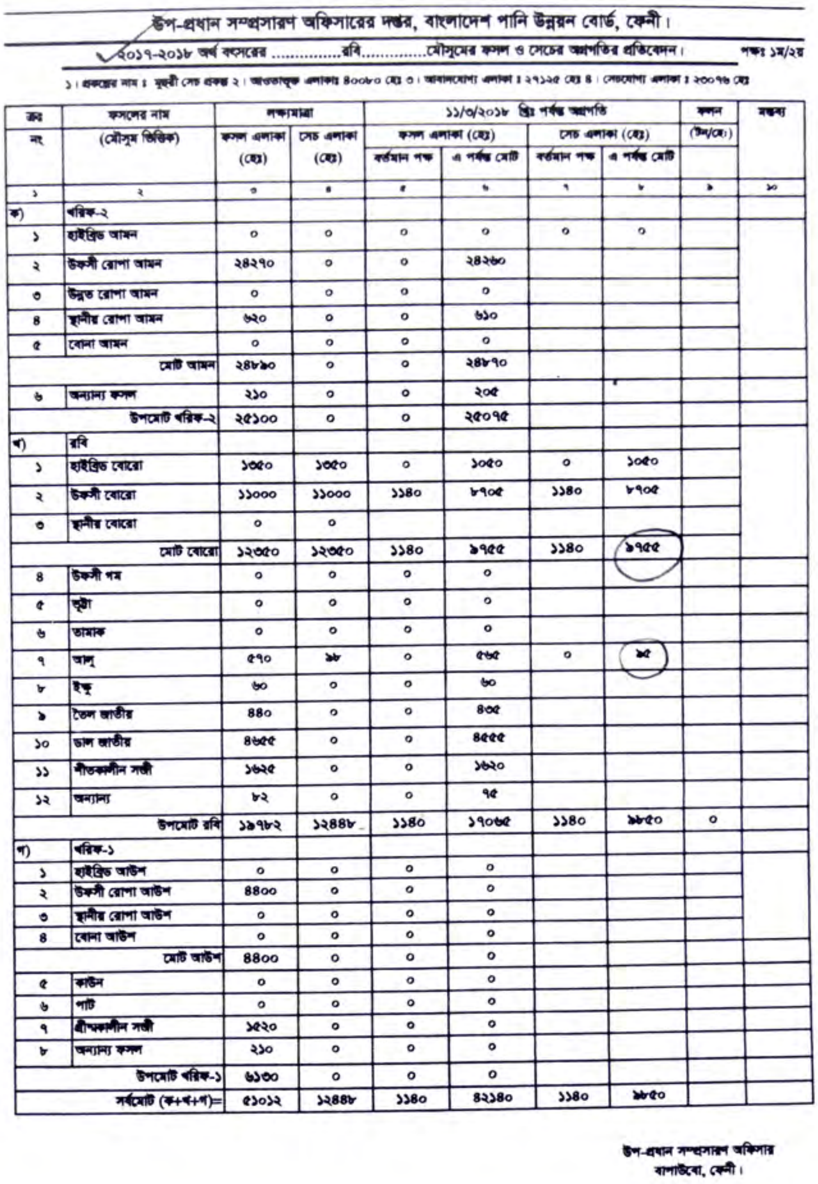
১। প্রকল্পের নাম ঃ মুহুরী সেচ প্রকল্প ২। আওতাভুক্ত এলাকা ৪০০৮০ হেঃ ৩। আবাদযোগ্য এলাকা ঃ ২৭১২৫ হেঃ ৪। সেচযোগ্য এলাকা ঃ ২৩০৭৬ হেঃ

ক্রম নং	ফসলের নাম (মৌসুম ভিত্তিক)	লক্ষ্যমাত্রা		৩১/০৫/২০১৯ খ্রিঃ পর্যন্ত অগ্রগতি				ফলন (টন/হেঃ)	মন্তব্য
		ফসল এলাকা (হেঃ)	সেচ এলাকা (হেঃ)	ফসল এলাকা (হেঃ)		সেচ এলাকা (হেঃ)			
				বর্তমান পক্ষ	এ পর্যন্ত মোট	বর্তমান পক্ষ	এ পর্যন্ত মোট		
১	২	৩	৪	৫	৬	৭	৮	৯	১০
ক)	খরিফ-২								
১	হাইব্রিড আমন	০	০	০	০	০	০		
২	উফশী রোপা আমন	২৪২৭০	০	০	২৪২৬০				
৩	উন্নত রোপা আমন	০	০	০	০				
৪	স্থানীয় রোপা আমন	৬২০	০	০	৬১০				
৫	বোনা আমন	০	০	০	০				
	মোট আমন	২৪৮৯০	০	০	২৪৮৭০				
৬	অন্যান্য ফসল	২১০	০	০	৭৫				
	উপমোট খরিফ-২	২৫১০০	০	০	২৪৯৪৫				
খ)	রবি								
১	হাইব্রিড বোরো	১৩৫০	১৩৫০	০	১০৫৫	০	১০৫৫		
২	উফশী বোরো	১১০০০	১১০০০	০	৮৭০৫	০	৮৭০৫		
৩	স্থানীয় বোরো	০	০						
	মোট বোরো	১২৩৫০	১২৩৫০	০	৯৭৬০	০	৯৭৬০		
৪	উফশী গম	০	০	০	০				
৫	ভুট্টা	৫০	০	০	৫২				
৬	তামাক	০	০	০	০				
৭	আলু	৫৭০	৯৮	০	৫৪৫	০	৯৮		
৮	ইক্ষু	৬০	০	০	৫৮				
৯	তৈল জাতীয়	৪৪০	০	০	৪৩০				
১০	ডাল জাতীয়	৪৬৫৫	০	০	৪৩৯৫				
১১	শীতকালীন সব্জী	১৬২৫	০	০	১৬০০				
১২	অন্যান্য	৮২	০	০	৭৬				
	উপমোট রবি	১৯৮৩২	১২৪৪৮	০	১৬৯১৬	০	৯৮৫৮		
গ)	খরিফ-১								
১	হাইব্রিড আউশ	০	০	০	০				
২	উফশী রোপা আউশ	৪৪০০	০	০	০				
৩	স্থানীয় রোপা আউশ	০	০	০	০				
৪	বোনা আউশ	০	০	০	০				
	মোট আউশ	৪৪০০	০	০	০				
৫	কাউন	০	০	০	০				
৬	পাট	০	০	০	০				
৭	গ্রীষ্মকালীন সব্জী	১৫২০	০	৭৫	১২২০				
৮	অন্যান্য ফসল	২১০	০	৩৫	১২০				
	উপমোট খরিফ-১	৬১৩০	০	১১০	১৩৪০				
	সর্বমোট (ক+খ+গ)=	৫১০৬২	১২৪৪৮	১১০	৪৩২০১	০			

উপ-প্রধান সম্প্রসারণ অফিসার
বাপাউবো, ফেনী।

Figure A.5: Seasonal crop and irrigation report of Muhuri Irrigation Area in session 2018-2019.

Figure A.6 is seasonal crop and irrigation report of the Muhuri Irrigation Project in session 2017-2018. Here data is in the Bangla language.



উপ-প্রধান সম্প্রসারণ অফিসারের দপ্তর, বাংলাদেশ পানি উন্নয়ন বোর্ড, ফেনী।

২০১৭-২০১৮ অর্থ বৎসরের ....রবি.............মৌসুমের ফসল ও সেচের অগ্রগতির প্রতিবেদন। পক্ষঃ ১ম/২য়

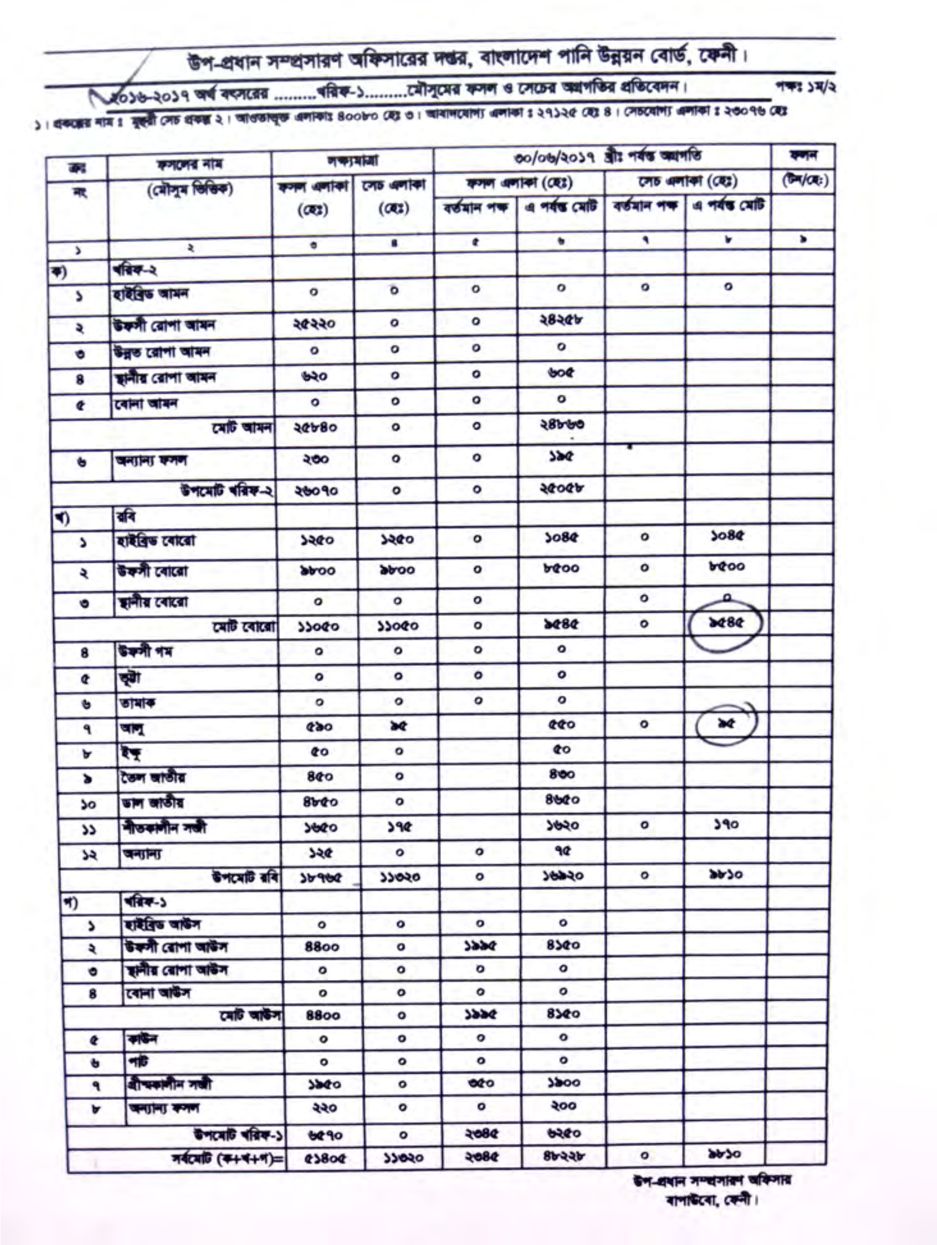
১। প্রকল্পের নাম ঃ মুহুরী সেচ প্রকল্প ২। আওতাভুক্ত এলাকাঃ ৪০০৮০ হেঃ ৩। আবাদযোগ্য এলাকা ঃ ২৭১২৫ হেঃ ৪। সেচযোগ্য এলাকা ঃ ২০০৭৬ হেঃ

ক্রঃ নং	ফসলের নাম (মৌসুম ভিত্তিক)	লক্ষ্যমাত্রা		১১/৩/২০১৮ খ্রিঃ পর্যন্ত অগ্রগতি				ফলন (টন/হেঃ)	মন্তব্য
		ফসল এলাকা (হেঃ)	সেচ এলাকা (হেঃ)	ফসল এলাকা (হেঃ)		সেচ এলাকা (হেঃ)			
				বর্তমান পক্ষ	এ পর্যন্ত মোট	বর্তমান পক্ষ	এ পর্যন্ত মোট		
১	২	৩	৪	৫	৬	৭	৮	৯	১০
ক)	খরিফ-২								
১	হাইব্রিড আমন	০	০	০	০	০	০		
২	উফশী রোপা আমন	২৪২৭০	০	০	২৪২৬০				
৩	উন্নত রোপা আমন	০	০	০	০				
৪	স্থানীয় রোপা আমন	৬২০	০	০	৬১০				
৫	বোনা আমন	০	০	০	০				
	মোট আমন	২৪৮৯০	০	০	২৪৮৭০				
৬	অন্যান্য ফসল	২১০	০	০	২০৫				
	উপমোট খরিফ-২	২৫১০০	০	০	২৫০৭৫				
খ)	রবি								
১	হাইব্রিড বোরো	১০৫০	১০৫০	০	১০৫০	০	১০৫০		
২	উফশী বোরো	১১০০০	১১০০০	১১৪০	৮৭০৫	১১৪০	৮৭০৫		
৩	স্থানীয় বোরো	০	০						
	মোট বোরো	১২০৫০	১২০৫০	১১৪০	৯৭৫৫	১১৪০	৯৭৫৫		
৪	উফশী গম	০	০	০	০				
৫	ভূট্টা	০	০	০	০				
৬	তামাক	০	০	০	০				
৭	আলু	৫৭০	৯৮	০	৫৬৫	০	৯৫		
৮	ইক্ষু	৬০	০	০	৬০				
৯	তৈল জাতীয়	৪৪০	০	০	৪০৫				
১০	ডাল জাতীয়	৪৬৫৫	০	০	৪৫৫৫				
১১	শীতকালীন সব্জী	১৬২৫	০	০	১৬২০				
১২	অন্যান্য	৮২	০	০	৭৫				
	উপমোট রবি	১৯৭৮২	১২৪৪৮	১১৪০	১৭০৬৫	১১৪০	৯৮৫০	০	
গ)	খরিফ-১								
১	হাইব্রিড আউশ	০	০	০	০				
২	উফশী রোপা আউশ	৪৪০০	০	০	০				
৩	স্থানীয় রোপা আউশ	০	০	০	০				
৪	বোনা আউশ	০	০	০	০				
	মোট আউশ	৪৪০০	০	০	০				
৫	কাউন	০	০	০	০				
৬	পাট	০	০	০	০				
৭	গ্রীষ্মকালীন সব্জী	১৫২০	০	০	০				
৮	অন্যান্য ফসল	২১০	০	০	০				
	উপমোট খরিফ-১	৬১৩০	০	০	০				
	সর্বমোট (ক+খ+গ)=	৫১০১২	১২৪৪৮	১১৪০	৪২১৪০	১১৪০	৯৮৫০		

উপ-প্রধান সম্প্রসারণ অফিসার
বাপাউবো, ফেনী।

Figure A.6: Seasonal crop and irrigation report of Muhuri Irrigation Area in session 2017-2018.

Figure A.7 is seasonal crop and irrigation report of the Muhuri Irrigation Project in session 2016-2017. Here data is in the Bangla language.



উপ-প্রধান সম্প্রসারণ অফিসারের দপ্তর, বাংলাদেশ পানি উন্নয়ন বোর্ড, ফেনী।

২০১৬-২০১৭ অর্থ বৎসরের ....খরিফ-১.........মৌসুমের ফসল ও সেচের অগ্রগতির প্রতিবেদন। পক্ষঃ ১ম/২

১। প্রকল্পের নাম ঃ মুহুরী সেচ প্রকল্প ২। আওতাভুক্ত এলাকাঃ ৪০০৮০ হেঃ ৩। আবাদযোগ্য এলাকা ঃ ২৭১২৫ হেঃ ৪। সেচযোগ্য এলাকা ঃ ২৩০৭৬ হেঃ

ক্রঃ	ফসলের নাম	লক্ষ্যমাত্রা		৩০/০৬/২০১৭ খ্রীঃ পর্যন্ত অগ্রগতি				ফলন
নং	(মৌসুম ভিত্তিক)	ফসল এলাকা (হেঃ)	সেচ এলাকা (হেঃ)	ফসল এলাকা (হেঃ)		সেচ এলাকা (হেঃ)		(টন/হেঃ)
				বর্তমান পক্ষ	এ পর্যন্ত মোট	বর্তমান পক্ষ	এ পর্যন্ত মোট	
১	২	৩	৪	৫	৬	৭	৮	৯
ক)	খরিফ-২							
১	হাইব্রিড আমন	০	০	০	০	০	০	
২	উফশী রোপা আমন	২৫২২০	০	০	২৪২৫৮			
৩	উন্নত রোপা আমন	০	০	০	০			
৪	স্থানীয় রোপা আমন	৬২০	০	০	৬০৫			
৫	বোনা আমন	০	০	০	০			
	মোট আমন	২৫৮৪০	০	০	২৪৮৬৩			
৬	অন্যান্য ফসল	২৩০	০	০	১৯৫			
	উপমোট খরিফ-২	২৬০৭০	০	০	২৫০৫৮			
খ)	রবি							
১	হাইব্রিড বোরো	১২৫০	১২৫০	০	১০৪৫	০	১০৪৫	
২	উফশী বোরো	৯৮০০	৯৮০০	০	৮৫০০	০	৮৫০০	
৩	স্থানীয় বোরো	০	০	০		০	০	
	মোট বোরো	১১০৫০	১১০৫০	০	৯৫৪৫	০	৯৫৪৫	
৪	উফশী গম	০	০	০	০			
৫	ভূট্টা	০	০	০	০			
৬	তামাক	০	০	০	০			
৭	আলু	৫৯০	৯৫		৫৫০	০	৯৫	
৮	ইক্ষু	৫০	০		৫০			
৯	তৈল জাতীয়	৪৫০	০		৪৩০			
১০	ডাল জাতীয়	৪৮৫০	০		৪৬৫০			
১১	শীতকালীন সব্জী	১৬৫০	১৭৫		১৬২০	০	১৭০	
১২	অন্যান্য	১২৫	০	০	৭৫			
	উপমোট রবি	১৮৭৬৫	১১৩২০	০	১৬৯২০	০	৯৮১০	
গ)	খরিফ-১							
১	হাইব্রিড আউস	০	০	০	০			
২	উফশী রোপা আউস	৪৪০০	০	১৯৯৫	৪১৫০			
৩	স্থানীয় রোপা আউস	০	০	০	০			
৪	বোনা আউস	০	০	০	০			
	মোট আউস	৪৪০০	০	১৯৯৫	৪১৫০			
৫	কাউন	০	০	০	০			
৬	পাট	০	০	০	০			
৭	গ্রীষ্মকালীন সব্জী	১৯৫০	০	৩৫০	১৯০০			
৮	অন্যান্য ফসল	২২০	০	০	২০০			
	উপমোট খরিফ-১	৬৫৭০	০	২৩৪৫	৬২৫০			
	সর্বমোট (ক+খ+গ)=	৫১৪০৫	১১৩২০	২৩৪৫	৪৮২২৮	০	৯৮১০	

উপ-প্রধান সম্প্রসারণ অফিসার
বাপাউবো, ফেনী।

Figure A.7: Seasonal crop and irrigation report of Muhuri Irrigation Area in session 2016-2017.

Appendix B

MatLab code

This section contains the modified MatLab code originally developed by Baskar (2015) for the NSGA-II method used to solve the MOP in Section 2.2, Chapter 2 and figures contained within this work. We have written Listing B.2 and B.3 files and partially modified Listing B.1 file. Others files remain unchanged.

Listing B.1: Main NSGA-II

```
clear all
close all
clc

%% Description

% 1. This is the main file for running this program.
%       Code defines population size in 'pop_size',
%       number of design variables in 'V', number of
%       runs in 'no_runs',
%       maximum number of generations in 'gen_max',
%       current generation in 'gen_count' and number
%       of objectives in 'M'.
% 2. 'xl' and 'xu' are the lower and upper bounds of the
%       design variables.
% 3. Final optimal Pareto soutions are in the variable
%       'pareto_rank1', with design variables in the coumns
%       (1:V), objectives in the columns (V+1 to V+M),
%       constraint violation in the column (V+M+1), Rank in
%       (V+M+2), Distance in (V+M+3).
```

```



%% references

% 1. BINH, Thanh. "A multiobjective evolutionary algorithm.
%       The study cases". Technical report. Barleben,
%       Germany. 1999.
% 2. DEB, Kalyanmoy. "Multi-Objective optimization using
%       evolutionary algorithms". John Wiley & Sons, LTD.
%       Kanpur, India. 2004.

%% code starts
global V M xl xu etac etam pop_size pm

M=2;                          % number of objectives
pop_size=100;                 % Population size
no_runs=1000;                 % Number of runs
                              % stopping criteria
gen_max=500;                  % MAx number of generations
fname='my_function';          % Objective function and
                              % constraint evaluation
V = 22;                       % number of design variables
xl = zeros(1,V);              % lower bound vector
xu = horzcat(70000*
        ones(1,10),300*ones(1,12));   % upper bound vector
etac = 20;                    % distribution index for crossover
etam = 100;                   % distribution index for mutation
                              % / mutation constant
pm=1/V;                       % Mutation Probability
Q=[];
for r=1
    data = my_data(r);
    for run = 1:no_runs

%% Initial population

        xl_temp=repmat(xl, pop_size,1);
        xu_temp=repmat(xu, pop_size,1);
```

```
        x = xl_temp+((xu_temp-xl_temp).*rand(pop_size,V));

% Evaluate objective function

        for i =1:pop_size
            [ff(i,:) err(i,:)] = my_function(x(i,:), data);
        end

% Normalisation of the constraint violation

        error_norm=normalisation(err);
        population_init=[x ff error_norm];

% Non domination sorting on initial population

        [population front]=NDS_CD_cons(population_init);

%% Generation Starts

        for gen_count=1:gen_max
               % selection (Parent Pt of 'N' pop size)
                % Tournament selection
        parent_selected=tour_selection(population);

%% Reproduction (Offspring Qt of 'N' pop size)

        % SBX crossover and polynomial mutation
        child_offspring  = genetic_operator
                                   (parent_selected(:,1:V));

        for ii = 1:pop_size
               % objective function evaluation for offspring
                [fff(ii,:) err(ii,:)]=my_function
                                   (child_offspring(ii,:),data);
        end

        error_norm=normalisation(err);
        child_offspring=[child_offspring fff error_norm];

```

```
%% Intermediate population (Rt= Pt U Qt of 2N size)

        population_inter=[population(:,1:V+M+1) ;
                        child_offspring(:,1:V+M+1)];
                        % Non domination Sorting on offspring
        [population_inter_sorted front]=NDS_CD_cons
                                        (population_inter);

%% Replacement - N

        new_pop=replacement(population_inter_sorted, front);
        population=new_pop;
        end
        new_pop=sortrows(new_pop,V+1);
        paretoset(run).trial=new_pop(:,1:V+M+1);
                % Combining Pareto solutions obtained in each run
        Q = [Q; paretoset(run).trial];
    end

%% Result and Pareto plot

    if run==1
        plot(new_pop(:,V+1),new_pop(:,V+2),'*')
    else
        [pareto_filter front]=NDS_CD_cons(Q);
                % Applying non domination sorting on the
                %combined Pareto solution set
        rank1_index=find(pareto_filter(:,V+M+2)==1);
                 % Filtering the best solutions of rank 1 Pareto
        pareto_rank1=pareto_filter(rank1_index,1:V+M)
        plot(pareto_rank1(:,V+1),pareto_rank1(:,V+2),'*r')

    end
end
xlabel('objective function 1')
ylabel('objective function 2')
title(' My Function')
end
```

Listing B.2: Import data

```
function [parametres] = my_data(r)
%% this function reads data from .csv files and returns the
% data as 'parametres'. r represent the number of row.
rain = importdata('rainfall.csv');
rain_water=rain.data;
parametres.rain = rain_water(r,:);
evopatranspiration= importdata('evapo-transpiration.csv');
ETo = evopatranspiration.data;
parametres.evopatranspiration= ETo(r,:);
crop_coefficient = importdata('crop_coefficiets.csv');
crop_coeff = crop_coefficient.data;
parametres.crop_coefficient = crop_coeff;
crop_production = importdata('crop_production.csv');
crop_prod = crop_production.data;
parametres.crop_production = crop_prod;
total_crop_income = importdata('total_crop_income.csv');
crop_income = total_crop_income.data;
parametres.total_crop_income = crop_income;
water_inflow = importdata('water_inflow.csv');
inflow = water_inflow.data;
parametres.water_inflow = inflow(r,:);
variable_cost = importdata('variable_cost.csv');
variable = variable_cost.data;
parametres.variable_cost = variable;
target_env_flow = importdata('target_env_flow.csv');
target_environmental_flow = target_env_flow.data;
parametres.target_env_flow = target_environmental_flow;
groundwater_pupming_cost = importdata
                               ('groundwater_pupming_cost.csv');
ground_water = groundwater_pupming_cost.data;
parametres.groundwater_pupming_cost = ground_water(r,:);
surfacewater_pumping_cost = importdata
                               ('surfacewater_pumping_cost.csv');
surface_water = surfacewater_pumping_cost.data;
parametres.surfacewater_pumping_cost = surface_water;
total_area = importdata('total_area.csv');
area = total_area.data;
parametres.total_area = 10*area;
```

```
total_pump = importdata('total_pump.csv');
pump = total_pump.data;
parametres.total_pump = pump;
m_area = importdata('minimum_area.csv');
marea = m_area.data;
parametres.minimum_area = marea;
water_req = parametres.crop_coefficient.*parametres
                    .evopatranspiration-parametres.rain;
parametres.water_req = water_req;
end
```

Listing B.3: Oblective functions and constraints

```
%% Description

% 1. This function returns the objective functions f1, and f2
%         in the vector 'fit' and constraints in the vector 'c'
%         for the chromosome 'x'.
% 2. 'V' is the number of optimization variables.
% 3. All the constraints 'c' are converted to the form h(x)<=0.

function [fit,err] = my_function(x,data)
%          Function 'my_function' to calculate fitness value and erro
%         the output for two input as specified in the problem.

% Input:
%    x - randomly generated initial population.
%    data - different data.

% Output:
%    fit - fitness value.
%    err - error
crop_coefficient = data.crop_coefficient;
crop_production = data.crop_production;
groundwater_pupming_cost = data.groundwater_pupming_cost;
surfacewater_pumping_cost= data.surfacewater_pumping_cost;
target_env_flow = data.target_env_flow;
total_area = data.total_area;
total_crop_income = data.total_crop_income;
total_pump = data.total_pump;
```

```
variable_cost = data.variable_cost;
water_inflow = data.water_inflow;
minimum_area = data.minimum_area;
water_req = data.water_req;
[crop,month] = size(crop_coefficient);
Xc = x(1:crop);
env_flow = x(crop+1:crop+month);

T1=(Xc.*crop_production)*(total_crop_income)';
water_allocation = (water_inflow - env_flow);
monthly_groundwater_pupming = Xc*water_req-water_allocation;
T2 = groundwater_pupming_cost*sum(monthly_groundwater_pupming);
T3 = Xc*variable_cost';
T4 = surfacewater_pumping_cost*sum(water_allocation);
f1 = -T1+T2+T3+T4;          % first objective function.
f2 = 0;
for m=1:month
    if target_env_flow(m)>env_flow(m)
               % second objective function.
        f2 = f2+sum(target_env_flow(m)-env_flow(m));

    end
end
c(1,1)= sum(Xc*water_req-water_allocation)-total_pump;
               % first constraint
c(1,2)= sum(Xc)-total_area;
               % second constraint
for j = 1:crop
    c(1,2+j)= Xc(j)*(minimum_area - Xc(j));
               % third constraint
end
err=(c>0).*c;
fit=[f1/10000000 f2/100];
end
```

Listing B.4: Normalisation of the constraint violation

```
function err_norm = normalisation(error_pop)

%% Description
```

```
% 1. This function normalises the constraint violation of
%        various individuals, since the range of constraint
%        violation of every chromosome is not uniform.
% 2. Input is in the matrix error_pop with size
%        [pop_size, number of constraints].
% 3. Output is a normalised vector, err_norm of size [pop_size,1]

%% Error Nomalisation
[N,nc]=size(error_pop);
con_max=0.001+max(error_pop);
con_maxx=repmat(con_max,N,1);
cc=error_pop./con_maxx;
err_norm=sum(cc,2);          % finally sum up all violations
```

Listing B.5: Non domination sorting on initial population

```
%% Description
% 1. This function is to perform Deb's fast elitist
%        non-domination sorting and crowding distance assignment.
% 2. Input is in the variable 'population' with size:
%        [size(popuation), V+M+1]
% 3. This function returns 'chromosome_NDS_CD' with size
%        [size(population),V+M+3]
% 4. A flag 'problem_type' is used to identify whether the
%        population is fully feasible (problem_type=0) or
%        fully infeasible (problem_type=1) or partly
%        feasible (problem_type=0.5).

%% Reference:
%Kalyanmoy Deb, Amrit Pratap, Sameer Agarwal, and T. Meyarivan,
%        " A Fast and Elitist Multiobjective Genetic Algorithm:
%        NSGA-II",IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION,
%        VOL. 6, No. 2, APRIL 2002.


%% function begins
function [chromosome_NDS_CD front] = NDS_CD_cons(population)
global V M problem_type

%% Initialising structures and variables
```

```
chromosome_NDS_CD1=[];
infpop=[];
front.fr=[];
struct.sp=[];
rank=1;


%% Segregating feasible and infeasible solutions

 if all(population(:,V+M+1)==0)
      problem_type=0;
      chromosome=population(:,1:V+M);
                      % All Feasible chromosomes;
      pop_size1=size(chromosome,1);
 elseif all(population(:,V+M+1)~=0)
      problem_type=1;
      pop_size1=0;
      infchromosome=population;
                      % All InFeasible chromosomes;
 else
      problem_type=0.5;
      feas_index=find(population(:,V+M+1)==0);
      chromosome=population(feas_index,1:V+M);
                      % Feasible chromosomes;
      pop_size1=size(chromosome,1);
      infeas_index=find(population(:,V+M+1)~=0);
                      % infeasible chromosomes;
      infchromosome=population(infeas_index,1:V+M+1);
end

%% Handling feasible solutions
 if problem_type==0 | problem_type==0.5
      pop_size1 = size(chromosome,1);
      f1 = chromosome(:,V+1);
                      % objective function values
      f2 = chromosome(:,V+2);
     %Non- Domination Sorting
     % First front
      for p=1:pop_size1
```

```
        struct(p).sp=find(((f1(p)-f1)<0 &(f2(p)-f2)<0)
                                | ((f2(p)-f2)==0 &(f1(p)-f1)<0)
                                | ((f1(p)-f1)==0 &(f2(p)-f2)<0));
        n(p)=length(find(((f1(p)-f1)>0 &(f2(p)-f2)>0)
                                | ((f2(p)-f2)==0 &(f1(p)-f1)>0)
                                | ((f1(p)-f1)==0 &(f2(p)-f2)>0)));
    end

    front(1).fr=find(n==0);
    % Creating subsequent fronts
    while (~isempty(front(rank).fr))
        front_indiv=front(rank).fr;
        n(front_indiv)=inf;
        chromosome(front_indiv,V+M+1)=rank;
        rank=rank+1;
        front(rank).fr =[];
        for i = 1:length(front_indiv)
            temp=struct(front_indiv(i)).sp;
            n(temp)=n(temp)-1;
        end
        q=find(n==0);
        front(rank).fr=[front(rank).fr q];

    end                              % Ranked population
    chromosome_sorted=sortrows(chromosome,V+M+1);


    %Crowding distance Assignment
    rowsindex=1;
    for i = 1:length(front)-1
      l_f=length(front(i).fr);

      if l_f > 2

      sorted_indf1 =[];
      sorted_indf2 =[];
      sortedf1 =[];
      sortedf2 =[];
          % sorting based on f1 and f2;
```

```
     [sortedf1 sorted_indf1]=
               sortrows(chromosome_sorted
               (rowsindex:(rowsindex+l_f -1),V+1));
     [sortedf2 sorted_indf2]=
               sortrows(chromosome_sorted
               (rowsindex:(rowsindex+l_f -1),V+2));

    f1min=chromosome_sorted
               (sorted_indf1(1)+rowsindex -1,V+1);
    f1max=chromosome_sorted
               (sorted_indf1(end)+rowsindex -1,V+1);

    chromosome_sorted(sorted_indf1(1)
               +rowsindex -1,V+M+2)=inf;
    chromosome_sorted(sorted_indf1(end)
               +rowsindex -1,V+M+2)=inf;

    f2min=chromosome_sorted(sorted_indf2(1)
               +rowsindex -1,V+2);
    f2max=chromosome_sorted(sorted_indf2(end)
               +rowsindex -1,V+2);

    chromosome_sorted(sorted_indf2(1)
               +rowsindex -1,V+M+3)=inf;
    chromosome_sorted(sorted_indf2(end)
               +rowsindex -1,V+M+3)=inf;

    for j = 2:length(front(i).fr)-1
      if  (f1max - f1min == 0) |
       (f2max - f2min == 0)
        chromosome_sorted(sorted_indf1(j)
               +rowsindex -1,V+M+2)=inf;
        chromosome_sorted(sorted_indf2(j)
               +rowsindex -1,V+M+3)=inf;
      else
        chromosome_sorted(sorted_indf1(j)
               +rowsindex -1,V+M+2)=
           (chromosome_sorted(sorted_indf1(j+1)
               +rowsindex -1,V+1)
```

```
            -chromosome_sorted(sorted_indf1(j-1)
               +rowsindex-1,V+1))
            /(f1max-f1min);
         chromosome_sorted(sorted_indf2(j)
               +rowsindex-1,V+M+3)=
            (chromosome_sorted(sorted_indf2(j+1)
               +rowsindex-1,V+2)
            -chromosome_sorted(sorted_indf2(j-1)
               +rowsindex-1,V+2))
            /(f2max-f2min);
           end
         end

        else
           chromosome_sorted(rowsindex:
                (rowsindex+l_f -1),V+M+2:V+M+3)=inf;
        end
        rowsindex = rowsindex + l_f;
    end
    chromosome_sorted(:,V+M+4) =
               sum(chromosome_sorted
                (:,V+M+2:V+M+3),2);
    chromosome_NDS_CD1 =
                [chromosome_sorted(:,1:V+M)
                zeros(pop_size1,1) hromosome_sorted
                (:,V+M+1)chromosome_sorted (:,V+M+4)];
                       % Final Output Variable
    end

%% Handling infeasible solutions
 if problem_type==1 | problem_type==0.5
    infpop=sortrows(infchromosome,V+M+1);
    infpop=[infpop(:,1:V+M+1)
                (rank:rank-1+size(infpop,1))'
                inf*(ones(size(infpop,1),1))];
    for kk = (size(front,2)):(size(front,2))+
                (length(infchromosome))-1;
        front(kk).fr= pop_size1+1;
    end
```

```
end
chromosome_NDS_CD = [chromosome_NDS_CD1;infpop];
```

Listing B.6: parent selection

```
function [parent_selected] = tour_selection(pool)

%% Description

% 1. Parents are selected from the population pool
%    for reproduction by using binary tournament
%    selection based on the rank and
%    crowding distance.
% 2. An individual is selected if the rank is
%    lesser than the other or if crowding
     distance is greater than the other.
% 3. Input and output are of same
%    size [pop_size, V+M+3].

%% Binary Tournament Selection
[pop_size, distance]=size(pool);
rank=distance-1;
candidate=[randperm(pop_size);randperm(pop_size)]';

for i = 1: pop_size
    parent=candidate(i,:);
       % Two parents indexes are randomly selected
    if pool(parent(1),rank)~=pool(parent(2),rank)
       % For parents with different ranks
        if pool(parent(1),rank)<pool(parent(2),rank)
       % Checking the rank of two individuals
       mincandidate=pool(parent(1),:);
       elseif pool(parent(1),rank)>pool(parent(2),rank)
         mincandidate=pool(parent(2),:);
        end
        parent_selected(i,:)=mincandidate
       % Minimum rank individual is selected finally
    else % for parents with same ranks
     if pool(parent(1),distance)>pool(parent(2),distance)
       % Checking the distance of two parents
```

```
                maxcandidate=pool(parent(1),:);
            elseif pool(parent(1),distance)< pool
                                        (parent(2),distance)
                maxcandidate=pool(parent(2),:);
            else
                temp=randperm(2);
                maxcandidate=pool(parent(temp(1)),:);
            end
            parent_selected(i,:)=maxcandidate
           % Maximum distance individual is selected finally
        end
end
```

Listing B.7: crossover and mutation

```
function mutated_child = poly_mutation(y)
global V xl xu etam pm

%% Description
% 1. Input is the crossovered child of size (1,V) in
%        the vector 'y' from 'genetic_operator.m'.
% 2. Output is in the vector 'mutated_child' of size (1,V).
%% Polynomial mutation including boundary constraint
del=min((y-xl),(xu-y))./(xu-xl);
t=rand(1,V);
loc_mut=t<pm;
u=rand(1,V);
delq=(u<=0.5).*((((2*u)+((1-2*u).*((1-del).^(etam+1)))).
        ^(1/(etam+1)))-1)+(u>0.5).*(1-((2*(1-u))+(2*(u-0.5).
        *((1-del).^(etam+1)))).^(1/(etam+1)));
c=y+delq.*loc_mut.*(xu-xl);
mutated_child=c;
```

Listing B.8: replacement

```
function new_pop=replacement(population_inter_sorted, front)
global pop_size
%% Description
% The next generation population is formed by appending
%        each front subsequently until the population size
%        exceeds the current population size. If When adding
```

```
%        all the individuals of any front, the population
%        exceeds the population size, then the required number
%        of remaining individuals alone are selected from
%        that particular front based on crowding distance.
%% code starts
index=0;
ii=1;
while index < pop_size
    l_f=length(front(ii).fr);
    if index+l_f < pop_size
        new_pop(index+1:index+l_f,:)= population_inter_sorted
                                                 (index+1:index+l_f,:);
        index=index+l_f;
    else
            temp1=population_inter_sorted(index+1:index+l_f,:);
            temp2=sortrows(temp1,size(temp1,2));
            new_pop(index+1:pop_size,:)= temp2(l_f-(pop_size-
                                                        index)+1:l_f,:);
            index=index+l_f;
    end
    ii=ii+1;
end
```

Appendix C

Result

In this appendix we include results that we have found from using the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) on the MOP Section 2.2, Chapter 2.

The results for 300 iterations is given in Tables C.1, C.2, C.3, and C.4.

The results for 600 iterations shown in Tables C.5 and C.6.

The results for 1000 iterations is focused in Tables C.7 and C.8.

The results for rainfall 10 % more, 10 % less, 20 % more, and 20 % less than the base level rainfall are given in Tables C.9, C.10, C.11, C.12, C.13, C.14, C.15, C.16, C.17, C.18, C.19, C.20, C.21, and C.22 respectively.

The model results for water inflow 10 % more, 10 % less, 20 % more, and 20 % less than the base line water inflow are shown in Tables C.23, C.24, C.25, C.26, C.27, C.28, C.29, C.30, C.31, and C.32 respectively.

The results for cyclic target environmental flow is given in Tables C.33, C.34, C.9, C.35, C.36, C.37, and C.38.

Table C.1: Details of 1- 17 Pareto solutions for the crops when maximizing total net benefits and minimizing deficit in environmental flow for 300 iterations.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
1	1452.18	1516.63	13504.46	2555.28	48610.52	6567.29	1072.37	69228.00	69227.79	16982.25	1877.48	35.53
2	1452.20	1516.63	13504.54	2545.76	48659.10	6569.55	1072.40	69228.00	69227.79	16982.02	1877.47	29.52
3	1452.89	1515.99	13504.50	2542.22	48640.24	6570.11	1072.34	69228.00	69227.77	16981.96	1877.43	28.15
4	1452.83	1515.95	13504.20	2557.02	48639.17	6570.94	1072.33	69228.00	69227.78	16985.11	1877.43	28.10
5	1452.18	1516.23	13504.35	2553.43	48621.53	6569.99	1072.36	69228.00	69227.79	16984.37	1877.42	28.07
6	1451.27	1507.02	13506.34	2552.25	48677.75	6505.70	1072.36	69228.00	69227.60	16987.30	1877.41	23.48
7	1451.39	1507.87	13505.91	2561.68	48659.80	6507.62	1072.37	69228.00	69227.60	16982.33	1877.40	23.04
8	1451.34	1509.33	13506.18	2552.71	48677.18	6505.74	1072.38	69228.00	69227.60	16982.50	1877.39	20.20
9	1451.32	1507.90	13506.36	2549.53	48661.38	6505.73	1072.37	69228.00	69227.60	16982.80	1877.38	20.06
10	1451.49	1515.86	13506.96	2555.23	48642.92	6566.26	1072.38	69228.00	69227.78	16989.75	1877.32	19.73
11	1452.97	1517.59	13506.43	2520.32	48670.56	6539.19	1072.36	69228.00	69227.79	16984.37	1877.28	19.42
12	1452.33	1517.27	13506.43	2543.84	48682.23	6540.07	1072.35	69228.00	69227.79	16982.17	1877.27	16.11
13	1452.34	1517.28	13506.44	2543.94	48679.75	6539.20	1072.35	69228.00	69227.79	16982.35	1877.27	16.08
14	1442.61	1522.08	13499.21	2854.59	48290.12	6538.69	1071.55	69228.00	69227.78	17059.79	1877.13	7.17
15	1442.54	1521.12	13499.07	2861.68	48298.97	6537.46	1071.56	69228.00	69227.78	17060.56	1877.13	5.41
16	1442.55	1521.20	13499.25	2861.65	48301.76	6537.01	1071.55	69228.00	69227.78	17059.33	1877.13	4.93
17	1441.94	1522.22	13504.05	2847.55	48308.61	6535.15	1071.56	69228.00	69227.78	17058.75	1877.05	3.19

Table C.2: Details of 18- 34 Pareto solutions for the crops when maximizing total net benefits and minimizing deficit in environmental flow for 300 iterations.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oilseeds	Pulses	Sugercane	Winter Veg-etablet	Summer Veg-etable		
18	1443.71	1521.77	13504.04	2846.21	48306.15	6539.21	1071.59	69228.00	69227.78	17060.69	1877.02	2.72
19	1443.16	1522.15	13503.99	2856.10	48294.13	6538.03	1071.57	69228.00	69227.79	17060.71	1877.01	2.67
20	1443.33	1522.05	13504.04	2849.83	48298.26	6537.86	1071.52	69228.00	69227.79	17061.53	1876.99	2.66
21	1443.33	1522.05	13504.04	2849.83	48298.26	6537.86	1071.52	69228.00	69227.79	17061.53	1876.99	2.10
22	1443.50	1521.45	13504.08	2859.98	48296.24	6539.67	1071.58	69228.00	69227.78	17060.71	1876.99	0.80
23	1452.84	1527.87	13531.50	2864.28	48205.75	6538.35	1071.70	69227.99	69227.68	17036.93	1876.98	0.362
24	1452.90	1528.23	13531.42	2864.45	48207.59	6538.36	1071.70	69227.99	69227.68	17037.71	1876.98	0.360
25	1452.83	1525.98	13531.47	2864.31	48205.78	6538.96	1071.68	69227.99	69227.69	17036.79	1876.98	0.35
26	1448.81	1551.75	13521.38	2871.88	48181.63	6520.27	1071.81	69228.00	69227.78	17041.33	1876.95	0.04
27	1448.64	1550.46	13521.32	2851.32	48182.81	6522.58	1071.79	69228.00	69227.78	17045.05	1876.87	0.017
28	1448.88	1551.25	13520.29	2851.37	48184.63	6522.41	1071.79	69228.00	69227.78	17044.01	1876.87	0.0152
29	1448.64	1551.21	13519.73	2851.22	48187.65	6522.12	1071.79	69228.00	69227.78	17044.49	1876.87	0.0151
30	1449.05	1552.30	13521.16	2851.44	48180.74	6522.62	1071.79	69228.00	69227.78	17043.59	1876.87	0.0148
31	1448.76	1551.92	13521.71	2841.49	48186.76	6521.53	1071.79	69228.00	69227.92	17043.48	1876.87	0.0133
32	1448.93	1551.42	13519.54	2851.25	48185.32	6523.30	1071.77	69228.00	69227.78	17044.14	1876.85	4.5×10^{-5}
33	1448.77	1552.20	13519.19	2851.26	48185.06	6531.23	1071.77	69228.00	69227.78	17043.90	1876.85	3.4×10^{-5}
34	1453.53	1529.59	13451.38	2854.91	48197.63	6631.99	1072.15	69227.99	69227.88	17026.76	1876.68	0.00

Table C.3: Details of 1 - 17 Pareto solutions for the environmental flow when maximizing total net benefits and minimizing deficit in environmental flow foo 300 iterations

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	99.03	97.53	90.94	99.82	128.59	163.71	101.79	101.92	92.15	144.99	249.63	84.99
2	99.07	97.52	90.70	99.82	128.53	163.65	101.81	102.09	98.50	144.97	249.64	84.88
3	99.05	97.52	91.72	99.82	128.91	163.86	101.81	103.47	98.59	143.41	251.05	85.15
4	99.09	97.56	91.45	99.82	128.57	164.00	101.80	103.44	98.61	144.97	251.08	85.37
5	99.18	97.53	91.76	99.82	128.16	163.58	101.57	103.33	98.60	144.62	250.99	85.03
6	99.10	97.76	98.16	99.82	128.97	148.95	108.04	104.21	98.47	150.96	250.91	83.22
7	99.23	97.68	96.60	99.81	128.92	148.57	108.01	104.13	98.59	150.75	250.93	85.05
8	99.12	97.75	102.24	99.82	128.62	149.37	107.98	104.18	98.57	150.95	247.60	84.54
9	99.10	97.69	102.42	99.82	128.93	149.27	107.96	104.20	98.59	150.95	247.33	84.74
10	102.56	97.41	98.15	99.85	129.43	161.82	102.16	104.14	98.58	150.96	249.81	86.28
11	99.04	97.55	100.02	99.83	135.46	163.16	101.85	103.43	98.64	150.70	251.05	85.51
12	99.06	97.50	100.11	99.83	135.23	162.97	101.85	103.43	98.67	150.83	250.93	88.82
13	99.06	97.50	100.03	99.83	135.27	162.97	101.85	103.43	98.68	150.81	250.93	88.86
14	98.97	99.79	97.85	100.00	129.43	164.92	102.12	103.78	96.24	143.52	247.57	105.07
15	98.97	99.95	97.84	99.99	129.42	164.71	102.12	103.78	97.83	143.62	247.58	104.77
16	98.99	99.95	98.09	99.99	129.38	164.73	102.15	103.77	98.05	143.72	247.55	104.77
17	99.43	99.82	97.56	100.02	126.74	165.46	102.19	103.75	100.40	150.36	251.43	105.16

Table C.4: Details of 18 - 34 Pareto solutions for the environmental flow when maximizing total net benefits and minimizing deficit in environmental flow for 300 iterations.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
18	99.38	99.90	97.99	100.00	135.32	165.52	102.20	103.79	100.40	150.66	246.96	104.76
19	99.44	99.90	97.99	100.00	135.36	165.49	102.22	103.76	100.35	150.67	246.96	104.87
20	99.45	99.90	97.99	100.00	135.36	165.53	102.22	103.76	100.43	150.67	246.95	104.87
21	99.44	99.95	98.51	100.00	135.58	165.52	102.28	103.76	101.62	150.65	246.97	105.18
22	99.38	99.82	101.30	100.00	135.31	164.09	102.24	103.79	100.36	150.67	246.87	106.24
23	100.87	100.04	99.94	100.26	136.33	150.57	101.57	103.79	99.69	148.89	251.40	107.76
24	101.05	100.04	99.92	100.27	136.16	151.21	101.59	103.79	99.72	148.81	251.54	107.69
25	100.87	100.14	99.94	100.26	136.32	151.00	101.62	103.79	99.71	148.89	251.40	107.73
26	101.21	100.02	100.10	99.95	140.85	142.66	107.29	103.07	100.13	154.12	249.87	103.96
27	101.32	100.06	100.06	99.98	141.34	153.66	107.30	102.96	100.28	153.89	249.60	103.48
28	101.29	100.06	100.07	99.98	141.42	153.61	107.64	102.96	100.24	153.89	249.66	103.50
29	101.30	100.06	100.06	99.98	141.68	153.64	107.75	102.97	100.24	153.84	249.65	103.55
30	101.37	100.06	100.19	99.99	141.37	153.20	107.55	102.95	100.28	154.02	249.62	103.54
31	101.19	100.02	100.24	99.99	141.75	153.58	107.66	102.96	100.30	153.95	249.60	103.16
32	101.26	100.14	100.00	100.00	141.58	153.99	111.48	102.96	100.23	153.63	249.69	102.06
33	101.39	100.14	100.00	100.01	141.74	154.10	111.51	102.96	100.24	153.65	249.69	102.06
34	103.76	100.35	102.73	100.37	144.91	162.29	106.26	102.56	100.42	157.08	255.90	102.07

Table C.5: Details of Pareto solutions for the crops when maximizing total net benefits and minimizing deficit in environmental flow for 600 iterations.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oilseeds	Pulses	Sugercane	Winter Veg-etablet	Summer Veg-etable		
1	1359.34	1187.93	2636.32	10391.06	45403.72	1011.75	1552.23	69228.00	53076.28	44897.37	1876.95	28.79
2	1352.36	1331.24	2623.69	10405.68	45403.22	1065.57	1552.76	69227.99	52918.83	44867.64	1876.83	16.23
3	1351.67	1331.27	2656.42	10406.77	45398.92	1066.56	1552.69	69227.99	52899.46	44867.93	1876.73	16.15
4	1363.76	1331.24	2614.55	9712.23	45523.69	1139.12	1556.00	69227.99	52863.12	45344.80	1876.66	1.77
5	1363.81	1331.24	2614.18	9699.24	45521.94	1138.88	1556.01	69227.99	52863.34	45323.20	1876.63	1.65
6	1366.26	1331.73	2644.31	9715.78	45384.43	1123.18	1557.37	69227.90	52859.01	45399.93	1876.59	1.62
7	1355.79	1331.79	2671.06	9737.43	45370.07	1021.54	1556.06	69227.90	52845.31	45416.60	1876.58	1.60
8	1361.02	1331.34	2635.10	9728.76	45366.41	1117.64	1556.11	69227.99	52850.40	45368.51	1876.50	0.77
9	1368.94	1331.17	2636.07	9689.29	45366.06	1117.71	1556.16	69227.99	52851.05	45371.10	1876.49	0.36
10	1209.79	1329.97	1885.50	10357.85	45240.21	1788.23	1561.33	69227.90	53243.27	44877.67	1876.42	0.17
11	1202.61	1329.88	1901.19	10378.08	45223.90	1821.70	1561.49	69227.89	53235.78	44859.58	1876.42	0.12
12	1075.60	1331.79	2003.98	10372.16	45196.48	1887.56	1546.13	69227.92	53183.71	44891.64	1876.36	0.04
13	1082.98	1331.74	2027.87	10378.12	45196.67	1878.93	1545.80	69227.89	53186.66	44876.65	1876.34	0.03
14	1076.97	1331.70	2024.50	10378.20	45189.88	1867.04	1545.89	69227.93	53190.33	44887.84	1876.34	0.02
15	1192.14	1330.56	1913.86	10375.42	45214.20	1772.70	1561.83	69227.91	53252.31	44852.63	1876.32	0.00

Table C.6: Details of Pareto solutions for the environmental flow when maximizing total net benefits and minimizing irrigation water for 600 iterations.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	212.46	95.98	222.25	208.12	99.83	133.76	98.63	161.31	84.10	101.09	92.88	99.79
2	217.60	103.05	215.19	208.73	100.01	122.34	98.86	161.00	91.20	99.72	94.20	99.80
3	217.33	103.04	216.47	208.65	99.99	133.74	98.86	160.97	91.33	99.73	94.14	99.79
4	207.41	108.46	237.07	208.66	100.08	133.48	103.93	164.82	98.69	100.46	100.28	99.54
5	207.87	108.87	237.92	208.66	100.08	133.48	103.48	164.76	98.81	100.47	100.55	99.54
6	214.18	102.88	237.24	208.82	100.01	133.66	103.89	165.33	99.15	99.71	100.31	99.52
7	213.03	103.31	236.47	209.49	100.04	133.63	103.98	163.81	99.11	99.70	100.05	99.59
8	212.69	109.16	237.32	208.77	100.02	133.45	103.97	165.40	99.75	100.44	99.91	99.56
9	212.81	107.54	237.52	208.77	100.03	133.45	104.20	165.38	99.80	100.45	99.88	99.96
10	225.04	105.10	236.19	204.48	102.73	132.75	104.50	152.56	102.85	99.84	105.29	99.99
11	224.11	104.86	236.07	204.72	102.78	132.79	104.50	152.59	102.98	99.88	105.37	100.18
12	228.53	101.44	235.69	201.59	100.10	133.15	102.92	167.05	100.76	99.96	103.67	100.46
13	228.60	101.54	235.02	204.89	100.10	133.12	103.01	167.18	100.80	99.96	103.68	100.47
14	227.67	101.51	235.28	204.93	103.91	133.22	103.07	165.25	100.54	99.98	102.81	100.45
15	225.88	105.06	235.71	204.61	102.45	132.90	105.38	160.75	102.20	100.06	106.82	100.35

Table C.7: Details of Pareto solutions for the crops when maximizing total net benefits and minimizing irrigation water for 1000 iterations.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
1	1066.93	1426.21	9377.00	6249.90	20997.15	1208.94	8748.70	69227.80	65860.97	46563.09	1877.54	29.57
2	1068.00	1425.95	9176.20	6251.31	20938.67	1420.98	8740.94	69227.94	65856.10	46637.86	1877.48	17.03
3	1068.02	1420.46	9365.91	6431.52	20934.35	1109.16	8741.66	69227.94	65773.73	46639.21	1877.48	16.36
4	1066.96	1426.18	9374.28	6249.91	21006.71	1206.73	8748.47	69227.80	65867.88	46561.28	1877.46	9.92
5	1066.92	1426.20	9377.70	6249.75	20998.89	1207.95	8748.71	69227.80	65865.81	46559.91	1877.41	6.93
6	1067.00	1426.08	9388.06	6249.93	20999.66	1206.34	8748.70	69227.80	65867.42	46565.94	1877.39	6.82
7	1067.00	1426.08	9388.20	6249.93	20999.66	1206.34	8748.70	69227.64	65867.43	46566.29	1877.38	6.73
8	1068.02	1425.96	9437.43	6251.14	20939.13	1118.18	8751.56	69227.90	65732.51	46649.99	1877.37	5.15
9	1065.12	1408.20	9391.21	6260.26	20940.66	1207.92	8752.83	69227.82	65734.87	46715.37	1877.35	3.06
10	1068.05	1425.94	9436.80	6251.17	20939.10	1113.57	8752.14	69227.89	65733.94	46650.04	1877.26	2.75
11	1068.07	1425.76	9437.62	6251.68	20939.08	1119.83	8913.12	69227.90	65717.58	46647.49	1877.26	2.50
12	1068.05	1425.96	9442.66	6251.17	20939.14	1113.49	8752.35	69227.89	65732.06	46651.96	1877.25	2.43
13	1068.03	1425.92	9442.97	6251.28	20937.47	1114.43	8752.56	69227.89	65731.95	46653.90	1877.25	2.42
14	1068.08	1425.66	9443.04	6251.22	20939.14	1115.50	8753.46	69227.89	65732.59	46650.41	1877.25	2.41
15	1067.39	1427.00	9416.96	6247.49	20938.35	1212.00	8766.01	69227.82	65820.48	46584.83	1877.22	2.35
16	1070.63	1429.66	9419.58	6252.69	20938.33	1209.21	8766.83	69227.83	65826.49	46585.86	1877.22	1.96
17	1070.56	1429.87	9424.08	6252.74	20938.93	1209.21	8766.41	69227.82	65820.00	46578.12	1877.20	1.92
18	1068.65	1429.88	9424.06	6252.67	20938.93	1209.24	8766.10	69227.82	65819.80	46579.49	1877.19	1.84
19	1067.38	1426.88	9416.80	6250.18	20833.23	1211.44	8765.89	69227.82	65818.89	46586.23	1877.14	1.80
20	1261.46	1382.83	9240.16	5995.73	20937.04	1343.26	8744.62	69227.86	65708.28	46573.34	1876.91	00

Table C.8: Details of Pareto solutions for the environmental flow when maximizing total net benefits and minimizing irrigation water for 1000 iterations.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	194.83	77.71	99.28	101.49	107.27	96.24	185.41	101.46	101.35	103.52	97.21	101.75
2	192.29	100.23	97.37	101.54	105.01	96.83	186.67	99.63	101.27	103.54	100.19	89.14
3	190.26	100.22	97.63	101.54	105.03	96.93	182.35	100.07	101.27	103.53	100.81	89.08
4	194.41	99.02	97.47	101.49	107.17	96.15	178.84	101.02	101.31	103.52	97.44	101.73
5	194.58	100.12	99.16	101.50	103.00	96.19	185.41	101.47	101.34	103.52	97.72	101.75
6	194.61	100.13	99.33	101.50	107.32	96.17	185.17	101.48	101.34	103.49	97.68	101.75
7	194.61	100.12	99.42	101.50	107.32	96.17	185.16	101.48	101.34	103.49	97.68	101.75
8	177.93	100.20	97.44	101.55	104.73	97.42	186.78	101.73	101.11	103.54	103.18	101.44
9	189.81	100.23	101.68	100.55	105.15	96.94	186.55	100.47	101.31	101.44	102.35	101.46
10	190.38	100.20	101.59	101.56	104.07	97.25	186.78	101.33	101.11	103.43	103.17	100.40
11	190.41	100.20	105.13	101.50	104.64	97.50	186.72	101.41	101.08	103.53	103.02	101.38
12	190.38	100.20	101.86	101.56	104.81	97.57	186.78	101.47	101.12	103.43	103.25	101.22
13	190.47	100.20	101.93	101.56	104.83	97.58	186.74	101.46	101.12	103.44	103.17	101.23
14	190.38	100.20	101.87	101.57	104.78	97.59	186.78	101.66	101.13	103.45	103.27	101.23
15	189.96	100.24	97.99	101.67	108.52	100.25	187.22	113.00	101.38	103.59	99.65	101.65
16	189.96	100.24	98.55	101.69	108.23	102.10	187.29	112.67	101.35	103.59	99.49	101.58
17	190.13	100.24	98.56	101.69	108.30	101.99	187.18	113.12	101.34	103.59	99.52	101.58
18	191.83	100.24	98.54	101.69	108.36	102.53	187.24	113.08	101.34	103.59	99.62	101.58
19	189.98	100.23	98.30	99.90	108.13	100.59	187.24	113.05	101.40	103.59	100.60	101.51
20	192.18	100.24	116.17	101.46	107.91	107.84	185.68	100.20	101.18	102.82	100.86	101.25

Table C.9: Details of 1- 15 Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 10 % more than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
1	1004.82	1053.67	3506.89	14254.97	9405.02	1019.40	2690.02	69227.96	63388.19	65199.77	1887.63	22.16
2	1004.82	1053.67	3515.36	14254.88	9405.02	1019.99	2686.47	69227.95	63388.33	65198.56	1887.59	17.28
3	1004.80	1053.67	3515.41	14254.96	9405.02	1019.40	2682.92	69227.96	63384.90	65199.05	1887.59	17.06
4	1004.81	1053.67	3515.38	14254.88	9405.02	1019.40	2682.43	69227.96	63382.00	65200.48	1887.58	16.96
5	1004.81	1053.67	3515.37	14254.89	9405.02	1019.40	2687.02	69227.96	63388.27	65198.21	1887.58	16.40
6	1005.11	1053.66	3513.63	14260.75	9405.11	1019.35	2550.96	69227.88	63546.70	65159.96	1887.50	14.61
7	1005.11	1053.66	3513.68	14261.42	9405.11	1019.35	2555.50	69227.88	63543.11	65162.38	1887.49	14.45
8	1005.11	1053.66	3513.63	14261.17	9405.11	1019.35	2548.49	69227.88	63543.43	65159.95	1887.48	14.11
9	1005.11	1053.66	3513.63	14261.18	9405.11	1019.35	2548.48	69227.88	63543.45	65159.94	1887.48	14.04
10	1005.11	1053.66	3513.63	14261.16	9405.11	1019.35	2548.33	69227.88	63543.41	65159.94	1887.48	13.72
11	1005.06	1053.66	3515.33	14254.43	9405.02	1019.40	2673.85	69227.88	63383.65	65201.53	1887.47	13.36
12	1005.04	1053.66	3515.25	14254.85	9405.02	1019.40	2676.87	69227.98	63385.21	65201.64	1887.42	9.50
13	1005.15	1053.66	3513.62	14261.87	9405.11	1019.30	2548.62	69227.88	63539.55	65161.85	1887.42	7.90
14	1005.15	1053.66	3513.62	14261.87	9405.11	1019.30	2548.65	69227.88	63539.58	65161.95	1887.42	7.80
15	1005.12	1053.87	3513.71	14261.68	9405.12	1019.30	2553.35	69227.88	63536.43	65159.94	1887.41	7.16

Table C.10: Details of 16- 27 Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 10 % more than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
16	1005.15	1053.67	3513.49	14262.12	9405.12	1019.30	2548.98	69227.88	63540.20	65159.92	1887.41	6.35
17	1004.91	1053.66	3513.64	14261.86	9405.11	1019.30	2548.60	69227.88	63543.27	65160.10	1887.40	5.50
18	1005.16	1053.66	3513.66	14261.88	9405.11	1019.30	2551.01	69227.87	63545.71	65160.08	1887.40	5.41
19	1005.16	1053.66	3513.66	14261.88	9405.11	1019.30	2551.12	69227.87	63545.65	65160.09	1887.40	5.20
20	1005.16	1053.67	3513.31	14262.05	9405.11	1019.30	2546.80	69227.88	63535.28	65182.01	1887.39	5.05
21	1005.17	1053.66	3513.89	14261.62	9405.12	1019.30	2561.46	69227.88	63545.77	65158.91	1887.36	3.63
22	1005.16	1055.99	3513.68	14261.54	9405.11	1019.30	2538.56	69227.88	63542.71	65160.03	1887.36	2.80
23	1005.20	1053.66	3513.80	14261.51	9405.11	1019.30	2553.95	69227.88	63544.45	65160.16	1887.35	2.11
24	1005.16	1054.30	3513.68	14261.49	9405.11	1019.30	2531.72	69227.88	63550.75	65159.97	1887.33	00.90
25	1005.16	1054.20	3513.73	14261.52	9405.11	1019.30	2535.22	69227.88	63547.48	65159.81	1887.33	00.34
26	1005.16	1054.20	3513.73	14261.82	9405.11	1019.30	2543.80	69227.88	63550.55	65159.81	1887.33	00.18
27	1005.16	1054.20	3513.68	14261.19	9405.11	1019.30	2538.84	69227.88	63544.97	65160.03	1887.32	0.00

Table C.11: Details of 1 - 15 Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 10 % more than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	107.38	100.54	170.85	100.81	119.68	99.70	102.86	165.81	83.79	100.06	124.52	94.35
2	107.47	100.51	171.51	100.96	119.69	99.67	102.83	165.75	84.03	99.98	124.52	99.03
3	107.26	100.57	171.13	100.86	119.68	99.37	102.84	165.92	83.56	100.01	124.50	100.2
4	107.19	100.54	171.05	100.85	119.68	99.34	102.82	166.15	83.70	100.01	124.50	100.20
5	107.45	100.58	170.81	100.81	119.68	99.63	102.86	167.02	84.01	99.96	124.52	100.21
6	112.37	102.54	157.80	101.09	119.74	91.41	102.43	192.38	95.05	100.70	124.52	98.94
7	112.73	102.49	159.23	101.07	119.75	91.55	102.36	192.37	95.06	100.70	124.52	98.93
8	112.39	102.54	159.24	101.09	119.75	91.89	102.34	192.37	95.06	100.68	124.52	98.94
9	112.39	102.54	159.24	101.07	119.75	91.96	102.34	192.37	95.06	100.68	124.52	98.95
10	112.39	102.54	159.25	101.01	119.75	92.26	102.32	192.37	95.08	100.68	124.54	98.94
11	97.32	101.13	162.05	96.77	119.80	98.67	102.82	193.87	95.29	99.80	124.71	98.79
12	107.15	100.16	161.74	97.69	119.67	100.68	97.95	193.82	95.26	99.78	124.53	99.82
13	112.68	102.44	159.22	97.63	119.74	102.63	102.32	192.24	95.36	100.71	124.54	99.12
14	112.68	102.44	159.22	97.73	119.74	102.75	102.31	192.24	95.35	100.71	124.52	99.12
15	112.38	102.50	159.16	101.08	119.58	102.93	102.09	192.19	94.88	100.83	124.51	97.96

Table C.12: Details of 16 - 27 Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 10 % more than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
16	112.60	99.29	158.67	101.09	119.74	112.87	102.20	192.24	95.29	100.64	116.86	99.06
17	112.50	102.15	158.93	101.10	119.74	102.91	102.31	192.24	95.38	100.69	124.52	99.12
18	112.48	102.48	158.85	101.06	119.74	102.89	102.17	192.24	95.16	101.67	124.52	99.43
19	112.48	102.48	158.82	101.06	119.74	102.96	102.17	192.24	95.36	101.69	124.53	99.44
20	112.39	102.24	159.88	101.11	119.74	112.10	102.28	192.24	95.88	100.64	117.18	99.07
21	112.18	102.70	167.30	101.10	119.76	98.90	98.72	192.17	101.76	98.77	124.51	99.97
22	112.39	97.53	167.32	101.09	119.74	100.25	102.37	192.24	101.47	100.67	122.39	99.67
23	112.16	102.66	167.56	101.11	119.75	99.32	98.61	192.25	101.56	100.81	123.84	99.96
24	112.49	102.48	167.26	101.06	119.74	99.98	102.46	192.23	101.59	101.12	122.30	99.12
25	112.40	102.53	167.42	101.09	119.74	100.05	102.30	192.28	101.23	100.71	122.21	99.66
26	112.40	102.55	167.43	101.11	120.44	100.06	102.45	192.26	101.20	100.75	122.23	99.82
27	112.41	102.53	167.34	101.09	119.61	100.07	102.47	192.25	101.93	100.81	122.33	100.27

Table C.13: Details of Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 10 % less than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
1	2515.48	7135.05	12084.59	2962.23	37381.95	1134.97	1094.07	69227.92	69153.55	28070.07	1868.60	59.87
2	2514.52	7075.18	12076.69	2924.95	37380.14	1148.05	1086.29	69227.92	69153.65	28079.45	1868.55	58.85
3	2508.53	7196.32	12029.30	2618.04	37383.83	1169.02	1082.65	69227.98	69184.99	28226.94	1868.53	44.69
4	2508.18	7196.81	12029.18	2620.73	37384.17	1168.73	1080.37	69227.99	69184.47	28230.35	1868.47	44.58
5	2504.82	7335.55	12063.98	2597.63	37337.14	1199.61	1127.92	69227.89	69225.80	28030.70	1868.44	42.09
6	2507.87	7339.62	12066.03	2608.87	37329.12	1202.91	1126.97	69227.89	69227.17	28039.89	1868.43	40.76
7	2507.77	7334.79	12065.92	2596.77	37328.54	1203.66	1127.53	69227.89	69226.15	28039.88	1868.43	40.74
8	2535.42	7239.20	11967.65	2525.83	37578.55	1170.87	1104.51	69227.92	69214.19	27931.91	1868.33	32.73
9	2528.13	7385.83	11897.07	2593.04	37607.39	1147.78	1128.55	69227.92	69155.63	27858.54	1868.10	23.56
10	2531.19	7249.03	11896.45	2648.95	37572.63	1144.65	1349.08	69227.92	69156.45	27847.70	1868.06	20.77
11	2606.39	5630.89	11093.18	5110.91	37264.92	1539.30	1817.68	69227.91	69218.69	27158.63	1867.80	16.02
12	2606.42	5631.07	11092.45	5110.92	37265.41	1539.67	1816.33	69227.91	69218.57	27153.13	1867.75	15.84
13	2606.62	5663.70	11036.61	5143.18	37265.41	1539.18	1813.35	69227.91	69218.91	27166.64	1867.75	14.63
14	2605.32	5650.31	11081.86	5066.92	37268.59	1535.92	1794.38	69227.91	69219.01	27180.27	1867.75	13.35
15	2625.44	5694.39	10847.14	5049.36	37251.65	1633.98	1808.97	69227.91	69219.30	27184.72	1867.72	11.05
16	2622.56	5703.89	10949.84	5047.45	37263.01	1618.56	1831.42	69227.91	69219.05	27170.82	1867.64	6.51
17	2508.20	5664.25	11045.06	5169.67	37266.31	1544.33	1852.30	69227.91	69214.10	27078.97	1867.51	4.22
18	2603.20	5665.23	11044.98	5170.17	37266.27	1544.10	1855.47	69227.91	69214.38	27083.07	1867.50	3.73
19	2603.26	5664.89	11045.08	5170.28	37266.26	1544.00	1854.47	69227.91	69214.28	27078.97	1867.49	3.64
20	2623.24	5410.50	12310.26	5326.27	37264.75	1423.47	1833.00	69227.95	69220.54	26107.53	1867.41	1.55
21	2682.28	5411.73	12310.77	5324.45	37265.03	1424.44	1829.25	69227.95	69220.50	26058.19	1867.36	1.52
22	2676.98	5449.00	12318.18	5333.37	37254.81	1429.81	1725.19	69227.94	69216.13	26123.80	1867.36	0.00

Table C.14: Details of Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 10 % less than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	98.96	203.23	51.85	147.77	142.40	116.64	217.06	89.82	109.08	99.51	208.14	140.71
2	98.09	203.31	53.91	147.86	142.40	116.61	217.07	89.53	108.97	99.62	208.60	142.23
3	98.67	209.24	68.64	147.62	141.27	118.94	208.72	90.42	108.17	97.57	204.08	147.45
4	98.64	209.25	68.62	147.62	141.29	119.09	216.73	90.74	108.16	97.42	204.08	147.50
5	104.23	207.55	67.04	141.93	141.41	118.79	213.75	90.87	108.89	100.98	202.97	145.80
6	104.43	207.91	68.94	141.66	141.36	118.88	213.78	90.30	108.83	101.00	203.29	145.89
7	104.24	207.87	68.96	141.86	141.36	118.85	213.76	90.30	108.86	100.98	202.97	145.89
8	100.70	211.90	70.06	148.80	135.68	111.94	216.66	97.21	107.29	100.26	203.98	152.34
9	110.27	211.20	79.53	148.59	141.85	111.74	216.39	96.91	110.64	100.29	201.52	152.65
10	109.78	212.16	79.23	151.30	142.08	111.41	216.18	102.62	107.38	100.30	201.58	152.89
11	131.67	180.27	90.26	138.78	144.17	110.48	218.19	96.32	101.63	102.93	228.66	97.40
12	131.67	180.27	90.26	138.74	144.16	110.36	223.69	96.36	101.61	102.97	228.66	97.55
13	131.14	180.33	91.08	138.87	144.47	111.07	223.48	96.33	101.72	104.54	226.66	97.96
14	130.75	179.35	91.48	138.81	144.45	111.07	223.50	96.34	101.66	104.68	226.67	98.83
15	132.26	173.05	100.09	139.10	144.57	107.20	223.50	95.88	101.51	104.61	228.34	93.07
16	132.08	185.17	99.31	139.05	144.49	106.93	223.71	95.88	101.76	104.52	228.94	98.30
17	134.47	180.35	96.95	139.00	144.11	111.00	228.82	100.01	102.01	98.83	225.64	108.41
18	134.42	180.34	96.37	139.00	144.11	111.00	228.87	99.89	102.03	104.69	225.54	108.75
19	134.42	180.34	96.42	139.00	144.11	111.00	228.95	99.94	102.02	104.73	225.52	109.26
20	115.92	180.75	98.59	134.86	133.21	101.94	232.86	103.63	100.48	99.86	231.08	112.70
21	115.87	180.74	98.62	134.93	133.15	102.83	232.83	103.65	101.66	99.86	230.52	114.75
22	115.59	182.46	100.41	133.50	128.08	106.27	232.13	104.04	104.93	100.79	229.38	116.20

Table C.15: Details of Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % more than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
1	8644.58	1613.97	11296.79	2422.57	25783.14	1099.32	4448.31	69227.96	65708.69	40502.52	1892.00	25.52
2	8644.35	1614.03	11281.70	2421.55	25783.91	1099.42	4411.85	69227.96	65733.36	40502.52	1892.00	20.39
3	8643.92	1614.03	11281.33	2422.52	25783.86	1099.32	4439.87	69227.99	65738.09	40502.46	1891.99	19.11
4	8644.70	1614.03	11284.67	2423.55	25783.03	1099.05	4438.79	69227.97	65731.78	40503.09	1891.96	13.43
5	8644.70	1614.02	11284.66	2423.55	25783.02	1099.05	4438.74	69227.96	65731.77	40503.09	1891.95	13.42
6	8644.70	1614.02	11284.60	2423.67	25783.01	1099.05	4439.10	69227.96	65732.01	40503.16	1891.94	13.41
7	8644.90	1613.98	11297.54	2422.71	25782.98	1099.22	4433.21	69227.96	65731.83	40503.15	1891.93	13.27
8	8644.90	1613.97	11297.87	2422.63	25782.99	1099.22	4433.36	69227.96	65732.32	40503.15	1891.93	12.96
9	8644.40	1614.10	11322.17	2422.96	25782.53	1100.02	4422.66	69227.96	65713.99	40502.85	1891.92	12.41
10	8644.34	1614.12	11292.17	2423.31	25789.40	1100.04	4439.05	69227.96	65715.75	40502.59	1891.91	12.35
11	8644.29	1614.19	11306.84	2423.24	25782.62	1099.51	4405.34	69227.96	65715.84	40502.68	1891.88	10.12
12	8644.29	1614.20	11307.40	2423.24	25782.62	1099.51	4406.02	69227.96	65715.84	40502.68	1891.87	9.82
13	8652.24	1615.37	10850.06	2391.49	25768.20	1112.74	5163.85	69227.97	65453.78	40498.54	1891.72	3.99
14	8651.80	1615.34	10851.08	2391.92	25859.88	1030.40	5145.52	69227.97	65455.45	40498.75	1891.72	0.00

Table C.16: Details of Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % more than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	171.02	100.51	104.92	177.41	289.62	103.03	211.19	114.98	117.09	81.60	103.31	92.87
2	168.38	100.57	104.93	177.66	289.58	102.93	211.00	114.99	115.42	93.91	103.32	85.70
3	168.50	100.56	104.94	177.54	289.66	102.97	211.04	114.99	117.00	93.94	103.30	86.95
4	164.74	103.20	104.91	177.62	289.61	103.03	208.53	116.06	117.08	93.40	103.19	93.17
5	164.55	103.27	104.91	177.60	289.61	103.03	211.13	114.96	117.08	93.41	103.18	93.17
6	171.02	100.55	104.91	177.62	289.60	103.03	211.13	114.94	117.10	93.43	101.69	93.16
7	171.02	99.76	104.95	177.44	289.65	103.02	211.13	115.09	117.09	93.90	103.29	93.07
8	171.02	100.58	104.95	177.44	289.65	103.02	211.12	115.09	117.09	93.98	103.28	93.06
9	171.06	100.60	104.91	177.67	289.64	103.04	213.81	114.95	113.42	93.56	103.29	94.04
10	170.87	100.49	104.85	177.50	289.67	103.04	211.07	114.91	117.18	93.55	103.26	94.09
11	168.95	100.57	104.94	178.57	289.63	102.78	211.03	115.84	117.18	93.63	103.25	96.35
12	171.06	100.57	104.94	177.37	289.63	103.03	211.02	115.81	117.19	93.63	103.25	96.55
13	171.05	96.01	105.70	160.29	287.27	104.60	212.25	114.12	112.11	100.21	103.07	105.51
14	171.05	101.14	105.69	161.68	288.36	104.52	212.52	111.70	113.58	100.02	103.10	105.34

Table C.17: Details of Pareto solutions from 1 - 20 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % less than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
1	2005.57	2007.02	1355.15	1376.73	12760.19	1235.80	13141.53	69227.99	69222.46	58422.12	1863.31	59.68
2	2005.58	2006.13	1355.06	1341.69	12758.70	1236.53	13142.95	69227.99	69222.45	58415.82	1863.29	58.79
3	2005.52	2006.09	1352.79	1336.77	12763.21	1223.57	13138.02	69227.99	69222.46	58411.75	1863.27	58.78
4	2005.27	1985.91	1362.35	1290.28	12807.17	1211.22	13104.47	69227.99	69222.30	58404.08	1863.18	57.08
5	2005.26	1985.67	1362.19	1286.02	12806.98	1208.32	13103.73	69227.99	69222.30	58402.84	1863.16	56.90
6	2000.68	2024.64	1361.33	1300.25	12813.20	1200.92	13101.32	69227.99	69220.33	58403.25	1863.14	50.64
7	2005.45	2008.12	1359.41	1296.97	12763.90	1202.14	13150.72	69227.99	69220.31	58397.00	1863.09	50.63
8	2006.37	2026.09	1370.21	1885.05	12811.62	1172.18	12884.92	69227.98	69221.93	58084.19	1863.01	44.67
9	2006.34	2021.34	1370.09	1884.72	12815.16	1204.91	12886.19	69227.98	69221.90	58079.97	1863.01	44.13
10	2006.34	2021.35	1370.11	1884.89	12815.29	1205.85	12886.33	69227.98	69221.90	58080.22	1863.01	44.00
11	2006.83	1988.29	1371.26	1890.30	12777.12	1207.18	13048.74	69227.99	69221.84	58006.44	1863.00	40.84
12	2005.62	2038.05	1343.52	1910.27	12947.35	1228.17	12791.50	69227.99	69222.12	58040.44	1862.98	36.50
13	2006.44	2024.45	1369.95	1906.78	12779.80	1204.37	12878.57	69227.98	69222.12	57959.00	1862.96	35.83
14	2006.41	2020.87	1370.09	1913.93	12802.21	1154.97	12880.51	69227.98	69222.17	58006.18	1862.88	35.32
15	2006.20	2021.07	1369.71	1901.56	12814.14	1175.01	12881.02	69227.98	69221.97	57988.33	1862.88	34.61
16	2006.20	2021.09	1369.85	1901.55	12814.14	1175.07	12881.16	69227.98	69221.97	57988.33	1862.88	34.58
17	2006.43	2020.76	1368.01	1913.73	12800.87	1155.04	12880.76	69227.98	69222.17	58007.35	1862.87	34.56
18	2006.26	2032.06	1342.32	1861.58	12836.09	1209.41	12834.48	69227.99	69222.14	58038.42	1862.83	25.47
19	2009.62	2064.26	1337.85	1863.21	12837.65	1205.15	12775.01	69227.99	69222.24	58065.41	1862.74	25.40
20	2005.32	2039.43	1342.46	1870.16	12802.42	1186.03	12833.45	69227.99	69223.29	57982.23	1862.72	22.26

Table C.18: Details of Pareto solutions from 21 - 40 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % less than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
21	2005.26	2039.26	1343.04	1870.19	12802.11	1186.46	12833.78	69227.99	69223.27	57985.76	1862.72	21.63
22	2005.29	2038.96	1343.85	1867.49	12802.42	1185.20	12833.81	69227.99	69223.28	57982.22	1862.72	21.32
23	2000.61	2042.05	1283.04	1862.70	12816.57	1082.26	12833.37	69227.99	69223.28	57981.38	1862.70	20.71
24	2009.08	2004.93	1336.33	1880.95	12824.76	1254.74	12901.25	69227.99	69223.16	57982.16	1862.70	19.12
25	2005.62	2020.02	1340.33	1870.65	12813.05	1265.34	12835.65	69227.99	69223.27	57983.81	1862.66	18.50
26	2005.54	2020.02	1340.26	1870.72	12812.53	1264.09	12834.81	69227.99	69223.28	57982.11	1862.65	18.47
27	2014.63	2031.05	1297.76	1807.81	13228.23	1831.83	12731.05	69227.99	69226.75	57305.10	1862.56	16.88
28	2014.69	2031.09	1300.03	1812.73	13223.73	1844.79	12735.98	69227.99	69226.74	57309.17	1862.56	14.98
29	1991.80	2154.09	1289.85	1738.89	13376.13	1848.15	12628.92	69227.99	69220.73	57249.77	1862.50	12.79
30	2010.96	2105.64	1288.76	1742.06	13293.21	1839.83	12773.80	69227.99	69222.54	57220.57	1862.47	12.77
31	2005.49	2117.77	1290.54	1737.03	13264.61	1783.66	12753.79	69227.99	69222.79	57259.84	1862.46	12.59
32	2010.92	2104.58	1288.17	1750.65	13293.24	1836.81	12792.79	69227.99	69222.53	57202.16	1862.45	12.23
33	2018.18	2019.96	1309.12	1736.71	13065.33	1874.17	12869.53	69227.99	69223.86	57224.11	1862.28	11.20
34	2018.12	2032.78	1308.86	1735.68	13065.22	1873.82	12874.54	69227.99	69223.87	57222.56	1862.28	11.13
35	2018.51	2032.38	1308.83	1735.50	13060.28	1874.00	12875.26	69227.99	69223.76	57221.83	1862.27	10.77
36	2010.37	1869.72	1313.87	1682.63	13156.21	1782.40	13127.90	69227.99	69225.21	57278.79	1862.12	9.82
37	2010.36	1863.61	1314.34	1694.48	13133.06	1801.47	13123.35	69227.99	69225.15	57328.09	1862.12	8.77
38	2010.33	1866.05	1314.45	1692.87	13130.94	1801.50	13127.48	69227.99	69225.09	57328.01	1862.11	8.76
39	1787.32	1938.51	1392.42	1748.13	13035.71	1848.53	13045.54	69227.99	69224.95	57393.21	1862.11	6.47
40	1781.39	1945.59	1393.54	1748.47	13036.15	1848.61	13037.22	69227.99	69224.86	57394.99	1862.09	6.44

Table C.19: Details of Pareto solutions from 41 - 51 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % less than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
41	1784.33	1932.69	1395.67	1758.84	12981.89	1833.51	13002.01	69227.99	69224.23	57402.83	1862.04	6.20
42	1781.23	1932.10	1395.88	1759.73	12978.50	1795.40	13003.36	69227.99	69224.21	57406.79	1862.03	5.89
43	1781.21	1932.13	1395.91	1759.73	12978.48	1796.60	13003.34	69227.99	69224.21	57406.79	1862.03	5.88
44	1788.26	1932.83	1399.91	1776.40	12933.19	1798.98	12994.41	69227.99	69224.57	57438.27	1862.03	5.62
45	2146.08	1111.82	1673.25	1101.07	10777.89	1459.60	15701.42	69227.98	69215.43	58240.11	1861.56	5.54
46	2150.04	1175.30	1675.23	1131.14	10730.53	1474.97	15640.53	69227.98	69215.50	58243.94	1861.56	5.53
47	1984.40	1003.69	1639.20	1011.90	10627.05	1485.58	16116.29	69227.98	69210.44	58409.09	1861.56	2.67
48	1979.89	1003.72	1639.12	1012.12	10620.13	1485.50	16118.95	69227.98	69210.43	58409.41	1861.50	2.66
49	2125.88	1082.32	1613.04	1052.43	10428.04	1473.16	16097.87	69227.99	69226.75	58342.02	1861.49	1.66
50	2125.73	1082.87	1613.24	1052.24	10428.23	1473.09	16097.53	69227.99	69226.46	58341.96	1861.49	00.72
51	2143.85	1168.63	1607.04	1153.06	10311.83	1407.00	16169.22	69227.98	69227.03	58334.88	1861.34	0.00

Table C.20: Details of Pareto solutions from 1 - 20 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % less than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	134.85	174.90	196.33	96.18	92.14	101.97	76.14	91.45	96.05	90.13	227.42	98.24
2	134.89	174.43	196.31	96.13	92.14	101.97	76.34	91.63	95.94	90.80	228.15	98.23
3	134.87	174.58	198.02	96.13	92.17	102.02	75.73	91.39	96.09	91.52	228.16	98.18
4	134.76	187.98	196.06	95.83	92.39	102.00	77.37	91.32	95.31	92.46	227.33	98.25
5	134.93	187.94	196.05	95.98	92.38	102.00	77.38	91.48	95.10	92.53	228.35	98.25
6	134.86	189.54	196.35	96.24	103.00	101.90	77.10	90.78	95.67	91.80	224.43	97.77
7	137.55	192.75	193.54	99.85	93.18	101.50	77.57	86.77	99.62	100.49	215.99	98.34
8	137.53	192.28	193.99	99.85	93.22	101.45	77.52	87.44	99.63	99.86	217.64	98.34
9	137.54	192.23	193.93	99.85	93.22	101.46	77.52	87.68	99.63	99.76	217.68	98.34
10	137.50	183.53	183.29	95.60	94.55	97.89	75.95	97.80	99.63	99.80	229.44	97.95
11	137.04	189.01	190.63	95.88	97.34	91.55	83.83	97.87	99.65	99.47	228.88	97.91
12	137.54	191.30	192.30	99.89	92.03	102.03	77.14	97.43	99.62	99.73	202.13	98.33
13	137.55	191.53	193.29	99.30	93.15	101.96	76.95	97.49	100.47	99.49	216.22	98.31
14	137.55	191.72	193.00	99.88	93.21	101.97	77.33	97.51	99.62	99.51	216.29	98.34
15	137.55	191.72	193.01	99.88	93.21	101.97	77.34	97.51	99.62	99.52	216.32	98.34
16	137.55	191.57	193.29	99.95	93.23	101.96	77.00	97.48	100.46	99.49	216.60	98.30
18	128.32	187.98	194.50	97.26	97.80	102.45	84.35	97.86	99.54	100.20	228.97	97.72
19	138.03	190.70	195.01	97.47	97.80	102.09	84.54	97.85	99.23	101.25	228.87	97.71
20	138.17	183.87	191.11	97.46	97.03	102.87	87.58	98.30	99.68	99.64	228.66	98.04

Table C.21: Details of Pareto solutions from 21 - 40 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % less than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
21	138.17	183.64	191.12	97.51	97.10	102.89	87.78	98.56	99.68	99.68	228.98	98.05
22	138.17	183.98	191.15	97.39	97.06	102.85	87.80	98.30	99.68	99.64	228.16	98.79
23	138.16	179.75	190.70	97.42	97.04	102.88	87.63	98.35	99.69	99.86	228.49	99.32
24	138.72	191.29	191.29	97.42	97.10	101.19	91.19	98.24	99.56	99.51	227.93	97.86
25	138.16	191.84	192.27	97.54	97.05	101.19	91.08	98.28	99.61	101.67	227.92	97.93
26	138.16	191.86	192.27	97.46	96.99	101.18	91.25	98.28	99.61	101.65	227.86	97.93
27	132.99	200.28	166.92	95.93	100.52	98.76	89.78	98.65	102.34	115.14	226.39	103.76
28	133.01	200.13	165.22	95.93	100.49	98.71	90.38	101.79	102.19	114.42	226.37	103.82
29	137.52	193.33	173.36	95.43	101.95	101.89	94.56	98.76	98.47	118.98	226.74	104.55
30	137.60	194.74	170.32	97.07	102.69	101.65	94.25	97.48	98.43	117.92	226.05	104.73
31	137.58	195.70	169.65	95.77	101.99	101.61	94.39	98.81	98.44	117.70	226.56	104.87
32	137.61	195.12	169.89	97.12	102.95	101.66	94.77	97.48	98.40	117.86	226.09	104.73
33	138.12	196.06	170.25	95.79	101.72	101.82	94.37	102.27	98.64	118.66	226.01	104.30
34	138.12	196.28	170.35	95.96	101.67	101.83	94.29	102.31	98.62	118.68	226.07	104.41
35	138.37	196.23	170.39	95.98	101.65	101.86	94.69	102.35	98.56	118.97	226.06	104.41
36	138.12	212.30	175.30	101.06	99.89	105.43	90.62	100.55	99.67	123.54	233.29	101.27
37	138.16	209.98	175.34	101.39	101.29	105.41	91.40	100.70	99.82	127.46	233.13	101.03
38	138.16	209.96	175.20	101.47	101.85	105.47	91.41	100.69	99.82	127.37	233.13	101.10
39	136.72	213.22	178.28	100.99	100.59	101.97	94.47	100.79	99.07	125.92	231.50	101.13
40	136.72	213.12	178.23	101.14	100.59	103.25	94.47	100.82	99.09	126.52	232.62	100.96

Table C.22: Details of Pareto solutions from 41 - 51 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using rainfall is 20 % less than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
41	136.28	213.12	178.16	101.26	100.60	103.34	93.80	100.82	100.04	126.50	232.45	100.99
42	136.28	213.18	177.74	101.28	100.48	103.37	94.11	100.82	100.01	126.22	232.44	101.28
43	136.28	213.18	177.75	101.28	100.48	103.37	94.11	100.82	100.01	126.89	232.44	101.28
44	136.40	213.19	178.04	101.28	100.45	103.61	94.38	100.83	100.00	126.11	232.28	101.28
45	126.56	213.06	167.37	98.22	103.23	96.24	101.28	101.85	103.43	128.16	226.09	101.73
46	126.20	212.43	167.38	98.19	103.45	96.27	101.01	101.86	103.30	127.84	226.13	101.77
47	120.68	217.11	177.05	100.25	101.24	97.33	100.11	100.58	101.99	129.94	221.85	101.38
48	120.61	217.11	177.05	100.26	101.22	97.34	100.08	100.57	109.60	129.92	221.86	101.39
49	117.83	217.23	163.28	100.60	102.02	98.34	100.90	101.10	103.32	131.44	224.54	101.47
50	117.83	217.27	163.31	100.60	102.06	99.28	100.90	101.10	103.31	131.41	224.56	101.46
51	125.83	213.44	177.51	100.63	100.87	101.23	101.02	100.50	103.07	127.14	226.51	101.26

Table C.23: Details of Pareto solutions from 1 - 21 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 10 % more than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
1	1043.03	4706.86	7339.41	1211.74	17737.24	1262.61	1177.66	69227.97	64680.65	62288.78	1884.31	34.86
2	1043.51	4712.08	7339.05	1212.01	17729.22	1262.53	1177.55	69227.97	64686.59	62285.38	1884.31	34.54
3	1044.02	4739.55	7334.69	1211.92	17723.38	1268.09	1179.54	69227.99	64616.30	62329.06	1884.26	32.98
4	1043.66	4741.08	7329.97	1212.28	17728.98	1268.26	1179.83	69227.99	64603.47	62326.21	1884.25	32.46
5	1037.69	4871.84	7298.66	1202.43	17594.89	1263.61	1208.56	69227.98	64327.84	62710.16	1884.20	28.89
6	1038.01	4871.76	7296.78	1202.42	17593.93	1263.64	1207.92	69227.98	64327.06	62699.11	1884.19	28.58
7	1037.07	4882.77	7320.37	1191.01	17524.94	1263.05	1211.91	69227.98	64383.91	62620.70	1884.12	28.54
8	1045.00	4985.66	7416.30	1209.26	17618.45	1409.32	1191.41	69227.99	64430.15	62215.33	1884.11	28.53
9	1037.55	5036.92	7277.44	1201.84	17599.02	1271.68	1223.96	69227.98	64330.41	62516.33	1884.11	26.58
10	1044.87	4906.99	7512.01	1210.36	17627.17	1264.90	1175.69	69227.98	64419.72	62323.25	1884.08	24.23
11	1036.91	4969.89	7307.57	1198.94	17602.62	1261.30	1213.63	69227.97	64348.46	62580.41	1884.05	18.14
12	1036.60	4886.30	7284.73	1199.71	17575.77	1257.37	1215.48	69227.98	64324.41	62601.86	1883.99	17.85
13	1047.14	5213.06	7329.69	1214.27	17531.13	1923.11	1181.46	69227.98	63680.97	62151.64	1883.11	13.13
14	1060.98	8928.70	8881.61	1244.22	17016.91	1049.69	1065.16	69227.84	63099.50	59158.80	1882.42	7.32
15	1060.98	8924.67	8881.58	1244.24	17017.67	1049.65	1065.07	69227.84	63097.19	59156.20	1882.41	0.07
16	1060.98	8918.97	8883.45	1244.34	17018.08	1049.81	1065.07	69227.84	63095.60	59160.19	1882.41	7.30
17	1061.30	9058.15	8864.72	1241.63	16997.93	1044.31	1071.64	69227.84	63203.23	58928.06	1882.37	7.25
18	1061.09	9057.62	8858.06	1243.56	16990.64	1049.37	1069.29	69227.84	63204.33	58933.68	1882.36	6.59
19	1061.91	9058.50	8968.90	1236.41	16994.89	1124.06	1067.77	69227.84	63213.60	58788.78	1882.31	6.40
20	1032.07	8678.23	9068.46	1228.07	16959.79	1123.82	1058.86	69227.80	63331.20	58889.27	1882.30	6.30
21	1031.37	8671.03	9068.58	1228.18	16959.80	1123.82	1058.84	69227.80	63330.68	58892.27	1882.30	4.15

Table C.24: Details of Pareto solutions from 22 - 42 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 10 % more than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
22	1032.93	8657.15	9068.59	1228.18	16959.96	1123.77	1058.95	69227.80	63330.23	58892.81	1882.30	3.91
23	1060.82	8714.48	9152.54	1237.51	16909.12	1112.28	1063.09	69227.79	63338.90	58891.13	1882.27	3.85
24	1030.82	9000.02	9084.70	1227.74	16947.49	1123.20	1062.06	69227.79	63336.23	58717.82	1882.26	3.71
25	1032.71	8997.67	9086.97	1225.51	16948.18	1121.88	1062.26	69227.79	63326.61	58721.96	1882.26	3.12
26	1031.48	8997.54	9090.40	1225.56	16947.13	1121.91	1062.25	69227.79	63326.74	58718.54	1882.25	3.07
27	1033.81	8878.58	9270.32	1230.97	16877.56	1132.61	1069.86	69227.80	63325.60	58666.68	1882.19	2.99
28	1060.81	8856.83	9054.49	1237.69	16911.35	1114.66	1067.79	69227.79	63318.14	58818.13	1882.17	2.56
29	1060.79	8853.74	9054.34	1237.97	16911.26	1114.41	1067.81	69227.79	63318.17	58820.26	1882.17	2.52
30	1063.21	9013.51	9046.34	1228.54	16978.96	1119.73	1065.90	69227.79	63321.48	58659.86	1882.15	2.50
31	1063.21	9007.81	9048.22	1228.64	16979.38	1119.90	1065.89	69227.79	63319.89	58663.85	1882.15	2.02
32	1063.27	9007.82	9048.17	1229.68	16979.64	1119.89	1065.68	69227.79	63319.98	58663.86	1882.15	2.00
33	1063.22	9008.07	9048.42	1228.58	16978.46	1119.90	1065.84	69227.79	63321.13	58662.70	1882.15	1.58
34	1061.69	8999.84	9057.06	1228.61	16979.05	1119.54	1065.84	69227.79	63321.41	58662.70	1882.15	1.52
35	1061.83	8888.35	9073.83	1284.51	17032.24	1107.46	1066.10	69227.78	63232.34	58692.79	1882.13	1.48
36	1061.83	8887.87	9073.92	1284.46	17028.92	1106.73	1066.05	69227.78	63232.39	58689.95	1882.11	00.79
37	1065.16	9028.84	9039.26	1285.26	16999.45	1110.87	1071.42	69227.77	63218.15	58675.82	1882.10	00.78
38	1062.68	9007.92	9039.92	1285.98	16998.94	1110.67	1071.65	69227.78	63216.70	58676.54	1882.09	00.61
39	1061.90	9007.49	9044.14	1283.07	16998.28	1109.78	1071.46	69227.77	63213.10	58676.06	1882.09	00.60
40	1062.00	9007.49	9057.65	1285.64	16998.65	1109.46	1071.27	69227.77	63213.12	58680.56	1882.08	00.56
41	1062.70	9056.51	9072.68	1287.78	16992.58	1104.42	1073.53	69227.77	63197.57	58682.22	1882.08	00.55
42	1068.10	8758.32	9081.86	1284.56	17064.19	1106.96	1067.85	69227.78	63241.15	58667.97	1882.05	00.00

Table C.25: Details of Pareto solutions from 1 - 21 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 10 % more than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	117.63	208.77	98.30	92.83	134.73	64.44	63.40	68.16	118.09	79.58	114.64	236.08
2	117.64	208.72	98.48	92.84	134.75	64.37	63.39	68.16	118.01	79.57	114.77	236.09
3	117.58	209.75	98.66	92.67	133.90	64.50	63.48	68.05	118.98	80.83	114.95	236.08
4	117.63	209.75	99.19	92.69	133.88	64.54	63.48	68.05	118.95	80.79	114.92	236.10
5	118.54	207.24	102.30	92.24	136.07	63.59	63.41	68.02	117.84	79.18	118.38	237.70
6	118.55	207.24	102.00	92.24	136.08	63.59	63.41	68.02	117.85	79.50	118.38	237.68
7	118.61	207.80	102.36	92.24	135.58	63.45	63.00	68.08	120.41	79.44	118.41	237.45
8	118.38	207.76	98.70	92.31	132.17	64.56	63.48	68.21	117.21	81.12	118.27	234.65
9	118.11	205.86	102.34	92.38	134.23	63.31	62.91	67.94	120.23	81.99	118.32	236.85
10	117.50	208.90	99.35	92.58	137.25	64.43	63.37	68.09	117.59	85.43	118.49	234.77
11	119.11	207.00	102.29	92.29	136.68	63.62	62.69	68.20	120.91	87.75	120.30	238.27
12	118.92	207.24	102.30	92.31	135.53	63.66	63.04	68.16	120.57	88.23	120.24	237.86
13	120.75	225.92	101.17	90.88	144.51	64.23	70.77	67.85	114.90	92.46	118.66	234.82
14	126.31	163.52	101.19	89.01	163.94	66.45	49.61	61.68	82.37	100.63	123.49	206.61
15	126.31	163.53	101.19	89.02	163.93	66.45	49.64	61.68	82.37	100.63	123.49	206.61
16	126.31	163.75	101.03	89.02	163.95	66.44	49.65	61.61	82.46	100.65	123.67	206.65
17	125.64	161.74	101.21	88.75	163.06	66.59	50.18	61.52	83.14	100.35	123.67	206.72
18	125.68	161.81	101.32	89.11	164.32	66.53	50.24	61.76	82.72	100.51	123.65	206.70
19	128.19	166.37	100.30	88.95	160.39	63.06	49.63	61.21	83.92	100.66	123.73	209.94
20	125.98	167.06	104.39	89.47	166.72	59.78	49.79	65.54	87.53	98.21	118.59	209.86
21	125.94	166.97	104.39	89.47	166.71	59.93	49.79	65.54	87.53	98.31	118.59	209.81

Table C.26: Details of Pareto solutions from 22 - 42 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 10 % more than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22	125.95	166.94	104.39	89.48	166.61	59.94	49.78	65.54	87.57	98.35	118.60	209.80
23	126.42	170.02	102.33	89.43	168.65	66.58	49.72	65.64	83.58	100.11	118.56	211.24
24	126.01	169.18	104.53	89.44	167.25	59.71	50.07	65.42	86.88	98.78	118.94	211.29
25	125.99	169.33	104.53	89.44	167.26	59.89	50.05	65.52	86.80	98.89	118.71	211.21
26	125.98	169.33	104.53	89.44	167.27	60.10	50.07	65.51	86.80	98.85	118.71	211.21
27	126.60	167.85	105.11	89.63	169.60	59.86	50.18	64.66	85.89	99.74	118.56	211.25
28	126.41	169.57	104.52	89.46	168.83	66.59	49.47	65.69	85.55	100.05	118.55	211.66
29	126.41	169.56	104.52	89.47	168.83	66.59	49.46	65.69	85.63	100.04	118.57	211.67
30	126.44	169.93	104.62	89.30	167.91	66.56	51.11	65.76	85.53	100.12	118.67	211.12
31	126.44	170.16	104.46	89.31	167.93	66.56	51.13	65.69	85.62	100.14	118.69	211.16
32	126.40	170.12	104.47	89.31	167.94	66.55	51.11	65.70	85.60	100.14	119.11	211.22
33	126.26	170.12	104.46	89.31	167.92	66.57	51.15	65.69	85.64	100.14	119.17	211.15
34	126.26	170.13	104.45	89.32	167.90	66.98	51.16	65.69	85.65	100.17	119.20	211.15
35	125.53	167.12	104.75	89.21	165.58	66.57	50.09	65.52	86.08	100.41	123.73	210.58
36	125.57	167.08	105.63	89.21	165.60	66.54	50.08	65.99	86.08	100.41	123.73	210.64
37	125.47	167.88	104.76	89.39	167.17	66.21	50.20	65.55	86.33	100.12	123.82	210.20
38	125.44	167.83	104.76	89.39	167.18	66.63	50.16	65.55	86.34	100.13	123.82	210.20
39	125.49	168.10	104.82	89.39	167.12	66.90	50.19	65.37	86.43	100.06	123.52	210.09
40	125.41	168.46	104.79	89.45	167.18	66.89	50.18	65.31	85.97	100.07	123.94	211.97
41	125.44	170.04	104.87	89.45	167.37	66.90	50.71	65.41	86.61	100.28	123.88	210.63
42	125.47	168.17	104.43	93.70	166.34	66.55	50.49	65.56	85.37	100.73	123.73	209.62

Table C.27: Details of Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 10 % less than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
1	3778.84	7349.30	12859.38	2049.11	17670.05	1210.82	1297.38	69228.00	47075.99	68208.69	1873.59	31.37
2	3778.84	7358.99	12862.99	2049.25	17669.01	1209.51	1297.38	69228.00	47079.53	68208.88	1873.55	26.22
3	3779.13	7059.31	13017.55	2049.36	17671.97	1203.88	1297.59	69228.00	47081.83	68211.38	1873.53	26.12
4	3778.94	7330.60	12867.01	2049.37	17669.80	1209.17	1297.39	69228.00	47084.79	68210.59	1873.52	24.70
5	3778.88	7341.60	12880.43	2046.83	17670.17	1208.81	1297.68	69228.00	47080.81	68219.22	1873.52	24.69
6	3793.26	7136.18	13014.62	2047.36	17669.19	1190.82	1297.39	69228.00	47072.17	68207.19	1873.52	16.38
7	3778.86	7278.20	12998.45	2065.77	17642.01	1198.00	1301.61	69228.00	47053.05	68208.36	1873.47	13.94
8	3779.23	7043.12	13014.10	2049.01	17671.24	1204.02	1299.05	69228.00	47152.30	68214.78	1873.47	13.85
9	3782.43	7047.30	13046.60	2122.01	17638.01	1185.22	1294.48	69228.00	47106.82	68241.63	1873.46	9.34
10	3782.46	7047.07	13046.46	2121.98	17638.00	1185.43	1295.63	69228.00	47106.79	68241.61	1873.43	8.09
11	3782.53	7042.10	13045.65	2123.80	17638.00	1185.57	1295.42	69228.00	47107.74	68241.54	1873.42	7.89
12	3781.34	7042.66	13050.05	2045.94	17637.77	1185.66	1395.06	69228.00	47133.98	68246.31	1873.41	5.73
13	3781.22	7042.90	13053.78	2048.03	17637.83	1185.67	1391.94	69228.00	47132.81	68246.78	1873.40	2.82
14	3781.23	7042.90	13054.24	2048.21	17637.83	1185.67	1391.94	69228.00	47132.81	68246.78	1873.40	2.71
15	3782.52	7046.95	13046.42	2119.39	17637.79	1185.82	1288.88	69228.00	47107.16	68240.73	1873.39	2.47
16	3781.20	7042.77	13047.32	2046.29	17637.86	1188.03	1297.79	69228.00	47108.93	68244.67	1873.39	00.31
17	3781.18	7053.09	13045.09	2046.33	17638.49	1187.43	1297.39	69228.00	47109.15	68245.70	1873.39	00.26
18	3781.18	7053.03	13045.09	2046.33	17638.47	1187.46	1291.15	69228.00	47109.14	68245.67	1873.38	00.19
19	3780.05	7043.84	13051.78	2046.18	17637.52	1185.73	1389.83	69228.00	47135.41	68246.95	1873.35	00.01
20	3780.07	7043.79	13046.74	2046.37	17637.52	1037.30	1391.13	69228.00	47135.44	68248.50	1873.34	0.00

Table C.28: Details of Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 10 % less than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	121.53	143.13	102.07	85.06	119.95	252.22	53.73	63.84	78.18	85.02	124.82	125.22
2	121.36	143.04	102.05	92.40	120.06	252.23	53.72	63.83	78.00	85.59	124.85	125.30
3	121.20	143.07	100.93	92.39	120.16	252.20	46.59	53.72	77.37	100.19	124.85	125.24
4	121.15	143.86	102.05	92.39	120.07	252.23	53.91	63.82	77.35	87.99	124.86	125.25
5	121.44	143.97	104.18	92.39	120.16	252.24	53.89	63.33	77.58	87.95	124.85	125.30
6	121.35	135.91	102.19	92.39	119.87	252.27	47.41	63.94	75.92	100.15	124.85	125.35
7	121.10	137.47	98.53	92.23	122.07	252.57	53.91	64.01	77.42	100.78	124.78	125.29
8	121.47	143.96	102.04	92.37	120.15	250.48	53.88	64.22	75.46	100.08	125.06	125.52
9	128.90	135.60	100.80	88.53	121.51	252.47	51.00	63.47	88.83	100.66	124.60	118.67
10	128.90	135.60	100.76	92.31	121.51	252.55	51.02	63.48	88.84	100.65	124.60	118.44
11	128.79	135.59	100.72	92.31	121.51	252.55	51.11	63.49	89.43	100.65	124.61	118.62
12	129.68	137.26	102.13	84.72	121.59	252.57	53.79	64.54	89.29	100.81	121.26	127.83
13	129.91	137.19	102.13	92.31	121.59	252.57	47.68	64.51	89.02	100.81	124.63	125.30
14	129.91	137.20	102.13	92.31	121.59	252.57	47.78	64.51	89.01	100.80	124.72	125.30
15	128.87	135.11	100.66	92.31	121.59	252.56	50.90	62.53	87.98	100.63	124.61	125.09
16	128.35	137.37	102.11	92.30	112.94	252.58	53.49	64.85	88.36	100.41	122.84	124.84
17	128.12	137.08	102.11	92.30	113.07	252.58	53.49	64.86	88.32	100.58	124.59	124.88
18	128.16	137.07	102.11	92.30	113.25	252.59	53.49	64.87	88.36	100.58	124.59	124.94
19	129.85	136.83	102.15	92.30	121.59	252.58	53.52	64.99	89.36	100.77	124.60	125.30
20	130.77	136.88	102.15	92.30	121.58	247.32	53.54	65.03	89.36	100.72	124.58	125.06

Table C.29: Details of Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 20 % more than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
1	2811.07	1905.23	2133.96	1007.96	24690.29	15649.12	4866.23	69227.46	63724.82	44693.47	1880.96	53.18
2	2710.30	1962.63	2098.84	1056.71	24705.20	15688.23	4864.35	69227.51	63745.96	44684.38	1880.94	49.87
3	1071.33	2893.08	1792.93	1642.68	23848.55	15949.62	4616.74	69227.74	65078.22	44599.49	1880.91	10.53
4	1068.65	2893.03	1792.81	1642.65	23848.55	15955.19	4616.67	69227.74	65077.98	44599.02	1880.89	8.74
5	1069.56	2892.73	1792.78	1645.40	23848.50	15954.61	4616.67	69227.73	65079.67	44599.31	1880.89	8.37
6	1057.01	2892.85	1792.67	1643.81	23848.44	15954.37	4616.69	69227.74	65084.67	44599.01	1880.89	8.13
7	1053.81	2900.22	1783.13	1726.45	23846.05	16074.22	4617.87	69227.86	64903.22	44597.51	1880.82	6.99
8	1022.24	2886.16	1773.79	1730.85	23877.24	15985.97	4616.40	69227.84	64995.48	44598.42	1880.81	6.54
9	1240.56	2832.86	1768.04	1699.41	23851.27	15885.69	4624.83	69227.90	65031.59	44561.10	1880.80	0.70
10	1238.22	2831.68	1767.80	1700.79	23851.15	15891.10	4624.82	69227.90	65019.29	44560.75	1880.79	0.69
11	1242.52	2832.33	1767.50	1698.40	23851.23	15885.87	4624.75	69227.90	65020.32	44561.16	1880.79	0.68
12	1241.03	2831.76	1767.77	1698.33	23851.22	15885.87	4624.72	69227.90	65019.28	44561.10	1880.79	0.67
13	1213.94	2886.39	1782.55	1725.16	23846.97	15907.58	4617.87	69227.85	64899.39	44561.44	1880.71	0.54
14	1213.48	2888.82	1782.35	1725.14	23846.97	15907.33	4618.22	69227.85	64900.46	44561.72	1880.70	0.53
15	1225.93	2888.73	1782.36	1726.69	23847.03	15903.76	4618.19	69227.91	64894.20	44562.01	1880.66	0.00

Table C.30: Details of Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 20 % more than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	171.02	100.51	104.92	177.41	289.62	103.03	211.19	114.98	117.09	81.60	103.31	92.87
2	168.38	100.57	104.93	177.66	289.58	102.93	211.00	114.99	115.42	93.91	103.32	85.70
3	168.50	100.56	104.94	177.54	289.66	102.97	211.04	114.99	117.00	93.94	103.30	86.95
4	164.74	103.20	104.91	177.62	289.61	103.03	208.53	116.06	117.08	93.40	103.19	93.17
5	164.55	103.27	104.91	177.60	289.61	103.03	211.13	114.96	117.08	93.41	103.18	93.17
6	171.02	100.55	104.91	177.62	289.60	103.03	211.13	114.94	117.10	93.43	101.69	93.16
7	171.02	99.76	104.95	177.44	289.65	103.02	211.13	115.09	117.09	93.90	103.29	93.07
8	171.02	100.58	104.95	177.44	289.65	103.02	211.12	115.09	117.09	93.98	103.28	93.06
9	171.06	100.60	104.91	177.67	289.64	103.04	213.81	114.95	113.42	93.56	103.29	94.04
10	170.87	100.49	104.85	177.50	289.67	103.04	211.07	114.91	117.18	93.55	103.26	94.09
11	168.95	100.57	104.94	178.57	289.63	102.78	211.03	115.84	117.18	93.63	103.25	96.35
12	171.06	100.57	104.94	177.37	289.63	103.03	211.02	115.81	117.19	93.63	103.25	96.55
13	171.05	96.01	105.70	160.29	287.27	104.60	212.25	114.12	112.11	100.21	103.07	105.51
14	171.05	101.14	105.69	161.68	288.36	104.52	212.52	111.70	113.58	100.02	103.10	105.34

Table C.31: Details of Pareto solutions for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 20 % less than normal day.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Vegetable	Summer Vegetable		
1	1640.57	9993.25	5574.76	4565.30	17740.23	7824.60	1943.46	69228.00	60960.44	51266.16	1870.46	13.98
2	1574.97	9989.79	5607.44	4565.91	17742.87	7822.92	1943.43	69228.00	60956.51	51263.67	1870.45	12.06
3	1575.37	9989.84	5602.56	4563.06	17742.82	7822.93	1943.61	69228.00	60971.52	51265.84	1870.39	11.81
4	1641.49	9994.49	5594.03	4565.43	17743.35	7825.52	1953.29	69228.00	60917.04	51253.81	1870.36	11.78
5	1621.34	9993.95	5564.64	4604.88	17740.22	7647.13	1953.33	69228.00	61030.20	51245.23	1870.33	02.08
6	1624.67	9993.94	5561.76	4605.03	17740.22	7636.97	1953.14	69228.00	61030.39	51245.08	1870.32	01.67
7	1650.64	9994.30	6910.49	4515.47	17748.81	7865.81	1952.02	69228.00	59597.78	51288.47	1869.69	01.65
8	1650.62	9994.40	6910.55	4515.67	17748.85	7866.22	1952.01	69228.00	59598.38	51287.61	1869.69	01.64
9	1647.73	9993.71	6923.04	4487.38	17752.46	7870.54	1953.69	69228.00	59569.05	51331.58	1869.67	01.26
10	1647.24	9993.75	6950.89	4475.71	17752.63	7866.81	1953.39	69228.00	59578.72	51302.88	1869.66	01.21
11	1649.48	9994.33	6959.11	4506.90	17749.27	7870.31	1953.42	69228.00	59522.88	51287.78	1869.61	01.08
12	1347.46	9977.25	6889.65	5308.76	17549.60	8124.49	1954.70	69228.00	59832.26	50536.11	1869.60	0.78
13	1347.91	9976.92	6885.28	5310.76	17549.54	8124.57	1954.68	69228.00	59829.65	50538.73	1869.60	0.77
14	1347.87	9976.94	6885.05	5310.87	17549.54	8124.57	1954.68	69228.00	59829.64	50538.76	1869.60	0.76
15	1359.61	9977.16	6893.39	5332.58	17546.93	8122.29	1954.66	69228.00	59826.35	50477.00	1869.57	0.75
16	1375.71	9977.34	6892.06	5338.20	17544.82	8122.63	1954.67	69228.00	59834.53	50486.51	1869.53	0.27
17	1356.33	9976.94	6891.56	5329.10	17546.76	8122.21	1954.66	69228.00	59827.60	50476.61	1869.51	0.26
18	1358.30	9980.35	6892.25	5341.01	17541.24	8133.34	1954.64	69228.00	59820.54	50468.22	1869.50	0.25
19	1302.44	9994.65	6938.32	5371.88	17556.48	8120.26	1954.81	69228.00	59740.09	50469.57	1869.49	0.00

Table C.32: Details of Pareto solutions for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using water inflow is 20 % less than normal day.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	194.05	117.48	103.09	155.29	61.10	221.92	126.66	66.28	84.98	114.31	166.32	124.94
2	193.97	116.95	103.09	155.25	62.99	221.75	117.71	66.27	97.52	115.02	161.56	124.95
3	193.94	116.95	103.19	155.28	63.24	221.60	126.65	66.27	97.52	114.91	161.56	124.94
4	193.95	117.25	103.11	155.34	63.30	221.87	126.66	66.26	97.67	114.07	161.56	124.92
5	193.84	117.10	103.01	155.42	72.97	221.88	126.67	66.27	97.05	113.90	161.47	124.95
6	193.84	117.10	103.01	155.42	73.38	221.88	126.67	66.27	97.06	113.93	161.46	124.95
7	195.22	120.31	103.11	154.34	73.68	212.52	126.59	66.28	96.26	112.44	161.54	124.67
8	195.22	120.31	102.97	154.34	73.68	212.72	126.59	66.31	96.26	112.43	161.52	124.67
9	195.21	119.95	103.07	153.68	74.06	215.02	126.81	66.28	96.56	114.10	161.66	124.67
10	195.17	119.96	103.07	153.67	74.12	215.01	126.80	66.28	96.58	114.11	161.66	124.67
11	195.22	120.11	103.11	154.30	74.04	215.42	126.83	66.28	96.28	112.55	161.58	124.88
12	186.87	118.22	102.11	132.74	75.99	221.83	126.97	66.32	102.16	99.49	161.69	124.74
13	186.86	118.21	102.08	133.09	75.88	221.83	126.94	66.32	102.09	99.49	161.41	124.75
14	186.86	118.21	102.08	133.09	75.89	221.83	126.97	66.32	102.12	99.49	161.42	124.75
15	186.70	118.27	102.15	132.85	75.88	221.88	118.56	66.33	107.50	100.43	161.55	124.74
16	186.06	118.27	102.18	133.02	75.92	221.89	126.98	66.32	107.70	100.56	161.68	124.74
17	186.70	118.27	102.18	132.83	75.89	221.88	126.98	66.33	107.50	100.43	161.68	124.74
18	186.91	118.38	102.12	132.91	75.73	221.92	126.98	66.33	107.29	100.26	161.64	124.75
19	190.96	118.15	101.09	133.16	76.77	221.85	126.79	66.17	107.41	100.46	152.35	125.10

Table C.33: Details of Pareto solutions from 1 - 20 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using cyclic environmental flow.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
1	1120.67	1322.60	12498.81	1236.88	11983.44	1516.33	6865.64	69227.58	69198.90	55778.18	1880.81	144.47
2	1188.48	1297.83	12520.59	1238.31	12061.66	1452.12	6823.74	69227.58	69207.72	55734.23	1880.77	143.21
3	1234.35	1349.73	12413.71	1289.19	13127.60	1396.86	5811.17	69227.95	69172.89	55715.59	1880.77	90.06
4	1234.35	1345.41	12416.12	1289.51	13132.53	1393.07	5810.20	69227.95	69173.05	55709.42	1880.71	89.54
5	1241.19	1337.92	12421.94	1291.36	13146.51	1371.45	5391.11	69227.97	69161.20	55931.24	1880.69	87.62
6	1234.87	1349.36	12427.83	1288.83	13142.43	1376.48	5812.89	69227.96	69172.71	55718.05	1880.68	87.05
7	1227.53	1350.35	12416.43	1282.52	13148.57	1379.04	5802.34	69227.93	69170.78	55720.46	1880.68	85.58
8	1234.78	1350.11	12422.73	1290.18	13142.94	1377.37	5812.54	69227.96	69173.16	55718.29	1880.66	84.07
9	1227.31	1340.23	12417.93	1282.64	13141.72	1381.06	5800.36	69227.93	69173.15	55707.31	1880.65	83.68
10	1234.89	1347.39	12417.48	1287.36	13144.13	1381.34	5812.44	69227.96	69173.21	55710.67	1880.65	83.37
11	1237.24	1337.99	12416.58	1296.61	13137.91	1368.10	5843.54	69227.96	69175.76	55714.83	1880.62	81.76
12	1243.04	1335.33	12425.47	1293.24	13128.41	1374.47	5830.65	69227.96	69175.06	55719.99	1880.61	80.23
13	1241.23	1348.39	12432.07	1326.53	13156.32	1349.05	5778.01	69227.96	69164.19	55735.91	1880.60	69.21
14	1241.22	1324.98	12432.10	1326.49	13158.07	1349.06	5779.74	69227.96	69164.23	55735.94	1880.59	68.98
15	1238.47	1300.99	12425.08	1328.08	13164.31	1338.30	5697.49	69227.96	69163.25	55752.84	1880.55	68.03
16	1241.83	1325.02	12428.94	1324.92	13154.84	1351.86	5784.68	69227.95	69165.63	55732.86	1880.54	66.08
17	1241.85	1323.65	12430.21	1326.74	13149.08	1337.59	5790.05	69227.94	69165.78	55731.39	1880.52	65.62
18	1253.76	1315.67	12426.68	1329.49	13094.73	1351.73	5755.80	69227.97	69165.75	55748.33	1880.47	63.39
19	1246.38	1323.62	12105.24	1356.03	13239.91	1347.95	5828.00	69227.94	69211.71	55711.21	1880.42	60.87
20	1246.78	1323.61	12102.44	1352.02	13166.11	1349.37	5827.80	69227.95	69211.65	55709.52	1880.36	60.36

Table C.34: Details of Pareto solutions from 21 - 40 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using cyclic environmental flow.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
21	1246.01	1322.24	12092.00	1351.43	13172.61	1345.86	5834.13	69227.95	69211.12	55709.72	1880.36	59.80
22	1229.39	1415.92	12509.94	1230.63	12627.87	1835.36	5867.56	69227.92	69193.18	55533.91	1880.27	58.81
23	1231.34	1403.92	12498.39	1233.00	12603.40	1838.96	5908.80	69227.92	69194.34	55572.47	1880.24	55.11
24	1228.85	1416.19	12507.72	1231.45	12629.26	1836.21	5867.61	69227.92	69194.19	55541.43	1880.23	55.10
25	1228.77	1421.50	12508.00	1233.28	12610.76	1867.26	5867.36	69227.92	69194.17	55541.21	1880.22	54.33
26	1207.88	1405.88	12523.95	1222.78	12720.11	1871.56	5812.21	69227.92	69198.28	55559.22	1880.13	52.72
27	1227.91	1413.42	12523.50	1218.95	12737.11	1878.21	5801.15	69227.92	69200.25	55516.08	1880.10	52.44
28	1226.46	1413.92	12524.29	1220.11	12708.16	1881.35	5797.14	69227.92	69196.35	55519.31	1880.08	52.34
29	1226.57	1411.21	12519.04	1217.29	12709.35	1885.32	5797.04	69227.91	69196.41	55511.69	1880.07	51.80
30	1238.09	1427.93	12510.90	1203.96	12693.07	1828.55	5857.64	69227.92	69196.68	55513.92	1880.04	49.89
31	1181.47	1433.46	12472.43	1242.15	12645.34	1882.88	5946.74	69227.89	69201.32	55474.58	1880.00	46.84
32	1178.24	1421.04	12472.38	1241.96	12645.86	1885.93	5947.41	69227.89	69175.73	55479.13	1879.96	46.81
33	1183.22	1420.17	12486.45	1234.63	12656.41	1869.99	5973.48	69227.94	69172.97	55442.08	1879.96	45.10
34	1183.39	1419.85	12483.66	1235.45	12657.38	1868.98	5966.11	69227.92	69173.32	55440.81	1879.95	44.59
35	1183.58	1411.26	12483.97	1235.41	12656.84	1850.71	5966.23	69227.92	69175.92	55440.94	1879.94	44.54
36	1253.33	1398.85	12467.07	1237.22	12643.26	1945.15	5994.58	69227.99	69175.00	55390.85	1879.91	43.24
37	1253.11	1398.80	12467.22	1237.81	12639.14	1965.91	5993.96	69227.99	69174.94	55389.05	1879.90	43.19
38	1253.32	1399.93	12467.32	1237.52	12646.67	1941.67	5995.79	69227.99	69174.94	55389.22	1879.89	43.14
39	1280.56	1845.32	12462.17	1217.89	12634.73	1564.63	5973.66	69228.00	69127.32	55388.02	1879.88	41.51
40	1265.87	1376.08	12476.24	1237.51	12564.28	1804.84	6038.52	69227.99	69174.65	55543.80	1879.87	33.11

Table C.35: Details of Pareto solutions from 41 - 56 for the crops when maximizing net return and minimizing deficit in environmental flow for 300 iterations using cyclic environmental flow.

Solution	Land area for each crop (ha)										NR $\times 10^7$AUD	EFD (GL)
	T. Aus	T. Aman	Boro Rice	Wheat	Potato	Oil seeds	Pulses	Sugarcane	Winter Veg-etable	Summer Veg-etable		
41	1265.03	1375.86	12476.41	1237.50	12568.17	1923.16	6043.38	69227.99	69174.69	55388.61	1879.79	32.94
42	1273.87	1389.11	12466.20	1258.84	12601.98	1935.38	6033.67	69227.99	69174.55	55392.98	1879.76	31.01
43	1268.60	1371.73	12464.01	1261.73	12599.66	1929.91	6045.39	69227.99	69174.18	55387.37	1879.73	30.70
44	1611.20	1028.64	12081.82	1048.36	11249.92	2018.54	6434.00	69227.95	69225.94	56819.15	1879.52	25.47
45	1526.32	1052.96	12147.59	1036.82	11150.41	2001.92	6342.36	69227.82	69209.17	57057.76	1879.46	22.32
46	1523.83	1065.23	12156.92	1035.27	11176.27	1999.17	6301.17	69227.82	69219.54	57026.72	1879.45	21.28
47	1532.44	1053.09	12165.30	1031.80	11330.77	1980.39	6393.73	69227.87	69224.41	56808.94	1879.42	18.11
48	1509.74	1056.44	12188.97	1041.91	11281.33	1966.04	6401.21	69227.86	69224.84	56853.99	1879.38	17.02
49	1523.81	1043.39	12153.54	1029.53	11351.03	1922.15	6398.94	69227.87	69224.56	56801.70	1879.35	13.20
50	1476.99	1076.39	12327.33	1041.79	11852.00	1464.25	6495.61	69226.80	69209.41	56572.90	1879.34	5.49
51	1485.08	1079.10	12318.78	1050.98	11822.36	1462.71	6531.95	69226.74	69226.26	56548.24	1879.33	4.06
52	1490.60	1071.88	12311.02	1035.13	11758.72	1512.18	6507.93	69226.81	69225.61	56601.66	1879.31	2.55
53	1485.39	1074.79	12319.65	1042.29	11816.11	1463.68	6523.79	69226.76	69226.01	56556.04	1879.30	2.54
54	1495.86	1076.30	12320.72	1040.46	11807.86	1479.26	6518.92	69226.78	69225.63	56557.02	1879.30	2.53
55	1468.80	1071.11	12331.31	1046.67	11841.98	1475.63	6535.99	69226.69	69209.38	56544.05	1879.26	0.53
56	1482.45	1080.90	12317.06	1048.68	11818.14	1464.95	6540.33	69226.79	69221.33	56557.81	1879.26	0.00

Table C.36: Details of Pareto solutions from 1 - 20 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using cyclic environmental flow.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	177.45	107.10	94.57	83.21	124.21	47.55	91.62	276.41	64.17	91.65	58.12	104.16
2	175.86	107.51	95.71	83.51	123.93	45.01	91.12	284.72	59.69	91.34	65.38	103.63
3	171.84	109.24	99.78	83.71	119.03	54.04	95.32	288.51	73.61	109.74	72.41	112.15
4	171.72	109.26	99.79	83.70	125.95	54.25	95.31	288.54	73.81	109.80	72.42	112.23
5	174.51	109.54	99.08	88.29	125.88	51.96	99.40	288.30	74.07	109.58	71.66	112.78
6	174.51	107.59	99.35	83.76	125.92	54.67	95.30	288.53	73.56	110.77	71.84	117.19
7	172.06	110.36	99.18	83.95	125.99	54.60	95.62	288.56	74.03	110.82	70.40	116.90
8	174.48	110.51	99.37	83.86	125.93	54.61	95.44	288.52	73.51	110.71	71.88	117.19
9	172.08	110.47	99.22	83.93	125.97	54.80	95.62	288.57	74.05	110.48	71.95	116.90
10	174.43	110.51	99.37	83.95	125.95	54.78	95.39	288.55	73.84	110.58	71.98	117.20
11	174.31	110.34	99.65	88.17	125.99	57.77	97.62	288.43	73.61	110.72	70.95	112.74
12	173.47	110.11	102.14	88.32	125.98	58.63	99.10	286.61	73.69	110.14	71.10	112.90
13	171.30	114.66	97.95	88.13	124.20	56.52	98.73	286.44	78.22	109.15	77.08	113.21
14	171.30	114.67	98.04	88.14	124.21	56.62	98.73	286.43	78.25	109.16	77.08	113.21
15	171.14	114.69	98.27	88.23	124.20	56.39	99.20	286.04	78.47	110.11	77.23	113.69
16	171.22	115.07	102.77	88.41	124.20	57.88	98.81	286.46	77.79	109.50	76.85	112.99
17	171.31	115.47	102.81	88.42	124.08	58.42	99.52	286.52	78.01	109.89	76.92	112.60
18	171.32	115.06	102.86	88.38	124.16	57.56	99.17	286.41	77.80	110.14	80.36	112.50
19	171.07	114.82	102.89	88.35	124.15	58.02	99.99	286.89	90.24	109.87	76.37	111.57
20	171.48	115.26	102.88	88.39	124.16	57.92	99.55	286.84	91.02	108.92	76.22	112.10

Table C.37: Details of Pareto solutions from 21 - 40 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using cyclic environmental flow.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
21	171.29	115.04	103.05	88.58	124.15	57.88	99.10	286.87	90.64	109.52	76.48	112.26
22	166.89	109.94	98.54	87.65	124.42	56.46	81.62	290.51	83.12	114.95	83.78	116.69
23	166.87	109.97	98.53	87.68	124.36	63.28	82.03	289.54	83.38	115.05	83.72	116.61
24	166.80	109.95	98.57	87.65	124.30	63.19	81.73	289.52	83.39	115.00	83.68	116.66
25	167.25	109.96	98.60	87.65	124.26	63.22	81.90	289.51	83.61	115.02	84.12	116.74
26	176.32	109.79	98.97	88.12	125.94	64.01	93.70	289.71	84.22	113.51	84.77	116.41
27	176.16	109.60	98.85	88.20	126.15	64.06	93.91	289.72	84.20	114.04	85.08	116.64
28	176.34	109.74	98.87	88.24	126.18	64.07	93.97	289.68	84.21	113.87	84.95	116.66
29	176.29	109.74	98.87	88.33	126.19	64.24	93.91	289.70	84.54	113.74	85.05	116.67
30	175.95	111.02	99.27	88.59	126.05	63.74	94.70	289.88	83.54	114.48	86.14	116.55
31	171.81	114.47	101.76	88.74	126.42	63.98	94.87	287.83	76.44	114.93	92.62	115.89
32	171.74	114.47	101.76	88.74	126.42	64.00	97.07	287.84	76.44	114.97	92.63	115.90
33	173.15	114.37	101.65	88.64	126.46	63.23	97.46	283.63	77.62	114.69	92.93	116.33
34	173.05	114.38	102.01	88.66	126.51	63.21	97.56	283.26	77.96	114.75	93.07	116.34
35	173.04	114.38	102.01	88.66	126.51	63.22	97.57	283.83	77.97	114.72	93.10	116.35
36	174.52	114.49	101.78	88.47	126.14	62.96	95.63	288.32	77.78	114.61	95.23	115.79
37	174.52	114.27	101.74	88.46	126.15	63.08	95.49	288.32	77.67	116.06	95.84	115.56
38	174.53	114.20	101.81	88.46	126.14	62.85	95.53	288.32	77.73	116.29	95.68	115.79
39	173.39	114.58	102.17	88.50	126.58	62.72	95.73	288.24	78.08	115.91	96.90	115.44
40	174.82	114.08	102.30	88.43	126.68	63.16	95.39	283.87	77.65	116.34	105.77	115.94

Table C.38: Details of Pareto solutions from 41 - 56 for the environmental flow when maximizing net return and minimizing deficit in environmental flow for 300 iterations using cyclic environmental flow.

Solution	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
41	174.81	114.09	102.30	88.44	126.67	63.16	95.34	283.87	77.66	116.33	105.94	115.94
42	175.25	114.78	102.55	88.54	130.49	63.86	93.94	287.97	77.67	115.45	106.72	116.29
43	175.57	114.76	102.39	88.48	130.50	63.94	94.92	288.35	77.98	115.41	106.86	116.21
44	189.90	116.57	97.33	91.82	121.28	53.91	102.28	291.22	86.08	131.40	108.64	119.65
45	196.57	113.17	107.09	88.47	122.46	53.88	102.53	292.62	84.61	135.02	107.56	125.12
46	196.49	113.15	107.12	88.44	122.40	53.91	102.23	292.60	84.62	134.96	108.59	125.17
47	198.59	113.24	99.90	88.56	122.76	55.51	102.12	292.12	85.55	136.88	110.62	124.07
48	199.35	113.20	107.63	88.68	121.89	54.52	101.42	291.96	84.31	136.27	112.83	124.45
49	198.87	113.01	100.09	88.56	122.77	55.33	102.10	291.91	86.02	138.18	115.34	124.56
50	193.77	115.44	108.25	87.31	134.96	61.79	108.72	291.81	84.41	125.16	117.79	125.38
51	193.71	114.89	108.27	87.47	133.93	61.73	108.80	292.49	85.59	124.51	118.58	125.08
52	194.95	115.16	107.64	87.45	133.80	61.37	108.93	292.00	85.80	124.48	120.05	125.00
53	193.92	115.09	109.28	87.46	134.15	61.38	109.48	292.07	85.79	124.51	120.10	125.04
54	193.01	115.09	109.43	87.51	134.05	61.42	110.37	292.00	85.95	124.41	119.96	125.38
55	194.19	115.44	109.00	89.47	135.49	61.50	108.95	291.84	85.72	125.45	120.54	125.42
56	193.82	115.11	110.10	92.43	134.03	61.35	109.52	292.04	85.83	124.50	120.60	125.05