EFFICIENT MANAGEMENT OF WATER RESOURCES IN IRAN WITH SPECIAL REFERENCE TO TEHRAN AND THE SURROUNDING AGRICULTURAL REGIONS

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To Vida and Jahan

ABSTRACT

The rapidly increasing demand for water, coupled with its comparatively limited supply, is a serious problem in most parts of Iran. In spite of this fact, the economic efficiency of the allocation and use of this scarce resource has seldom been examined. The present study aims to investigate this problem and suggest guidelines for efficient management of water resources.

After an economic appraisal of the institutional and legal framework within which the allocation and use of water in the country takes place, the study concentrates on the question of efficient allocation and use of water in Tehran and the surrounding agricultural regions.

Using mathematical programming, a detailed model for determining the optimum allocation and use of different sources of water in the Varamin region for the purpose of irrigation is developed. In this model a number of important but usually neglected issues involved in the regional management of water resources are examined.

Since this region, along with the Karaj agricultural region, competes for the available surface water with Tehran, an inter-regional optimisation model for the allocation of water resources for the purpose of irrigation subject to a given urban requirement is then developed. This model demonstrates the potential economic gains which could be achieved through an integrated inter-regional approach to the allocation of water.

Efficient management of water supply, both in the short and long run, requires an accurate picture of the behaviour of demand. Using econometric techniques, a demand model for urban water is estimated. Among the determinants of demand, price (water rate) is found to be important. Expressions for demand as a function of price in future years are obtained, using forecasts for other explanatory variables such as population and income.

Finally, the projected demand functions (1976-85) obtained above are incorporated in the objective function of a chance constrained multi-reservoir multi-region programming model which optimises the allocation of water resources on the basis of opportunity cost rather than a prespecified 'requirement' approach. This model also considers the stochastic nature of water flows and looks at operating policies for the reservoirs which would provide a more reliable supply than the current practice.

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ABBREVIATIONS

m	metre
cu.m.	cubic metre
m.cu.m.	million cubic metres
L/S	Litre/Second
L/D	Litre/Day
Rls/ha	Rials/hectare
Rls/cu.m.	Rials/cubic metre
Rial	£1 = 110-120 Rials
ha	hectare
km	kilometre
kg	kilogram
MWP	Ministry of Water and Power
TRWB	Tehran Regional Water Board
FAO	Food and Agricultural Organisation of the United Nations
WHO	World Health Organisation

CHAPTER 1

THE PROBLEM AND THE APPROACH

1.1 An Overview

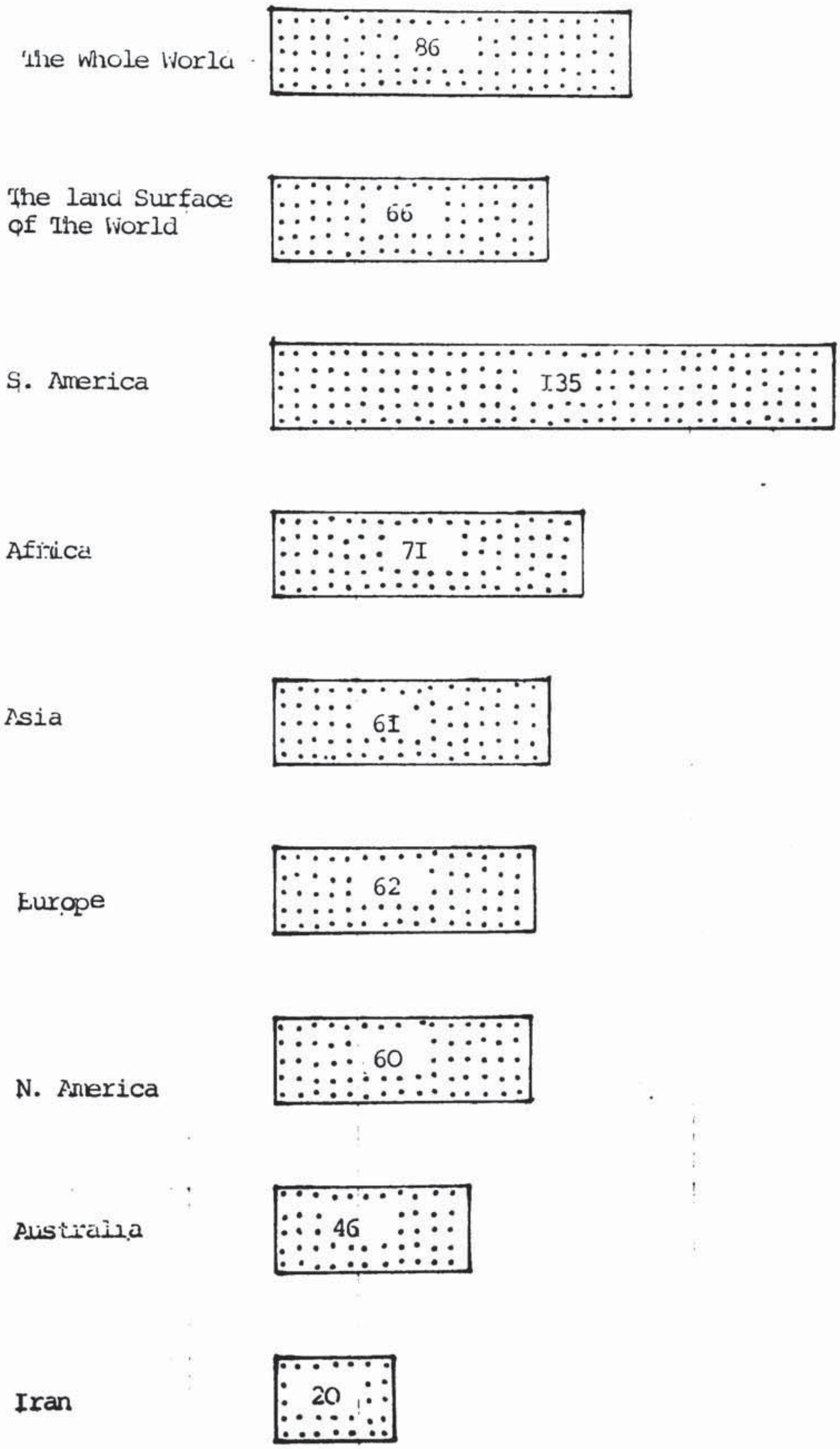
Iran lies in the Northern Hemisphere between latitudes 25° and 40°. Precipitation in this band of latitudes in North Africa and the Middle East is typically below world average. Rainfall in Iran suffers further owing to the special nature of the country's topography. A series of mountain ranges in the North and West of the country prevent air currents bearing water vapour from the Mediterranean and Atlantic Ocean and the Caspian Sea from reaching the Central Plateau on which most of Iran is situated. As a result, only the Northern and Western parts of the country (about 8% of the land surface) receive relatively high rainfall, while in remaining regions, which comprise the major part of fertile plains and population centres, the precipitation is as low as 40-200 m.m.

To illustrate the degree of aridity of Iran in relation to the rest of the world, a comparison is made in Fig. 1.1 of the mean annual precipitation of Iran with that of the whole surface of the world, the land surface and the Continents. According to this Figure the mean annual precipitation in Iran is equivalent to only one third of the whole surface of the world and less than the average of all the continents.

It is not difficult, therefore, to understand that in the long history of civilisation in Iran, adequate supplies of water for human consumption and

Fig. 1.1

WORLDWIDE AVERAGE ANNUAL RAINFALL (Centimitre)



agricultural use have been a major concern. For example, among the rock inscriptions of Persepolis there appears the following prayer by Dariush the Great (1000 B.C.)

> "Protect my country from drought, falsehood and enemies, O Lord".

Great efforts have therefore been exercised from time immemorial to harness the available water. In this respect one could mention the existence of about 50,000 ghanat systems in the country. These are hand excavated underground galleries which usually start at the most elevated points of arable land and, with gradual increase in depth, reach the water tables more or less horizontally. The length of some of these systems is as much as 50-70 km and the depth of some of the shafts from the land surface to the galleries constructed to provide air for the workers and remove the dug out soil are as deep as 300 metres. It has been said that the total length of these systems is more than the circumference of the earth. Henri Goblet, a French civil engineer, noted that the Eiffel Tower could be hidden in a shaft sunk to a ghanat. All this represents the perpetual struggle and perseverance of the nation over thousands of years in quest of water in the face of aridity and the threat of drought. Indeed the ancient Iranians should be praised for their ingenuity and efforts in the construction of weirs, reservoirs, dams and underground galleries. However, relatively little new development particularly in relation to the efficiency in the use of water resources has taken place since the middle ages.

An inventory of the water resources of the country, (Vahidi, 1968, Chap. 1) shows that roughly two-thirds of the water which falls on the land surface of the country as precipitation is returned to the atmosphere through evaporation and transpiration. Of that which remains, approximately 13 percent is used directly for irrigation and Urban-Industrial uses. Based on Figure 1.2 which represents the balance sheet of water resources of the country, one might wonder why there are water problems while more than half of the available water is still annually unused. There are four basic reasons for water problems. These are:

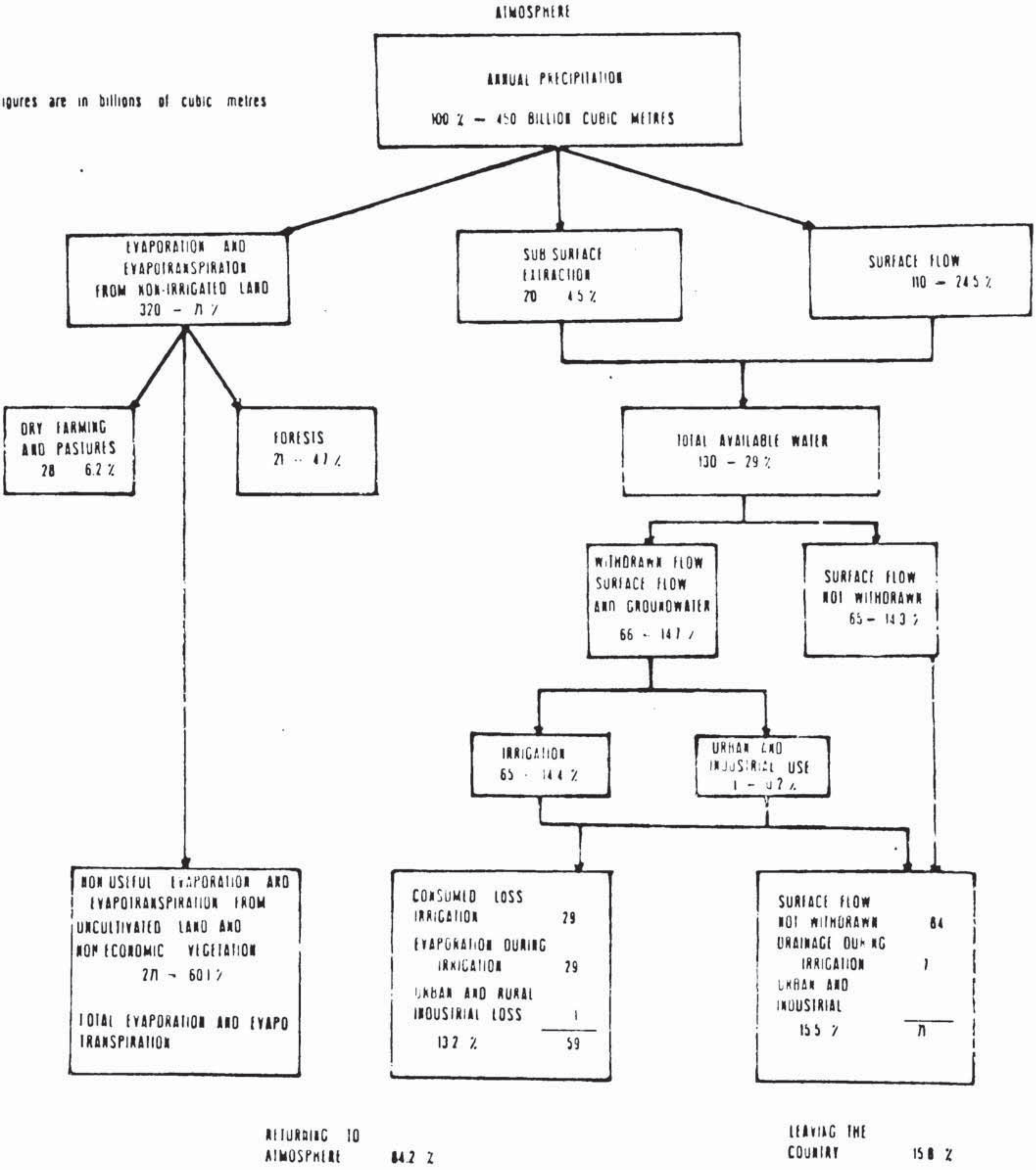
1. Non-uniform precipitation and evaporation, with respect to both time and location.
2. Non-uniform demand, with respect to both time and location.
3. Increasing demand in the face of an essentially fixed supply.
4. Quality of existing supplies.

Precipitation rate, as has already been indicated, is extremely variable, both with respect to time and location. One third of the entire rainfall occurs in the Caspian Sea drainage area which occupies one-tenth of the land surface of the country while another third occurs in the Central Plateau, the area of which is more than one half of the country's land surface. In addition, the precipitation usually occurs

FIG 1.2

Water Balance and Water Cycle of Iran

Figures are in billions of cubic metres



Note The above figure only covers water produced from atmospheric precipitation, the 7.5 billion cubic metres received from rivers flowing into Iran being equated with the amount leaving the country as surface flow towards the end of winter and early spring while during the summer months, when the need for water is at its peak, the rainfall is almost non-existent.

Another basic problem is an increasing demand for water in the face of an essentially fixed supply. This problem particularly manifested itself in recent years in most urban areas as a result of a mass migration of people to industrial and commercial centres in search of work. The problem will become even more serious when we envisage the transformation of the economy from basically agrarian, where 60-70 percent of population is currently living in villages, to the society of the year 2000 when 75 percent of population (40 million) will be working in towns and cities (Iran Statistical Bureau,1973).

The final problem is the quality of existing water, both ground and surface supplies. As a result of the large extent of evaporation from geological formations containing lime and salt, a considerable number of rivers and groundwater basins are brackish.

In order to attempt to solve these problems, the policy-makers have recently put water resources of the country under public ownership and have initiated an ambitious plan to harness the unregulated supplies. The plan makes use of high levels of engineering skills and incorporates impressive design features. However, the planning and operation of water systems have not always been submitted to a critical economic efficiency review. Engineering consideration aside, however, the satisfaction of growing demand by added supplies from new sources is a simplistic solution that will become increasingly expensive in the future. It bypasses entirely the question of the economic efficiency of the production and distribution of water already available to a system. This is a matter of no small importance because obtaining additional water is becoming more costly and difficult. Water planners in the future in most parts of the country may not have the luxury of exercising the option of reaching out to distant sources because suitable sites will no longer be available, or their costs will be prohibitive.

It is therefore important to examine closely the efficiency with which water resources are managed in an environment of growing scarcity and rising marginal costs.

1.2 Objective and Scope

The general objective of this research is to assess the present state of water resources management in Iran and develop mathematical programming models and suggest guidelines for economically efficient allocation and use of water.

We have considered in detail the problem of providing sufficient water for Tehran, a rapidly growing city, at minimum cost in terms of loss of agricultural production. In addition to some groundwater, Tehran currently obtains its water from two reservoirs which also serve two important irrigated agricultural areas.

It is planned that Tehran will obtain more water from two additional reservoirs over the next fifteen years to meet its increasing requirement. The Government have commissioned a number of studies from consultant engineers and have sought help from the International Bank for Reconstruction and Development in order to make the best possible use of available water resources. We have developed a number of mathematical programming models which would be a useful aid to policy-makers. In this respect our approach and preliminary results were found to be of considerable interest to the Tehran Regional Water Board and the Water Resources Development Division of the International Bank for Reconstruction and Development.

There are several economic objectives of an operational nature which might be considered regarding allocation and transfer of water. They include; (i) economic efficiency, (ii) greater equality of income distribution, (iii) stabilisation of economic activity, etc. (Beattie et al, 1971). The scope of this research is limited to the consideration of economic efficiency of allocation and use of water in Tehran and the surrounding agricultural area.

Perhaps the ultimate decision may only be partly dependent upon economic efficiency criteria, and other goals of public policy-makers may or may not be achieved concomitantly with economic efficiency. In any event, the costs of deviations from economically efficient allocation of water should be considered when the decision is made.

1.3 Organisation and Order of Presentation

In analysing the efficiency of any economic activity, particular attention should be paid to the legal framework within which the activity is performed, since it may facilitate or hinder the initiatives and enterprise of individuals concerned in achieving an efficient use of the resource.

In Iran, the government has recently nationalised all water resources of the country and has legislated a detailed statute concerning the manner in which water resources should be developed, allocated and used. With this in mind, the study begins by examining water resource management in the past, relating new legislation to it and investigating the economic soundness of the Nationalisation of Water Resources Act.

Since regional water authorities, by virtue of the new Water Law, are responsible for the allocation and use of water resources of a region, Chapter 3 develops a mathematical programming model for the optimum conjunctive use of surface and groundwater supplies of the Varamin Plain. The model is refined and elaborated as far as possible to allow for intra-regional allocation of different sources of water and also determining the optimum cropping pattern in different parts of the region.

Considering that this is one of the two regions which compete for the available surface water with the city of Tehran, Chapter 4 brings into focus the potential economic gains which could be achieved through the integration of all the water resources within a single model. To this end an optimisation model for the given current release policies and other physical attributes of the systems is developed in order to maximise net value added from agriculture in each region subject to a pre-determined level of urban water consumption.

The growing requirement of water for urban use in the face of limited present and potential sources of water for Tehran cause concern. On the basis of the current trend of water consumption and under the present demand management policies, it would be a matter of only a couple of decades before demand outstrips the available sources of supply. In view of all this, the need for improved demand management policies in which greater emphasis is placed on the pricing of water is required. Chapter 5, therefore, discusses the current misconception concerning the nature of the demand for urban water, develops a demand function which can be used to project future consumption given projections of explanatory variables including pricing policy.

Chapter 6 reconsiders the urban-rural allocation of water but it differs in a number of ways from that of Chapter 4. First, it substitutes the estimated urban demand function for the pre-determined requirements for water so that the allocation would be based purely on the efficiency criteria, i.e. willingness to pay by the urban beneficiaries. Secondly, the formulation is made within a stochastic supply environment. To this end, the current average deterministic releases have been dropped and instead the optimum operation of the systems is derived on the basis of a chance-constrained programming model. Thirdly, since an additional reservoir with associated irrigation region is planned to come into operation in 1980, the model has been expanded to incorporate this and parametric programming has been carried out to assess shifts in optimum allocation of water up to the year 1985 when a further reservoir comes into operation.

We summarise our findings and make recommendations for future research in the final Chapter.

CHAPTER 2

LEGAL FRAMEWORK AND REGULATION OF WATER RESOURCES ALLOCATION : HISTORY AND CURRENT PROBLEMS

2.1 Introduction

In this chapter we consider the institutional framework within which allocation of water resources takes place in Iran. This is important since the use to which the mathematical programming models we develop in subsequent chapters can be put will depend to a considerable extent on the institutional framework.

We outline first the historical development of regulations and institutions governing water resource allocation and then go on to appraise the recent nationalisation of water resources. Broadly speaking, until late 19th century regulations governing water allocation were based on the teachings of the Islamic religion. The institution of Civil Law in 1930 led to piece-meal legislation governing water allocation until the comprehensive Nationalisation of Water Resources Act in 1968.

The Act gives the government power to make very detailed decisions about the allocation of water resources. The feasibility and efficiency of this is considered in this chapter.

2.2 Historical Background

2.2.1 Water in Zoroastrianism

Zoroastrianism is the major ancient, pre-Islamic religion of Iran. This religion, which is still practiced in parts of the country, recognizes water as a source of life and treats it with much respect.

"Avesta" the holy book of Zoroastrianism, gives a great deal of emphasis and importance to water. It admires those people who use water for irrigation and increase of production. "Anahita" (holy angel of water) has a special place in this religion. Herodot (5th Century B.C.) admired the Iranians for being careful not to pollute water. However, little evidence with regard to procedures for allocation of water exists.

2.2.2 Water in Islam

Following the invasion of Iran by Arabs in the 7th Century A.D., Islam became the religion of the state. Before Islam, in the Arab world, there were no established regulations governing the allocation and use of water. Water was the property of the tribesmen and mainly under the control of the strongest one (Mohandes, 1965 pp. 218). In general, the widespread shortage of water in this part of the world on one hand, and lack of recognised regulations among the Bedouins on the other, were the cause of continuous bloodshed and violence.

Emergence of Islam changed this situation since the teachings of Islam on practical matters and affairs of state became a basis for the law of the land in Islamic states. Private ownership of water was abolished. Water was considered to be public property available for use by all members of the Moslem community (Sarmad, 1971 pp. 43). Water was recognised as the symbol of purity, fertility and cleanliness to which no price could be attached. The owners of wells and other sources of water were asked to provide their surplus water to the community free of charge. In this respect Koran says:

> "To the man who refuses his surplus water,
> God will say: Today I refuse thee my favour."

According to the original Islamic doctrine, water ceased to be a commodity that could be owned and its sale was prohibited.

However, over the passage of time and appearance of different sects and branches on one hand, and the growth and complexity of societies on the other, the original doctrine which was based on brotherly love was found to be inadequate. It is not difficult to anticipate, for example, that the problem of determining how much water was "surplus" to a well-owner's use would create conflict. The original regulations accordingly were modified to meet the needs and requirements of different sects. Shiite doctrine came to be adopted as the religion of Iran.

Although most sects of Islam have developed their own rules and regulations (customary laws)* regarding the allocation and use of water a few basic principles underly them all.

2.2.2(i) Ownership of Water - The question of ownership is basically decided by the nature and origin of water. Inflow of major rivers with abundant supply, or natural precipitation, for instance, belong to the public. Individuals are free to make use of it as long as their action does not harm other users. However, when human effort is employed in the acquisition of water, those

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* "Customary laws" referred to here as uncodified Islamic laws.

who develope the resource become its owners. The sinking of a well in unoccupied land, confers on the sinker the ownership of both the well and the water.

2.2.2(ii) Acquisition of Water Right - In the case of small rivers, water is usually allocated to the bordering land.

The up-stream users have the right to irrigate their crops in full before the down-stream users could receive any at all. In pursuing an irrigation right, the up-stream user is not required to compensate the down-stream user.

In periods of inadequate inflow, however, the up-stream users should irrigate their crops in such a way that "plants should only be covered with water" and "water should only reach the feet of the trees" (Mohandes,1965,pp.225)

In the case of wells and other water at oases, the first come first served principle applies. In cases of dispute, the question is settled either by drawing lots or establishing equal shares (Caponera, 1954 pp. 20 and 23).

2.2.2(iii) Transfer of Ownership and Sale of Water Rights - In general, both Sunnites and Shiite (the two main branches of Islam) treat irrigation water as a saleable resource. Transfer and sale of water is also possible. However, it usually attaches to the land and changes hands in most transactions involving the bordering or overlying land. Irrigation rights could also be leased while retaining possession of the right itself. In this case, the Shiite doctrine leaves the right of cancellation to the owner of the right.

Generally the sale of water rights is done in a competitive environment. Water transactions take place in water markets held in a particular spot and at a set time. Price is determined by the degree of scarcity, amount, season, requirements of crops, quality etc. and usually goes to the highest bidder. The buyer in this connection enjoys only a usufructuary right, that is the right of use not the possession of water. This, in other words, means that once water is in a joint or public course, the owner of the right is forbidden to alter the physical setting of the water or to undertake any action which may harm other users.

A detailed study of Moslem rules and regulations concerning the use and allocation of water indicates their improvised nature. They were developed through the years influenced greatly by the geographic and climatic conditions of different parts of the Moslem world. The basic problem with Islamic law, however, is lack of administrative structure to implement the principles.

2.3 The Position of Water in Civil Law

During the early 20th Century customary law based on the tenets of the Shiite sect were codified into Civil Law. Accordingly many of the regulations described in the previous section hold good in law. Our discussion here will be limited to the major body of the laws having a direct bearing on water resource allocation.

2.3.1 Water Rights and Irrigation Regulations - Under civil law, water, like land, is a recognised property entitled to legal protection under the constitution. A private individual, group of individuals, religious organisations or public agencies acting for people, may have perpetual rights to the use of available surface or groundwater resources.

The rights are basically the same as those which have devolved down the generations. The owner of the right may withdraw water from a natural water course or underground basin and use it to his best advantage, provided that his action does not violate the rights of other parties concerned. All classes of claimants, whether private or public, enjoy equal privileges regarding the security of rights. There is, however, a certain order of precedence especially to protect the community's rights for domestic consumption.

There are two types of water rights, riparian and appropriate.

2.3.1(i) Riparian Rights - Use of water for irrigation usually falls under riparian rights which go with ownership of the land bordering a natural stream or overlying land. The up-stream proprietors have priority in the event of shortage of water.

In special circumstances where right owners withdraw water on both sides of the bank of a river, disputes are usually settled by drawing lots. The owner of the rights can divert water from a natural stream for his private gain without payment provided that his action does not violate the established rights of others.

This right is, however, a usufructuary in the sense that water comes under the ownership of the right holder once water reaches the land owned by him.

Rights to the use of groundwater resources similarly occur to any owner of a tract of land which overlies a groundwater basin.

The principle governing the use of groundwater resources, however, comes under the doctrine of absolute ownership. Article 38 of the Civil Law in this respect states that "ownership of land comprises ownership of everything above and below the surface, to any height and to any depth except where limited by law". The owner of the overlying land, therefore, is free to make unrestricted use of the groundwater on his land.

The great bulk of riparian rights are held by individual villages. These villages are usually owned by dozens of farmers. The volume of water which each village derives from a stream is the result of an accretion of autonomous historical incidents through which such titles have been acquired. The ownership of rights falls into three categories; some with round the year rights, others with spring and winter and still others with only spring rights.

2.3.1(ii) Appropriation Rights - The appropriation doctrine which operates concurrently with riparian rights, sanctions the taking of water from a water course which may not have a common border with the stream or overlying land. An example is the city of Tehran's Right on water from Karaj River which is about 60 km away from the city.

The Appropriation doctrine also applies to the newly developed sources of water. In these cases the government decides upon the use of water. This water could be appropriated for irrigation purposes (Ghazvin Irrigation Project receives water from Taleghan Dam), or for industrial use (Diversion of water from Darush Dam to the Aryamhre Steel plant)or could be used for urban use (supply of water from Latiyan Dam to Tehran).

It could also be argued that water conduits (ghanats) come under this doctrine, since the gallery can be extended to other people's lands and consequently collects the whole, or some of the water from those lands. The owner(s) of such a water system can independently decide upon the future direction of the gallery without the consent of the overlying land owner. His freedom is, however, limited in as much as this should not damage other water systems.

2.3.2 The Law's Impact on Allocation of Water Resources - A careful examination of the historical development of water laws reveals their complexity, inadequacy and in some cases conflicting interactions between different statutes. This stems partly from the piece-meal nature of the legislation. Whenever a particular intervention or action on the part of the government was felt necessary (on some occasions too late), the responsible body asked for the relevant legislation. There are about forty different statutes and bills concerning one or another aspect of the water resource industry (Mohandes, 1965, pp. 210).

Lack of a comprehensive legal and institutional framework governing the regulation and use of water has resulted in many conflicting statutes. For instance, Article 154 of civil law states "no one could convey water from other people's property without prior consent of the third party even if no alternative routes are available", while Article 3 of ghanats law requires the third party to provide the necessary access or development land.

Conflicting statutes of this kind are quite common in different laws concerning the water industry. Owing to such conflicting regulations court actions take a very long time - in some cases a few years. In the meanwhile the operation of the system under dispute usually stops.

The extent and amount of water which the holder of a right may withdraw from the stream and the times of withdrawal during the course of irrigation are governed by a complex and very ill-defined traditional procedure.

The unit of water, for instance, not only varies substantially from one region to another but also changes with the time of the year. For example, in the Tehran area the unit of measurement is "sang" (stone). Theoretically one sang is equivalent to 12 lit/sec. In practice, however, the volume according to the time of year and inflow of water could go down even to 4 lit/sec. In spite of the reduction of the inflow the water is still measured as before.

Misallocation among different tracts of riparian land is also quite common. It basically results from the generous water rights which are attached to particular parcels of land settled in the early days and from the priority of use to the upstream users. A system of water rights giving priority to owners of upstream land has a tendency to induce an inefficient or uneconomic allocation of a scarce commodity,regarded as free by these users, Another deficiency of this system is the insecurity of downstream users' supply of water (Tinney and O'Riordan, 1970)

Although the law provides the senior downstream users with regular water, in practice, in many instances, due to lack of adequate monitoring, the upstream users take a large portion of the inflow and downstream users suffer,particularly in droughts.

The acceptance of the doctrine of absolute ownership of land in which the proprietor is free to make unrestricted use of underground water resources has resulted in an unplanned extraction of water basins. It is quite common to observe few deep wells close to each other pumping water from a small water basin. The consequence of such a policy has been a rapid decline of water tables. On many occasions wells have completely run dry. Figure 2.1 shows the loss of ghanat systems which is caused by over pumping of aquifer by deep wells in the Varamin Plain. This figure, in other words, is an indication of the rate of water mining in many parts of the country.

The doctrine of absolute ownership is inappropriate because of the problem of commonality which is inherent in the very nature of this resource (Young and Bredehoeft, 1972). Pumping in a given region usually takes place in common with many individual pumpers. However, as long as the rate of replenishment matches the withdrawal rate the problem of common usage does not arise, but the problem of commonality does arise when mining of groundwater is practised (Milliman, 1956). This is because users are interdependent and the action of any one user affects withdrawals by others. This type of interdependence usually creates a major type of external diseconomy since pumpers individually do not have any security with regard to future use of

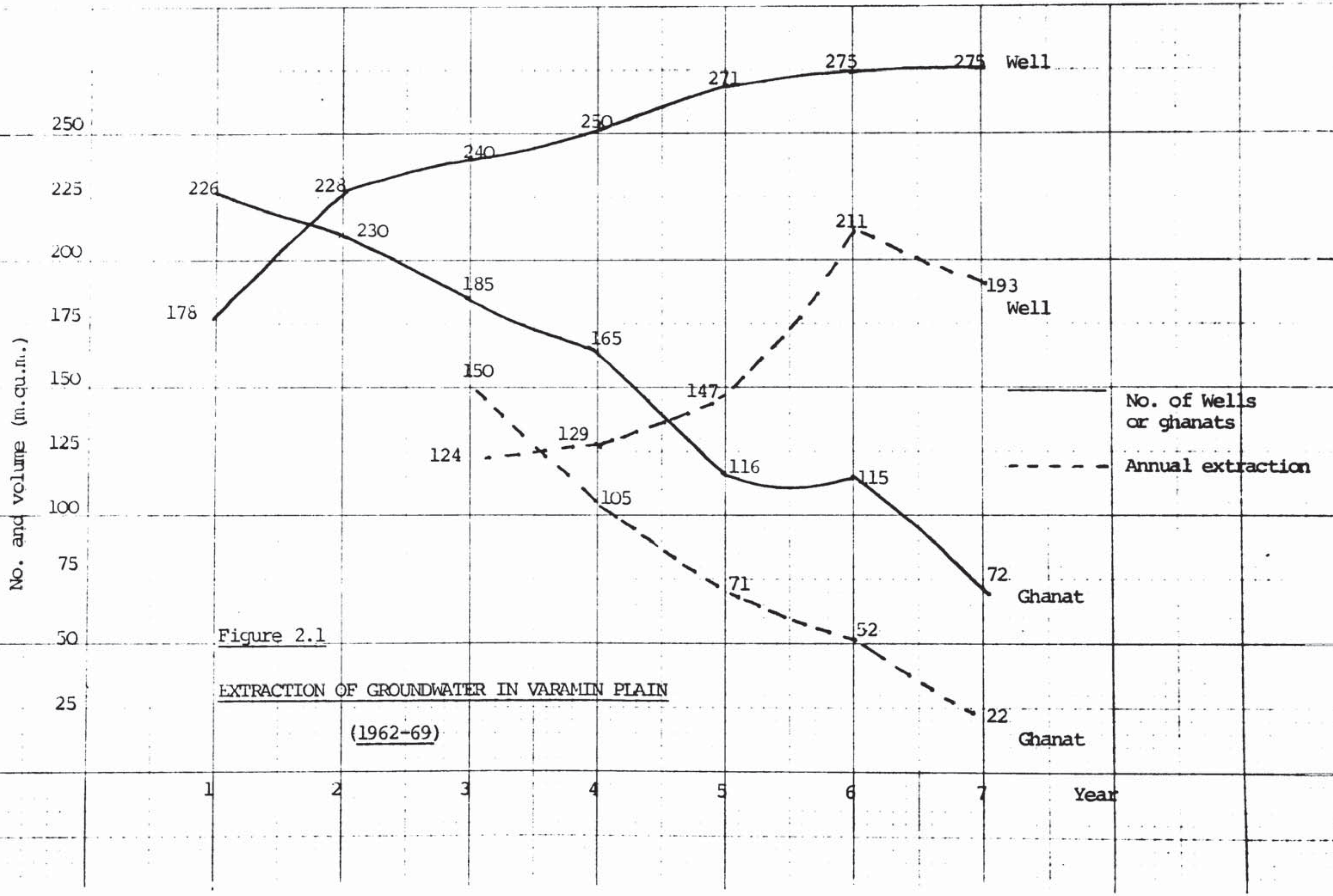

Figure 2.1

EXTRACTION OF GROUNDWATER IN VARAMIN PLAIN

(1962-69)

water, each producer would try to maximise his immediate profit by extracting water to the point where the current marginal return just covers his current marginal cost. If this competitive mining continues, the optimum long-run operation of the aquifer may be jeopardised (Maddock and Haimes, 1975).

This is not to say that accumulated storage should not be mined merely because certain future benefit would be lost. On the contrary, as long as there is a positive discount rate, mining of water might be justified (Bagley, 1961,pp.150). Our objection here is with the principle of the doctrine of absolute ownership which does not allow for the evaluation of future use.

The problem of commonality, even in the Groundwater Law of 1963 which forbids drilling of new wells in some parts of the country, has not been satisfactorily dealt with. This is simply because the law is mainly concerned with the spacing aspects of new wells without due attention to the present pumping system. For instance, in the so called restricted area such as the Meshed water basin, the "law of capture" and heavy mining of groundwater is still extensively practised (MWP Annual Report, 1971).

2.4 Inadequacy of Capital Investment

Lack of a comprehensive government investment or conservation policy for developing water resources and irrigation combined with the construction of numerous water courses by farmers to meet their individual needs have led to the development of a fragmented irrigation system resulting in high loss of water through seepage and evaporation. The magnitude of irrigation losses becomes clear when we consider the balance sheet of the country's water resources.

It was noted in Chapter 1 that on average 457.5 billion cubic meters of water enter the country every year, of which 117.5 billion becomes surface flow; an estimate of 63 billion percolates the ground, and the remainder returns to the atmosphere in the form of evaporation or evapotranspiration. From the potential 200 billion cu.m. of available water, only 30 billion is utilised in the following way:-

Table 2.1

Estimated Annual Uses and Losses of Water in the Country.
(in billion cu.m.)

Surface water consumed for agriculture	16
Surface water consumed for urban/industrial use	1
Groundwater utilized for agriculture	13
	30

Against this, 150 billion cu.m., which is potentially controllable, is lost as follows:-

Leaving the country as surface flow	78.5
Irrigation losses	29.0
Groundwater lost through evaporation	43.0
	150.5

This Table highlights the alarming size of irrigation losses. That is, 100 percent loss, which simply means for every unit of water utilized in irrigation, an equivalent is wasted. Assuming that 7 billion of this water drains back to the rivers, the net wastage is about 22 billion. Had this wastage been avoided the total average of irrigated croplands throughout the country could be increased by two-thirds (Vahidi,1968, pp. 75-79).

Observation of irrigation techniques and networks throughout the country, except in a handful of government sponsored projects, reveals the causes of wastage as follows:-

- use of old and open water courses;
- lack of insulation of canals especially those with high permeability such as sandy soils;
- hairpin canals on steep slopes - to reduce the pressure of inflow instead of straight canals and construction of small barrages across them;
- inadequacy of dredging and clearing water courses which results in a reduction of the rate of flow and therefore higher evaporation;
- existence of several channels, each of insignificant flow which run parallel to each other in wasteful fashion.

The inadequacy of capital investment is a major stumbling block in improving the irrigation systems. The problem should however be viewed from two angles; one is the lack of direct investment in improving the irrigation system, and the other is the insufficiency of investment in educating the actual farmers (Mozayeny 1967).For example, during the Fourth Economic Development Plan, no significant investment was carried out in developing the present irrigation networks. From a total of 55150×10^6 Rials development funds, 10 percent was allocated to irrigation studies and these studies were usually carried out on a handful of government sponsored irrigation projects.

2.5 Nationalization of Water Resources and the New Water Law

The problems discussed in the previous section were particularly in the minds of the Government when it brought in the Nationalization Law.

The basic concept embodied in the nationalization of water law is that water is a gift of God and since in obtaining it, at precipitation stage, human effort is virtually nil, it naturally cannot be claimed by any individual but the public at large (Vahidi, 1973, pp. 198). This attitude towards water is not new in Iran. It is deeply rooted in the minds of most politicians for historical, religious and philosophical reasons.

Ancient Iranians, as it was noted, gave water a special status. Later on, Islam promoted the idea by declaring that:

"We made from water every living thing"

and in this respect they advocated the public ownership of water. The philosophy behind nationalization of water resources in Iran, therefore, is but the revival of the original Islamic doctrine. In fact, the above paraphrase is the current slogan of the Ministry of Water and Power and could be seen in almost all the Ministry's properties.

In Mordad 47 (Sept. 68), upon the approval of both Houses of Parliament, the Nationalisation of Water Resources Bill came into force. Accordingly all waters running in rivers, natural streams, valleys, brooks or in any other natural courses, either surface or underground, as well as flood, sewage and drainage waters, and those of lakes, marshes, natural ponds, springs, mineral water (Article 1) were declared to be a national wealth resource and the property of the public.

As agriculture is the country's largest consumer of water the main theme of the Act is oriented towards the problems of irrigation water and its gradual implementation is entrusted to the Ministry of Water and Power (Article 1 - Part 1).

2.5.1 Economic Appraisal of the New Water Law

The new Water Law creates a highly centralised framework for making decisions about allocation and use of water resources.

It is evident from Articles 6, 7, 8, 14 and 17 that the authority of government with regard to the utilization and management of water resources is almost unlimited. Article 6 empowers a three-man party (two from the Ministry of Water and Power and the other from the Ministry of Agriculture, Article 8) to issue water-use permits to individual users. Permits are only granted for "beneficial and reasonable use of water" (Article 7). They are issued only for a particular use and the holder of a permit cannot use it for any other purpose or transfer it to anybody else without the consent of the Ministry of Water and Power (Article 13). Article 14 takes a step further and states that the water should only be used on an assigned tract of land, or other stipulated uses, unless the government makes a decision to the contrary or for any reason finds out that the use is not beneficial or economical. In these circumstances the Ministry of Water and Power issues a notice to the holder of the permit to correct its measure. If the instructions of the Ministry are not followed, within a period of three years, the right of use is withdrawn. The definition of "beneficial use" according to Article 16, is vested in the hands of the legislators and can vary with time and place. Decisions on the water requirement of crops is taken by the Ministry of Agriculture (Article 17) and upon their recommendation the Ministry of Water and Power grants the necessary permits.

Our prime objection here is not with the actual nationalization of water resources, but with the manner with which the new water law has been prepared. It is the apparent outright rejection of the market mechanism and the implied irrationality of individual dicision makers which are disturbing. This is likely to put a very heavy responsibility in terms of administration and policing on the central decision-maker who is required to direct the farmers to produce the optimal cropps while evidence from other parts of the world (see Yaron, 1967, pp. 466) as well as some tentative calculations for Iran (see Appendix 2.1), suggest that farmers tend to behave rationally in the economic sense in allocating their available water among competing crops.

The new water law, which is basically tied up with the ownership of land in its present form, cannot move towards optimal allocation of water. Although the concept of "reasonable and beneficial use" is a desirable policy objective, it could best be achieved through the mechanism of market, not legislation. The exclusion of market and prohibition of free transfer does not direct water towards its most beneficial and economical use. On the contrary, it hampers the way towards an optimal allocation and use of it. If a potential user is prepared to pay for water and the seller is willing to make the transaction, assuming there are no external diseconomies, the transfer should be allowed since the new user has found a more productive use for it. This automatically implies that the water is going to be used more rationally, more beneficially and still more economically.

Under the present system, only those permit holders with negative marginal productivity from the use of water, are prepared to report to the Authority for the transfer of their permits. In other words, in the absence of a market for the transfer of right-of-use, or sale of excess water, no rational farmer is prepared to give his right or even his excess water away in exchange for nothing. He would not be prepared to make such an irrational decision for he could, for instance, switch to a more intensive irrigation regime. Assuming that the marginal contribution of water remains positive, his decision would add to his revenue, in spite of the fact that the marginal revenue from the use of the last unit of water is lower than the price that a prospective buyer is prepared to offer him.

We could also argue that under the present system, managerial efficiency is not rewarded. Article 17 leaves the decision on the water requirements of crops in the hands of the Ministry of Agriculture. This simply implies that managerial efficiency in the use of water throughout an irrigation region is taken to be the same. In practice, however, it is quite conceivable to observe different levels of managerial efficiency in a given irrigation region. In the absence of a free market for the sale of water, the more efficient farmer, who cannot dispose of his excess water profitably, would presumably work less hard or would not contemplate employing a more efficient irrigation technique.

It is important to note that the general logic of market exchange for the transfer of right-of-use or sale of water between competing uses and users, does not rule out the role of Government as a regulatory body. What would be objectionable from the standpoint of promoting efficiency in water use is the abolition of right of sale and the introduction of a centrally directed allocation process.

The only restrictions that are desirable to be placed on the use of water could be related to the possible "spillover" or "external diseconomies" effects (Milliman, 1965). It is in this respect that the role of Government through appropriate legislation is necessary in order to transfer the burden of "spillover" effects to the persons who benefit from the transaction.

The problems of "spillover" and external economies and diseconomies are extensively dealt with in the new law. Articles 35, 38, 42, 44 and 51 are exclusively devoted to problems such as pollution, injuries inflicted on the holder of a right by others, right of passage etc. However, the proposed method of compensation is to some extent objectionable.. In the case of groundwater for instance, Article 35 states that whenever the water table in an aquifer or a well or ghanat system, as a result of a new drilling, loses its yield or dries up, the junior user is obliged to make up the lost water by supplying the senior user from the new source. The senior user in turn should contribute to the operating cost of the new source. But if the transfer of water is not possible, the junior user must compensate the damaged party by an amount which is determined by the

Ministry of Water and Power. The level of compensation, however, is the average revenue during the last five years of the beneficial use of water.

It is this method of compensation which causes objections. First of all the old question of the definition of "beneficial use" crops up. It is quite conceivable to envisage the possibility of conflict which may arise on the interpretation of beneficial use. Secondly, the fixed period on which the level of compensation is based could be questioned for the value of irrigation in agriculture varies from one region to another. For example, the intensity of irrigation in arid or semi-arid parts of the country is quite high and its contribution to the yield in turn is essential, while in humid regions irrigation is only used as complementary to the natural precipitation. Loss of irrigation in the latter case does not drive the farmer totally out of business. It normally reduces the yield and in turn the revenue. While in the former case loss of water usually means loss of yield and this in turn forces the farmer out of business.

Under these conflicting conditions, payment of compensation based on a fixed period of time would not appear to be just and equitable.

Considering the fact that land and water can be used perpetually (on a sound basis) the calculation of compensation should in fact be based on the present value of future uses of water (Howe,1971,ch.5). Accordingly, in arid agricultural regions, the level of compensation, due to higher contribution of water, would be higher than that of those regions where water is used to complement precipitation.

Another inherent deficiency of the new water law could be sought in the inadequacy of "security" for the development of irrigation farming. As already indicated, the definition of "beneficial use" (Article 16) and priority of appropriation (Article 14) are entirely left with the Government who, in turn, could adjust them as circumstances require (Article 16). Under this uncertain environment, where "beneficial use" is a matter of political determination, an entrepreneur farmer would not make his investment policies on a long term basis. This is so because a particular use which is considered beneficial today could always be considered "non beneficial" later.

On the interpretation of "reasonable" and "beneficial" Sarmad (pp. 151) says that: "Provision of water for fish farming when the country is in short supply of necessities such as grain is not "reasonable" though it might be "beneficial". Under the existence of such an uncertain environment where a beneficial use in one year could be considered as an "unreasonable" one in the next year, an appropriator could not establish a long-term policy for investment and use of water. Furthermore, a right-of-use which is always subject to a future determination and redefinition of "reasonable-beneficial" use would weaken the transfeasability of the adjoining land, since the prospective buyer does not have the necessary assurance of a regular supply of water.

Of course, we do not deny that climatic uncertainty is an inherent characteristic of water supplies. Rainfall varies from year to year or drought may occur. In these situations all the parties involved are subject to same degree of hardship (Ciriacy-Wantrup, 1956). The degree of hardship in the new Water Law, however, varies according to the established preference classes among the beneficiaries of water. The highest class is "domestic" followed by "municipal"; the next highest is "irrigation" with "industrial" given the lowest preference class (Sarmad, 1971, pp. 150).

Giving the highest priority to "domestic" uses is not objectionable during droughts and other emergencies, at least from a social viewpoint since some water is essential for survival and hygiene. What is objectionable is that the exercise of preference is given without due consideration to the value of water in alternative uses. For instance, considering the relatively high average value product of consumptive use of water in industry, which according to Sir Alexander Gibb & Partners (1972, pp.40) is as high as 190 Rls/ cu.m., a fairly good economic argument could be made in favour of a reversal of the current ranking preference against agriculture which has an average value product of below 10 Rls/cu.m.

Although the reasonable-beneficial users of water are given their right-of-use in perpetuity, they may lose the right in the following circumstances:

1. utilization of water without a licence or more than what is allowed by the permit;
2. abandonment through relinquishment or otherwise of a water system for a period of more than four years;
3. failure to utilize the right-of-use for a period of more than three years;
4. transfer of right-of-use without permission of the Ministry;
5. failure to observe the legal requirement of the Act.

The idea behind forfeiting for non-use basically stems from the fact that the most immediate and efficient use of water should be considered. This clause of the new law in fact does not leave the decision of whether to use the water or not at the discretion of the owner of the permit. This, to our view is an objectionable prerogative for, if someone else can make productive use of the water, the solution is not the deprivation of use through legislation. Instead, the potential user could, in the presence of a free market, purchase the "right-of-use". If the owner chooses not to sell, he in fact foresees the possibility of greater use in future, that is, turning the water to a still more profitable use; a use which makes up for the present non-use of it. However, if a market for the sale of water was operative, due to the fugitive nature of the resource, especially surface water, the loss of income would definitely serve as an automatic means of preventing excessive reserves for the future.

The question of "waste" has also been given emphasis in the new law (Article 15). Waste of water is strictly prohibited and its practice could lead to loss of permit. At first, this clause of the Act appears to be desirable, for water is a scarce resource and, therefore, should not be wasted at all. But, if the rights were saleable, it would be difficult to see why people are so irrational as to waste water instead of using it in the most efficient and productive manner or, alternatively, sell it to someone else who could do so. To deny rationality in the use of water, is in fact to object to the basis of any private decision making (Milliman, 1959,pp. 50).

On the question of pricing of irrigation water, Article 53 instructs the Ministry of Water and Power to fix water charges in all regions where nationalization has been put in force. The water rate in each basin should bear current expenses including management, operation and fixed charges including depreciation and interest on capital invested etc.

The new water charge is not in fact based on a "full-cost" pricing principle because it is stipulated (Article 53) that water rates for a particular crop should gradually converge throughout the country. To bring in the required parity, the losses incurred by those companies or organizations in a water basin with a high cost of acquiring it, should be compensated by the incomes of those companies or organizations in another basin where the cost of water acquisition is lower. (Gardner et al, 1974).

The intention of the Government is apparently to extract the "economic rent" accruing to farmers in regions with low water costs and transfer it to farmers in less fortunate areas where water costs more. But the idea of an exact uniformity in water rates, which is the ultimate objective of the policy maker, as far as the pricing of irrigation water is concerned, does not automatically lead to a more equitable distribution of income. This is so because it is quite possible that in one region both revenue and costs could be high while in another part the situation could be the other way around. Accordingly, the proposed pricing policy used in the latter region (where cost is low) should price water more than the former region. But the fact of life is that farmers in the former region are already better off through better physical (e.g. land) and environmental (e.g. market) factors other than water. Under these circumstances, an exact uniformity in water rates would only aggravate the distribution of income.

On the basis of the stated objective, water rates should in fact be based on the benefit accruing to farmers from the use of water. Furthermore, in extracting the "economic rent" care should be exercised not to levy any charge attributable to managerial efficiency. In other words, variation in rates should be allowed to encourage efficiency in the use of water (Ansari, 1968, pp. 103).

2.6 Performance of Public Water Agencies

Centralisation of decision making, which is strongly advocated in the new Water Law, however, has some definite advantages. In fact the performance of a number of public water agencies which have been established prior to the new Law and are operating in some parts of the country is quite remarkable. The main factors responsible for improved performance are outlined below.

2.6.1 Economies of Scale: The overall responsibility of public water agencies for the management of a basin allows for the economies of scale in storing, channelling and conveyance of water. Gazvin Agricultural Development Plan serves as an example of a highly successful irrigation network which has made great use of economies of scale. During the first phase of the development plan (1962-72) the agency managed to increase the irrigated acreage from a mere 3,749 hectares to 26,121 with a substantial saving in the use of water per ha. According to Table 2.2 prior to the implementation of the project (1965) each well had been supplying only 62.4 ha of land while by 1972 the figure had gone up to 102.89. This substantial saving was obtained through the construction of major and secondary lined canals and also more efficient irrigation techniques.

Table 2.2 Growth of Irrigated Agriculture in the Gazvin Development Region

(Phase 1)

Land Use (hectare)	Up to 1965	Up to 1966	Up to 1967	Up to 1968	Up to 1969	Up to 1970	Up to 1971	Up to 1972
Irrigated Crop lands	2,576	5,476	8,282	10,456	13,371	16,817	20,338	22,069
Orchards	903	1,309	1,406	1,440	1,549	1,601	1,860	1,958
Vineyards	-	-	29	200	650	969	1,000	1,690
Pilot farms	270	270	288	280	280	235	326	404
Total	3,749	7,055	10,005	12,376	15,850	19,642	23,524	26,121
Employment/ Family	4,971	6,384	6,878	7,746	8,806	9,506	9,625	10,047
Water (No. of deep wells)	60	99	126	140	187	203	245	259
Ratio of total acreage of cropland to number of wells	62.4	71.26	79.40	88.40	84.75	96.75	96.26	102.89

In the second phase, a further 38,703 hectares of virgin land will be brought under cultivation. This increase will be achieved by importing surface water and using it in conjunction with the local groundwater.

2.6.2 Internalization of External Effects:

Another advantage of such a system is that it internalises the external economies and diseconomies which the use of water may create. In many parts of the country, where fragmented farming is practised, artificial recharge of aquifer which is vitally important to the future of the area has been totally ignored. And, as the withdrawal is usually more than natural replenishment, there is a net overdraft. Naturally, under these circumstances, individual members have little interest in recharging the aquifer because, as we have already seen, it is quite possible that their effort, if not done by all, has to be recovered by others. Of course, it is quite conceivable for these users to get voluntarily together and work collectively (Kristjanson,1954), but in practice such a spirit of cooperation, due to the ignorance of farmers about the hydrology of the basin, existence of external diseconomies and many other institutional and financial stumbling blocks is unattainable.

On the contrary, in the controlled areas, the water agencies regard these side-effects of their operations internally - rather than disregarding them as external effects impinging on outsiders (Kneese and Bower, 1968, pp. 75-95).

For instance, in the Ghazvin case, there is concerted effort to replenish the groundwater table. This is simply because the water agencies can expect to recover much of the water it spreads for percolation and thus has an inducement in more efficient overall practice in water use. In other words, the public agencies tend to internalise effects which would be external to the individual users (Mishan, 1972, pp. 109-114). As a result they act more efficiently in the overall management of a basin.

2.6.3 Reducing Waste: The public water agencies have also shown to be more efficient than a number of independent individuals with respect to allocation of water and reduction of waste. We have already seen that in many unregulated areas most villages have their own independent water courses free from any upstream interferences. As a result, instead of utilizing only one or two principle channels, which is potentially possible, there are sometimes more than a hundred long-distance channels running parallel to each other, each carrying only a tiny volume of water. For this reason, in some cases, the loss of water from evaporation and seepage is more than three to four times the actual on the gate requirements of crops. In the regulated areas, on the contrary, the irrigation networks are highly developed, and consequently there is substantial reduction of waste.

The substantial saving of water which is envisaged to be achieved as a result of a modern and comprehensive irrigation network in the Varamin Plain is another example which backs the argument in favour of a public water agency. According to Table 2.3 the diversion of 80 m.cu.m. of available surface water from Latiyan to Tehran would reduce the irrigated acreage of the Varamin Plain from 30,000 to 26,000. In addition, the control of overdraft of groundwater basin takes a further 4,000 hectares out of the present irrigated crop land. The planned integrated irrigation network would restore the original 30,000 hectares without any additional new sources of water. The net saving in water is therefore 144 m.cu.m. (Varamin and Garmsar Development Plan, 1972). These projects have also shown to be financially profitable. For example, the Internal Rate of Return for the Varamin project is over 14 percent, about 5 percent higher than the current bank rate. (Plan Organisation 1973, Vol.9)

Table 2.3 Conjunctive Use of Surface and Groundwater Resources in the Varamin Plain

Description	Water 10^6 cu.m.			Ave.use of water per hectare	Acreage of Irrigated Land
	Surface	Ground	Total		
Before the construction of the Latiyan Dam	213	229	442	14,700	30,000
After the diversion of 80 m.cu.m. to Tehran	151	229	380	14,700	26,000
Phase 1(improved irrigation network and control of groundwater	189	109	298	10,000	30,000

2.7 Summary and Conclusion

This Chapter was basically concerned with the impact of water laws on the efficiency of water allocation. To this end a brief review of historical evolution of water laws was carried out and it was shown that the laws and regulations which existed prior to the nationalisation were not entirely satisfactory for promoting economic efficiency in the use and allocation of water.

In the discussion of the nationalisation of water resources we observed a strong philosophical link between the concept of nationalisation and the original Islamic regulations. We noticed that the new Water Law gives all the managerial responsibilities, from investment to the allocation and use of water, to a central planning body and, at the same time, implicitly denounces the market mechanism and rationality of farmers. This we believe would create too much responsibility for the Government and could be too costly in terms of administration and policing to cause additional complications. In this respect, we advocate a "mixed system" where public water agencies operate in line with the objectives of the existing agencies and work alongside the actual farmers. The functions of water agencies, should be limited in providing the necessary tools for making use of the values discussed in Section 2.5.2 in establishing the "ground rules" for the operation of an efficient market, in educating farmers to utilise water efficiently, etc. while leaving the final decisions about the actual use of the resource to the beneficiaries to be solved by the market mechanism.

In fact, the experience in other parts of the world would seem to favour the development and management of water resources in line with the "mixed system" proposed here (Ostrom 1962, Papadopoulos 1967).

CHAPTER 3

REGIONAL ALLOCATION AND USE OF WATER FOR AGRICULTURAL PURPOSES

3.1 Introduction

The Nationalisation Act , discussed in the previous chapter, has vested the responsibility for safeguarding and utilisation of water resources of the country to the Ministry of Water and Power. This chapter is therefore designed to assist the authorities in their planning for an optimum allocation and use of water resources of the Varamin Plain. But the importance and contribution of this chapter is not simply as a mechanism for allocation and use of water in the Plain. Its wider significance becomes apparent when we consider that the Plain competes with the adjoining Tehran urban area for the available sources of surface water.

The ever increasing demand for urban water (see Chapter 5) will inevitably raise the question of the redistribution of water and, in the light of the priority of use, discussed in the preceding chapter, the value of water redirected from the irrigation region should be estimated. The broad purpose of this chapter is therefore to determine, using a linear programming model, the optimum allocation and use of water resources of the Plain and the consequences of possible changes in the availability of water on the future of the region. The model is used to investigate the effects on the distribution and use of water of problems such as:

- conveyance loss,
- different irrigation regimes,
- cost of pumping

- change in the "release" policy,
- disaggregation of aquifer.

The approach, would therefore bring to light many critical but neglected problems arising from regional analysis of water.

3.2 Background

The Varamin Plain has been an important agricultural area of the Central Iranian Plateau since ancient times. It came into being as a result of the Jajerud, a perennial river, which originates in the Alborz Mountains, northeast of the capital Tehran.

The rapid growth of the city of Tehran in recent years, and the pressing need for food, has added much to the importance of the Varamin Plain as a main producing centre for varieties of agricultural produce. To improve the efficiency of farming in the area, in 1966 the Food and Agricultural Organisation (FAO) of the United Nations was designated to carry out a series of development studies in the Plain. The results of their studies were later on consolidated and reappraised by Mahab (a water resource engineering firm). It is this wealth of information which has enabled us to carry out our detailed study.

3.2.1 Physical Features

The physical features of the Varamin Plain are illustrated in Map 3.1. The area is about 125,000 ha. of which 95,000 ha. are claimed as the territory of 203 villages, the rest being towns, roads, mountains, desert etc. The Plain is bound in the north by the Alborz Mountain chain. In the east, the Pishra Hills separate the Plain from the Central Iranian Desert. The southern and western part of the Plain adjoin the Central Iranian Desert.

The Varamin Plain is located about 30 km. to the east of Tehran with Varamin city as the centre of the Plain. The strategic location of the Plain, i.e. short distance from the capital on the one hand and the availability of water on the other, have given a great advantage to the Plain. The ever increasing population of Tehran, already over 4m., has made the plain an attractive place for the development of agriculture and related industries.

3.2.2 Climate

The climate of the plain may be described as continental, semi-arid to arid, with distinct winters and summers. The annual rainfall on the plain is relatively little, being about 200 mm, hence the need for irrigation. Seasonally, a rainy period December and April and a dry period between July and September when irrigation is at its peak can be distinguished.

3.3 Sources of Water

3.3.1 Surface Water

Jajerud and its tributaries are the only natural sources of surface water in the plain. Jajerud originates in the Alborz range, north of Tehran, and flows in a south-east direction before entering the plain.

Aston University

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The total distance from its origin to the mouth of the river is about 80 km. which covers an area of 1,890 sq.km. Approximately 60 km. from its origin, the Latiyan Dam controls the flow of the Jajerud. This dam is basically used to provide a secure supply of water to Tehran and also to regulate the irrigation water of the Varamin Plain. In addition, the dam generates hydroelectricity during the flood season and peak hours. The technical characteristics of the dam will be given in Chapter 6.

The only major tributary of the Jajerud is the Demavand River which joins the Jajerud approximately 20 km. downstream of the dam. Flow records of this river over long periods do not exist. However, the calculated average annual catchment is 59 m.cu.m. Some of this water, particularly during the irrigation season, is harnessed by the local farmers, only the excess is left to join the Jajerud. A plan is under way to build a regulatory reservoir to control the flow of this river. The total volume of inflow to the dam, about 317 m.cu.m. plus catchment of the tributary, is not all available for downstream irrigation. Allowing for the supply of water to Tehran, the subsurface percolation and the loss of water to the desert, the net annual volume of water available for irrigation is in the order of 200 m.cu.m. Table 3.1 shows the average monthly distribution of surface water.

Table 3.1

AVERAGE MONTHLY DISTRIBUTION OF THE REGULATED FLOW OF JAJERUD AND THE SHARE OF VARAMIN FROM THE DAMAVAND RIVER

(m.cu.m.)

Month ***	Regulated Release from Dam	Tehran Require-ment *	Irrigation Allocation *	Tributary Demavand **	Total available for Irrigation
1	14	6	8	4.11	12.11
2	26	6	20	10.32	30.32
3	32	7	25	9.29	34.29
4	29	7	22	1.22	23.22
5	32	8	24	0	24.00
6	40	9	31	0	31.00
7	26	8	18	0	18.00
8	15	0	7	1.49	9.49
9	12	6	6	3.04	9.04
10	5	5	0	2.57	2.57
11	5	5	0	3.18	3.18
12	7	5	2	3.03	3.03
Total	243	80	163	38.25	200.25

Source: * "Iran's Dams", Ministry of Water and Power.

** FAO.

*** The first month of irrigation cycle here corresponds to the 20th Feb.-20th March

3.3.2 Groundwater

The low level of rainfall in the Varamin Plain (approximately 200 millimetres) on the one hand, and the variable inflow of the Jajerud river on the other, make the utilisation of groundwater basin essential for a regular supply of irrigation water. It has been estimated that the Plain enjoys a huge underground water basin with approximately 15 x 10^9 cu.m. of water. Two thirds of this water is considered of good or fair quality and is suitable for irrigation. In most parts of the Plain the quality of water is good with only 1.5 - 10% dissolved sodium which implies that high salinity does not threaten the Plain. However, in the southern and south western parts of the Plain, the quality of water is poor mainly because the water table is shallow so that there is high evaporation which causes a build up of residual salts.

In the northern apex of the Plain, the water table is at 60-80 metres below the surface. In the centre, the aquifer is subdivided into 4-6 tables with a depth of between 20-50 metres. In the lower part of the basin water almost reaches the surface. However, since both water and soil in this part of the basin are saline they are of no agricultural value.

The amounts of water which currently each year go to recharge the aquifer have been estimated (Mahab - Chapter 4) to be as follows:

- natural precipitation	4	m.cu.m.
- subsurface flow from Jajerud	65	"
- subsurface flow component from Jajerud tributaries	5	"
- percolation of irrigation water	125	"
- seepages from Canals	52	"
- seepages from ditches	13	"

Ultimately, of course, the last five of these derive from the Jajerud and its tributaries.

Against these sources of recharge, the groundwater resource is currently used in the following way:

- pumping of ghanats	250	m.cu.m.
- subsurface outflow	6	"
- evaporation from shallow water table	36	"

Balancing this inflow and outflow of water to and from the basin, we can see that the aquifer currently has an annual overdraft of 30 m.cu.m. This inbalance will be aggravated once the lined canals and new irrigation systems are adopted. Without necessary measures to correct the imbalance, this valuable source of water is subject to exhaustion, either through the lowering of water table or the intrusion of saltwater.

The current over-pumping of aquifer and the diversion of 80 m.cu.m. to Tehran, has resulted in an average annual decline of water table by about 0.2 to 1.0 m. This has caused drying up of many ghanats in the Plain.

The effect of the drop in water table, due to low transmissivity, is not uniform throughout the Plain. For instance, the result of a simulation study by FAO shows that the diversion of 80 m.cu.m. of water to Tehran will cause a drop in the water table of from 8 to 10 metres in the north of the Plain, 5 to 8 metres in centre and much less in the south east within the next ten years.

The simulation model produces a long-run annual extraction policy for different parts of the Plain. The result of this simulation study is used in our model (to be discussed shortly) for the derivation of upper bounds on the safe aquifer yield in the sub regions of the basin.

3.3.3 Tehran-Canal Water

Tehran does not currently have a sewer system. The sewerage is drained to the ground, and as a result, the water table in the southern part of the city is rising very rapidly. To control the level of water table from reaching the surface, plan is under way to pump the water and, after minor treatment, transfer it to Varamin for agricultural use.

The construction of the conveyance canal according to Mahab (Chapter 9) will be completed by 1980. The canal will have a conveyance capacity of 12 cu.m./sec. The annual volume of water reaching the Plain is estimated to be 205 m.cu.m. eventually.

3.4 Some Previous Work and Some Features of the Model

Making optimum use of the water resources of the Plain requires that all the water resources cannot be considered in isolation from each other since there is a close relationship between ground and surface water resources and their possible uses in various parts of a basin (U.N. 1958).

The problem of integration or conjunctive use of ground and surface water has long been recognised. Buras (1963) illustrates the optimum operation of a surface and aquifer system through a dynamic programming model. Burt (1964) explores methodological procedures for measuring expected value of net output from a basin operating under conditions of conjunctive use of ground and surface water. Dracup (1966) employs parametric linear programming to find out the optimum use of a conjunctive use of ground and surface water in Southern California. Young and Bredehoeft (1972) describe a procedure for determining optimal management policies for inter-related surface and ground waters in a 50 mile reach of the South Platte River in the U.S. They use a simulation model to investigate the response of the stream-aquifer system to changes in river flow and a two stage linear programming model to observe the response of irrigators to variation of water supply and cost. Mobashari and Grant (1973) develop a non-linear programming algorithm to find the optimum operating strategy for conjunctive management of a surface water and ground water system. Chaudhry (1974) considers the optimal conjunctive use of the Indus Basin waters in Pakistan by employing a decomposition strategy for dealing with the size and the complexity of the problem.

Most of these studies, however, do not simultaneously include the following refinements in their investigations:

Alternative irrigation regimes

Specific yield of aquifer in different parts of the basin

Evaporation-seepage loss as a function of length of canal

Cost of pumping as function of depth of water table.

These are some features of our model to be set out in the next section below. Because they tend to be neglected and because they turn out to be quite significant in the model solution it is worth noting these features briefly here.

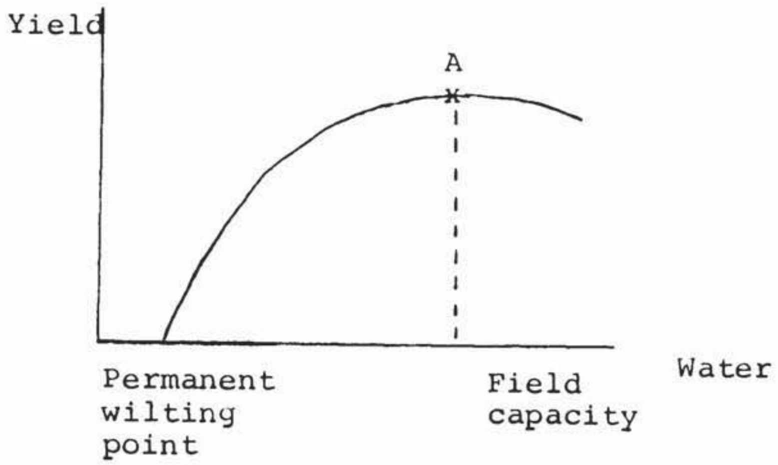
3.4.1 Alternative Irrigation Regimes

It is a common practice among majority of irrigation engineers to assume that any crop has a unique water requirement (Flinn and Musgrave, 1967). Such a procedure needs a strong defence especially with regard to arid environs, where water is not a "free good" and the possibility of substitution between water and other inputs, in particular land, exist.

The widespread use of "unique" water requirement reflects the fact that agricultural scientists, in calculating the water requirements of crops, tend to maximise the yield rather than the revenue. In other words, efforts are concentrated on obtaining the highest point on a crop production possibility curve. The following schematic diagram illustrates this view.

Fig. 3.1

A Typical Crop Prediction Curve



This approach could be desirable in situations where water, in relation to other factors of production, is plentiful. Therefore, by obtaining the point of highest yield, the efficiency in the use of other limiting inputs could be increased (Leftwich, 1966, pp.111-116). In arid environs, where water usually carries a positive "opportunity cost", the point of highest yield does not necessarily bring about the most economical use of available water supply (Shipley and Regier 1970). The current view, in other words, reflects inadequate co-operation between agricultural scientists and economists. Agricultural scientists are mainly concerned with the maximisation of yields of individual crops or sometimes revenue without due consideration of the value of water in alternative use.

In terms of economic efficiency, such a policy may not lead to the optimum use of a scarce resource once the possibility of output as well as input substitution is considered (Sun Po-Chuan, 1972, pp. 45-49). This is simply because the marginal product of irrigation water is not necessarily the same at a particular point in time in the production of different crops, or even one crop under different irrigation regimes. This point has been illustrated by Osborn and Ethridge (1967) in a study in the High Plain, Texas. They found that change in the price of one crop sometimes forces other crops with highest yield and water use out of the optimum production plan. In another study, Yaron (1967) incorporates flexible irrigation practices for major field crops in a model of a family farm in Negev, Israel, and found an increase of between 15-30 percent in the marginal productivity of water as compared to the conventional irrigation practices restricted to rigid "irrigation norms". Lane and Littlechild (1975) consider crops under different irrigation intensities in a weather-dependent pricing model and found that the most intensive irrigation regime does not always appear in the optimal solution. Gisser (1970) investigates the effects of change in the price of imported water on cropping patterns under different irrigation intensities and techniques and comes to the same conclusion.

To demonstrate the practical implication of this argument to the study area, the present model considers the possibility of growing crops under different irrigation regimes. For the purpose of comparison, we have also included the selected irrigation regime for each crop by Mahab which are considered here as the "control crops".

3.4.2 Specific safe yield of Aquifer in different parts of the Basin

Consideration of the safe yield of aquifer in different parts of the basin is important for an orderly extraction of water over a long period of time. This is particularly important in situations where transmissivity rate is slow or the basin consists of a number of confined aquifers. In this situation, treatment of the aquifer as a single reservoir, while heavy pumping in some parts exists, could hinder the subsurface flow from recharging the aquifer evenly. This could result in a drop in the water table in some parts of the basin and, in turn, could create external diseconomies through intrusion of saltwater or higher pumping costs in the affected parts. (See Chapter 2 . 3.2.)

3.4.3 Conveyance Loss

Inadequate attention to conveyance loss may adversely affect the efficiency of allocation. Tolley and Hastings (1960) show that ignorance of this fact leads to a sub-optimal allocation of water. This is because it usually takes considerably more water from the point of diversion to supply a hectare of land at the foot of a canal than a similar tract of land at the head of the canal.

3.4.4 Pumping Cost as a function of depth of Water Table

Consideration of cost of extracting groundwater as a function of depth of watertable from the land surface, may affect the efficiency of allocation since in periods of less heavy demand for water it might be possible to irrigate those parts of the region, where cost of pumping is relatively high, from the surface sources and use the ground water in parts where extraction cost is low. Pumping cost obviously here is not the only determinant. The optimum extraction policy is decided through the interaction of pumping cost and conveyance loss.

3.5 The Model

The quantitative analysis has been made by means of a linear programming model. The model includes 460 variables or activities and 185 constraints including limits or bounds on individual activities. The activities include those for crop production including crops with different irrigation regimes, and water allocation. Bounds on specitic activities serve as restraints on the marketability of some perishable crops, crop rotation requirements and the possibility of intra-regional transfer of water. Other restraints are provided to limit the availability of different sources of water and land.

The programming model is described in greater detail below.

3.5.1 Notation

In the construction of the model the following notations are employed:

Suffices

i	the crop index;	$i=1,\ldots,10$
m	the irrigation regime index	$m=1,\ldots,10$
k	the sub-region index;	$k=1,\ldots,5$
h	the water source index; $h=1$ river, $h=2$ Tehran-Canal, $h=3$ groundwater;	$h=1,\ldots,3$

Variables

X_{imk}	hectares of crop i under irrigation regime m in sub-region k;
W^h_{jk}	water sent to sub-region k from source $h=1,2$, or extracted from the ground $h=3$ during month j, cu.m;
y_{gjk}	groundwater transferred from sub-region g to sub-region k during month j, cu.m;

Data

a_{imj}	water applied to crop i under irrigation regime m during month j, cu.m;
r_{im}	revenue from crop i under irrigation regime m, Rials/hectare;
c^h_k	cost of water from source h in region k Rials/cu.m;
f_k	loss factor incurred when supplying sub-region k from river and Tehran-Canal, $(0 < f_k < 1)$

d_{gk}	possibility of transferring groundwater from sub-region g to k (0 if water cannot flow from g to k otherwise 1)
df_{gk}	loss factor incurred in transferring groundwater from sub-region g to k, ($0 < df_{gk} < 1$)
$\bar{W}^1_j$	Constraint on water available from river $h=1$, during month j, cu.m;
$\bar{W}^2$	constraint on the monthly capacity of Tehran-Canal, cu.m;
$\bar{W}^3_k$	constraint on the monthly pumping capacity of groundwater in sub-region k, cu.m.
$\bar{\bar{W}}^2$	constraint on the annual yield of Tehran-Canal, cu.m;
$\bar{\bar{W}}^3_k$	constraint on the annual yield of aquifer in sub-region k, cu.m;
L_k	constraint on the availability of land in sub-region k hectare;
$\bar{x}_i$	constraint on the acreage of crop i, hectare;

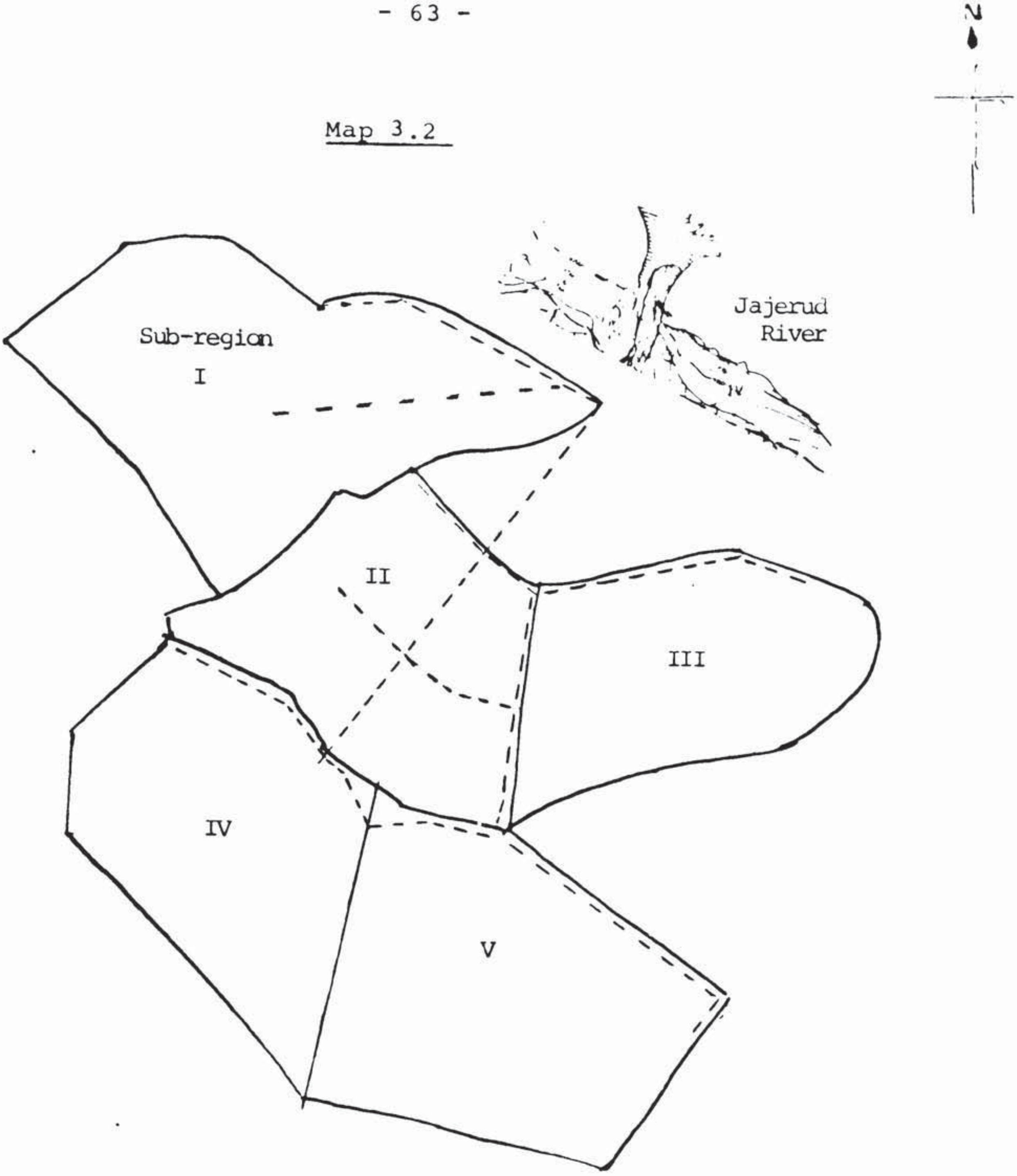
3.5.2 Region and its Delineation

The programming model is of "intra-regional competition" nature since it determines the location of crops and water use in different parts of the region. To reflect the intra-regional nature of the analysis, the entire Plain has been partitioned into five sub-regions (Map 3.2). The boundaries are those which are suggested by Mahab and are basically marked by the main conveyance canals.

3.5.3 Activities

Two groups of activities are employed to represent crop production (x_{imk}) and water allocation (W^h_{jk}, y_{gjk}). There are altogether 10 different crop activities. The first four, however, can be grown

Map 3.2



Schematic Representation of the Sub-regions under different irrigation regimes, (the first three have ten different water intensities and the fourth only 4). Each crop is allowed to grow in any of the five sub-regions. Accordingly there are 200 crop activities. Considering that the irrigation cycle takes ten months (starting in late February, and continuing until November), the total number of water-allocation activities is 260 (50 river, 40 Tehran-Canal, 170 groundwater), which makes the overall number of activities in the model 460.

3.5.4 Constraints

There are four sets of water restraints limiting water requirements of crops and availability of water in different months and sub-regions. They are as follows:

3.5.4 (i) Crops Water Requirement

$$\sum_{i=1}^{10} \sum_{m=1}^{M_i} a_{imj}\, x_{imk} - \left(\sum_{h=1}^{2} W_{jk}^{h} + \sum_{k=1}^{5} y_{gjk}\right) \leq 0$$

$$j=1,\ldots,10$$
$$k=1,\ldots,5$$

The first term of this constraint, represents the monthly water requirements of crops grown in a particular sub-region, the second term, the net-availability of surface water (river and Tehran Canal) and the third term the net volume of groundwater transferred from a sub-region to other sub-regions, including itself. This constraint, in other words, balances the demand for and supply of water during each month of the year for each sub-region.

3.5.4 (ii) River Water Supply

$$\sum_{k=1}^{5}\sum_{j=1}^{J'} \frac{1}{1-f_k} W^{1}_{jk} \le \sum_{j=1}^{J} \bar{W}^{1}_{j} \qquad J'=1,\ldots,10$$

This constraint states that total amount of river water supplied to all sub-regions during each month of the growing season should not exceed the accumulated average volume of surface water released from the dam plus the tributary water reaching the Plain.

Originally, this constraint was formulated without the summation sign on the right-hand side of the constraint. Algebraically we had

$$\sum_{k=1}^{5} \frac{1}{1-f_k} W^{1}_{jk} \le \bar{W}^{1}_{j} \qquad j=1,\ldots,10$$

However, in a preliminary run, it was found that the efficient use of water (in terms of a higher value for the objective function) could be obtained by allowing the model to decide on the optimum release requirements. To this end, it is assumed that the current monthly release, (see Table 3.1) could be augmented in the reservoir and be released as and when it is required. For instance, if the current release during the first month is not required, the model assumes that the water can be accumulated in the reservoir and can be released in the following period. The accumulated water, plus the second period release, is then available for use in the second period. However, if this water in full, or a proportion of it, is not required it can be saved for the third period and so on.

3.5.4 (iii) Tehran-Canal Water Supply

There are two sets of constraints determining the use of water coming from Tehran.

a) $$\sum_{k=1}^{5} \left(\frac{1}{1-f_k}\right) W^2{}_{jk} \leq \bar{W}^2 \qquad j=1,\ldots,10$$

The first constraint above limits the supply of water to the capacity of the canal

b) $$\sum_{k=2}^{5} \sum_{j=1}^{10} \left(\frac{1}{1-f_k}\right) W^2{}_{jk} \leq \bar{\bar{W}}^2$$

while the second constraint (b) limits the annual use of water to the proposed potential extractable volume of water.

3.5.4 (iv) Groundwater Supply

There are three sets of constraints determining the operation of groundwater:

a) $$\sum_{k=1}^{5} \frac{1}{1-df_{gk}} y_{gjk} - W^3{}_{jg} \leq 0 \qquad \begin{array}{l} j=1,\ldots,10 \\ g=1,\ldots,5 \end{array}$$

This constraint requires that the supply of groundwater by a sub-region to others, including itself, does not exceed the amount of water extracted from that region.

b) $$W^3{}_{jk} \leq \bar{W}^3{}_k \qquad \begin{array}{l} j=1,\ldots,10 \\ k=1,\ldots,5 \end{array}$$

This constraint limits the extraction of water in each sub-region to the pumping capacity of that region.

c) $$\sum_{j=1}^{10} W^3{}_{jk} \leq \bar{\bar{W}}^3{}_k \qquad k=1,\ldots,5$$

Finally, the above constraint controls the extraction of water in each sub-region to the annual safe yield of aquifer in the same sub-region.

3.5.4 (v) Land Restraint

Land restraint allocates the available land in each sub-region among competing crop activities. The general form of the land restraint for the kth sub-region is

$$\sum_{I=1}^{10} \sum_{m=1}^{M_i} X_{imk} \leq \bar{L}_k \qquad k=1,\ldots,5$$

3.5.4 (vi) Crop Restraint

$$\sum_{k}^{5} x_{imk} \leq \bar{X} \qquad \begin{array}{l} i=2,7,8,9 \\ m=1,\ldots,10 \end{array}$$

This constraint puts an upper bound on the growing of some crops. The bound is based on the proposed cropping acreages by Mahab.

3.5.4. (vii) Non-negativity Restraint

Finally all variables in the model are required to be greater than, or at least equal to zero, i.e.

$$x_{imk} \geq 0$$
$$y_{gjk} \geq 0$$
$$w^h_{kj} \geq 0$$

3.5.5. The Objective Function

The objective in obtaining a solution for the programming model is to maximise the crops revenue minus costs of providing water. Formally we have

$$\max \sum_{i=1}^{10} \sum_{m=1}^{M_i} \sum_{k=1}^{5} r_{im}\, x_{imk} - \sum_{h=1}^{3} \sum_{k=1}^{5} \sum_{j=1}^{10} c^h{}_k\, w^h{}_{kj}$$

The first term represents the revenue generated from x hectares of crop i under irrigation regime m grown in sub-region k and the second term represents the cost of providing w cu.m. of water from source h during month j in sub-region k.

3.6 Basic Assumptions underlying the Model

In developing the model, specific assumptions were made concerning the nature of behavioural and physical relationships of the agricultural sector of the study area. A brief resume of the most significant ones is listed below.

3.6.1 Management Objective

It is postulated that the decision maker (Varamin Irrigation Authority) is in search of a planning strategy for the most efficient use of scarce resources. In doing so, his entrepreneurial motive is the maximisation of crops revenue grown in the entire region.

3.6.2 Farmers' Response to Economic Incentives

It is assumed that farmers who are members of a cooperative society respond in a positive way to the decisions taken by the authority and this response corresponds favourably to the profit maximisation goal set by the planner.

3.6.3 Aggregation of Inputs

Since the model is based on regional consideration, all the inputs within the entire region were aggregated and were treated as if they were homogeneous with respect to natural (e.g. soil, yield, water requirement of crop, etc.) as well as technical (cost, managerial efficienty etc.) characteristics. However, with respect to cost of groundwater lifting, the homogeneity assumption is narrowed down to the average depth of water table in each sub-region.

The assumption of an identical input-output matrix and quantitatively homogeneous output vectors, which are necessary for a satisfactory aggregation (Miller, 1966), can be justified once we consider that all farmers are members of a cooperative society and receive similar help and assistance from the Varamin Irrigation Authority.

3.6.4 Efficiency Level

It is assumed that farmers operate on a medium level of efficiency defined by FAO for the Plain, and within this level combinations of factors of production in each activity is optimum. This assumption, in other words, implies that proportionality prevails in the production of crops. That is, inputs and outputs to and from an activity are proportional to the level of that activity.

3.6.5 Yield Level

The crop yields presented in Appendix 3.4 are assumed to approximate the average yield in all sub-regions. These yields are based on field experiments conducted in the region under the supervision of either the Soil Institute of Iran or FAO.

The response of yield to alternative combination of other inputs such as fertilizer, irrigation techniques, etc. although important, due to lack of reliable data have been disregarded. The effect of soil characteristic is not reflected in the yield. Climatic factors are considered as uncontrolled variables although it is acknowledged that correlation exists between weather variables and yields, especially temperature and soil moisture conditions (Lewis,1969). However, the observation of temperature, natural precipitation, solar radiation and wind, shows that the occurrence of these growth factors are almost uniform at each point in time in most parts of the regions especially during the reproductive stage of major crops growth.

Accordingly controllable factors in our model are, the amount and time of irrigation, the cropping patterns, the irrigation regimes and inter-regional transfer of groundwater.

3.7 Sources and Implication of Data

The data used in our model is discussed below.

3.7.1 Available Water $\left[\bar{W}_k^h, \bar{\bar{W}}^h\right]$

Monthly distribution and availability of river water, the capacity of Tehran-Canal and the annual yield of Tehran-Canal water are given in Section 3.3 However, in order to obtain the safe yield of aquifer in different sub-region, a hydrological map of the entire aquifer containing 27 polygons and representing the safe yield of aquifer in different parts of the basin (App. 3.1) is superimposed on Map 3.2. The number of polygons (with given yield) falling within each sub-region are then aggregated to represent the annual safe yield of aquifer in each sub-region (Appendix 3.2).

3.7.2 Pumping Capacity $\left[W^3_{kj}\right]$

Monthly pumping capacity of wells operating in each sub-region is derived by summing the number of wells in each sub-region. The total number of wells in each sub-region is then multiplied by the maximum monthly pumping capacity of an average well (Mahab Chap.4). App. 3.2 presents information about the number of wells, pumping capacity and safe yield of aquifer in each sub-region.

3.7.3 Intra-regional Transfer of Groundwater $\left[d_{kg}\right]$

Considering the particular topography of the basin, and the point of entrances of river and Tehran-Canal, the flow of water from river and canal can be directed to all sub-regions with the exception of use of canal in the first sub-region. Exchange and transfer of groundwater, however, is directed by the force of gravity and could only be carried out according to the following matrix.

Table 3.2 Possibility of Intra-regional transfer of Groundwater

Sub region	I	II	III	IV	V
I	1	1	1	1	1
II	0	1	1	1	1
III	0	0	1	1	0
IV	0	0	0	1	1
V	0	0	0	1	1

According to the above matrix, groundwater from sub-region 1, for example, can be conveyed to all other sub-regions, while the possibility of transfer in the case of sub-region 4 is limited only to the contiguous sub-region 5 and vice versa.

3.7.4 Water Loss through Conveyance $\left[f^{1,2}_{k} \text{ and } df^{2}_{gk}\right]$

Unfortunately little relevant statistical evidence has been traced in Iran to show the relation between loss of water and length of canal. However, Tolley and Hastings (1960, pp.281), find a loss rate of 1 percent per mile for North Platte Basin in U.S. This rate is very similar to the tentative rate suggested by FAO for the Garmsar Irrigation Project in Iran . In the absence of any field experiments we have therefore employed Tolley's rate in our model.

With reference to the proposed canal network (Map. 3.2) the loss factor, as a percentage of water available at the apex of the Plain, is as follows:

	Sub-region				
	I	II	III	IV	V
Percentage of water lost from the point of diversion	0.0355	0.0646	0.0629	0.1511	0.1842

The same loss rate is also considered for the intra-regional conveyance of groundwater. However, the loss factor associated with the groundwater which is extracted and used in the same sub-region is set to be zero. The elements of the following Table shows the percentage of groundwater reaching a sub-region. In this matrix, rows and columns represent the "sender" and "receiver" of groundwater respectively.

Table 3.3

Loss Factors associated to the Intra-regional Conveyance of Groundwater

Sub region	I	II	III	IV	V
I	1.000	0.943	0.903	0.863	0.827
II	0.000	1.000	0.926	0.939	0.884
III	0.000	0.000	1.000	0.906	0.000
IV	0.000	0.000	0.000	1.000	0.920
V	0.000	0.000	0.000	0.920	1.000

The zero elements in the above matrix indicate that the possibility of conveyance between the respective sub-regions does not exist.

3.7.5 Cost of Water $\left[C^{1,2}, C^{3}_{k}\right]$

Considering that the river water is supplied to the Plain practically free of charge, no cost is assigned to this source of water in the model. Unit cost of Tehran-Canal according to Mahab is set to 0.4 Rls/cu.m. No direct information with regard to the unit cost of groundwater in different sub-regions is available. However, according to Buras (1963) pumping cost of groundwater is basically a function of two factors; the capacity of the pump and the depth of water table.

Considering the plan for the elimination of small pumps (Mahab, Chap. 4) we have assumed a constant pumping capacity throughout the region. The only variable factor is therefore the depth of water table from the land surface. The cost of electrical energy for pumping a certain cu.m. of water according to Mahab can be derived through the following formula.

$$G_n = \frac{V \times H \times C}{3.6 \times 102 \times E}$$

where

G_n = annual energy cost Rls.

V = pumped water cu.m.

H = lifting height

C = energy tariff Rls/Kw (Rls 0.8/Kw)

E = efficiency rate (60%)

Considering the average depth of water table in different sub-regions (derived by superimposing the counter map of water table depth App.3.3 on Map 3.2) the unit cost of pumping water as a function of depth of water table is calculated and presented in the following Table.

Table 3.4

Cost of Groundwater in Different Sub-Regions

Rls/cu.m.

Sub-region \ Depth in metres	20	30	40	50
1	-	-	-	0.941
2	-	-	0.905	-
3	-	0.868	-	-
4	0.8326	-	-	-
5	0.8326	-	-	-

3.7.6 Crops revenue $\left[r_{imk}\right]$

Crops revenue contained in Appendix 3.4 are mainly compiled by FAO . Production costs of crops with multiple irrigation regimes are treated the same as the "control crops" in order to avoid the existing discrepancy between different sources of data. Price of outputs are however updated to reflect the 1973 level.

3.7.7 Crops Water Requirements $\left[a_{im}\right]$

Water requirements of crops with one irrigation regime as well as the control crops are compiled by Mahab. The water requirements of crops under multiple irrigation regimes are the result of field experiments which are conducted by the Soil Institute of Iran in the Plain. Appendix 3.5 presents monthly water requirements of all the candidate crops.

3.7.8 Land Limitation $\left[\bar{L}_k\right]$

The acreage of land prepared for irrigation farming in each sub-region is as follows:

Sub-region	I	II	III	IV	V
Available Land (Hectare)	9500	12000	8000	1000	1000

3.7.9 Crop Limitation $\left[\bar{X}_i\right]$

The type of crops which are included in the model are those which are extensively cultivated and others which are recommended by agronomists.
The acreage of some crops is limited to reflect the marketability and agronomic characteristics of the crop. Perishable crops acreage, for example, is limited simply because the demand for these crops is very elastic and adequate facilities for storage are not available. Therefore a sizeable increase in

the production of these crops may cause the collapse of the market. From agromonic point of view, successive growing of a crop is not feasible so the acreage of some crops should be limited by an upper bound to allow for this fundamental requirement. Acreages of crops with upper bound are given in Appendix 3.6.

3.8 Discussion of the Model Result

The linear programming model of the Varamin Plain which is developed in the preceeding section, is run under two alternative water supply conditions. In the first run (phase I) which represents the current state of water supply, only the surface water (river) and sub-regional groundwater are considered, while in the second run (phase II) which corresponds to the planned state of water supply from 1980 onwards, an additional source of water, viz., Tehran-Canal is added to the sources of water.

3.8.1 Distribution of Water

The optimum monthly distribution of water under the two phases are diagrammatically represented in the following two figures. During the first phase, both surface and groundwater resources of the plain have similar fluctuations. Pumping of aquifer and release from the reservoir

Fig. 3.2 OPTIMUM MONTHLY DISTRIBUTION OF WATER

Phase 1

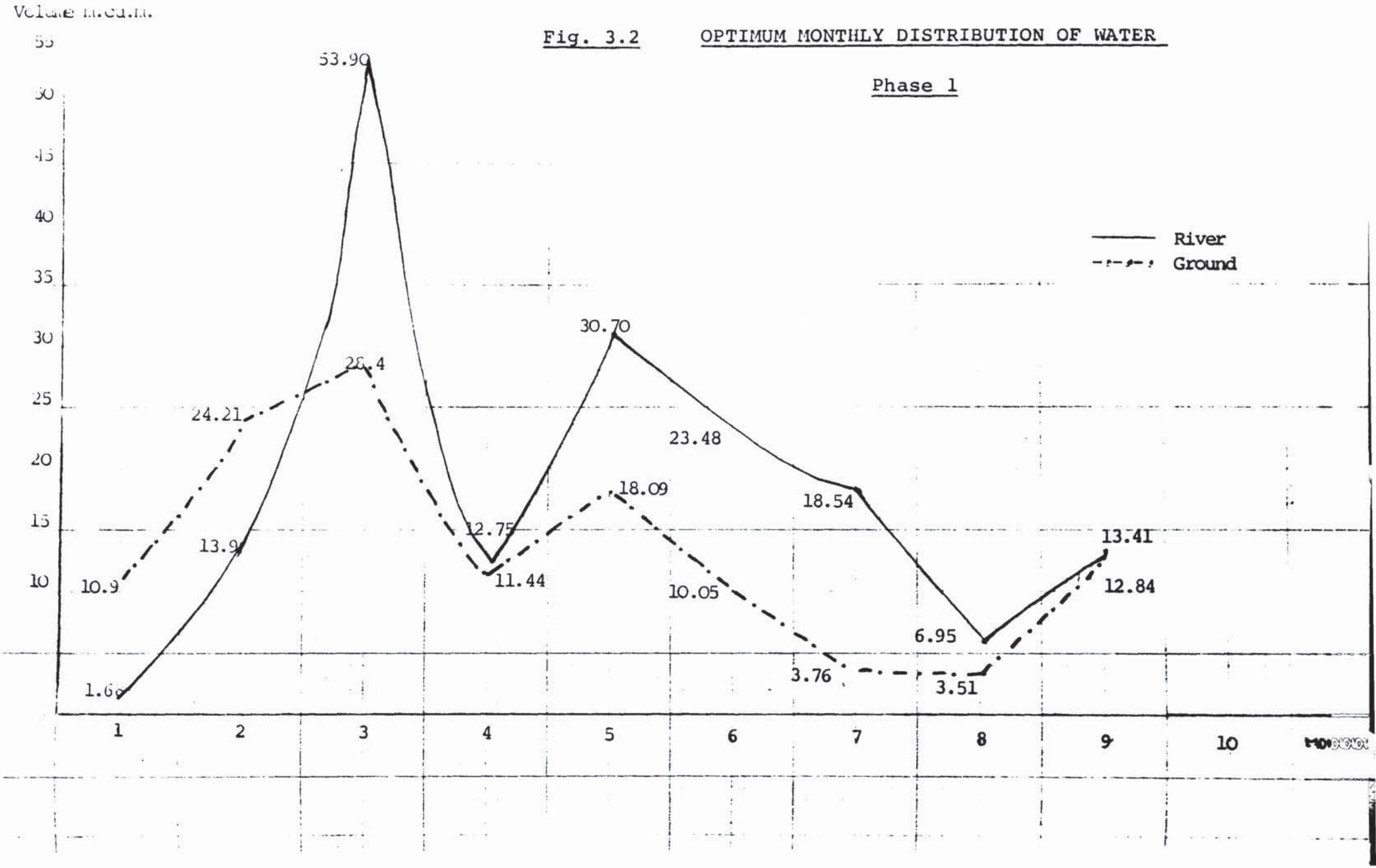
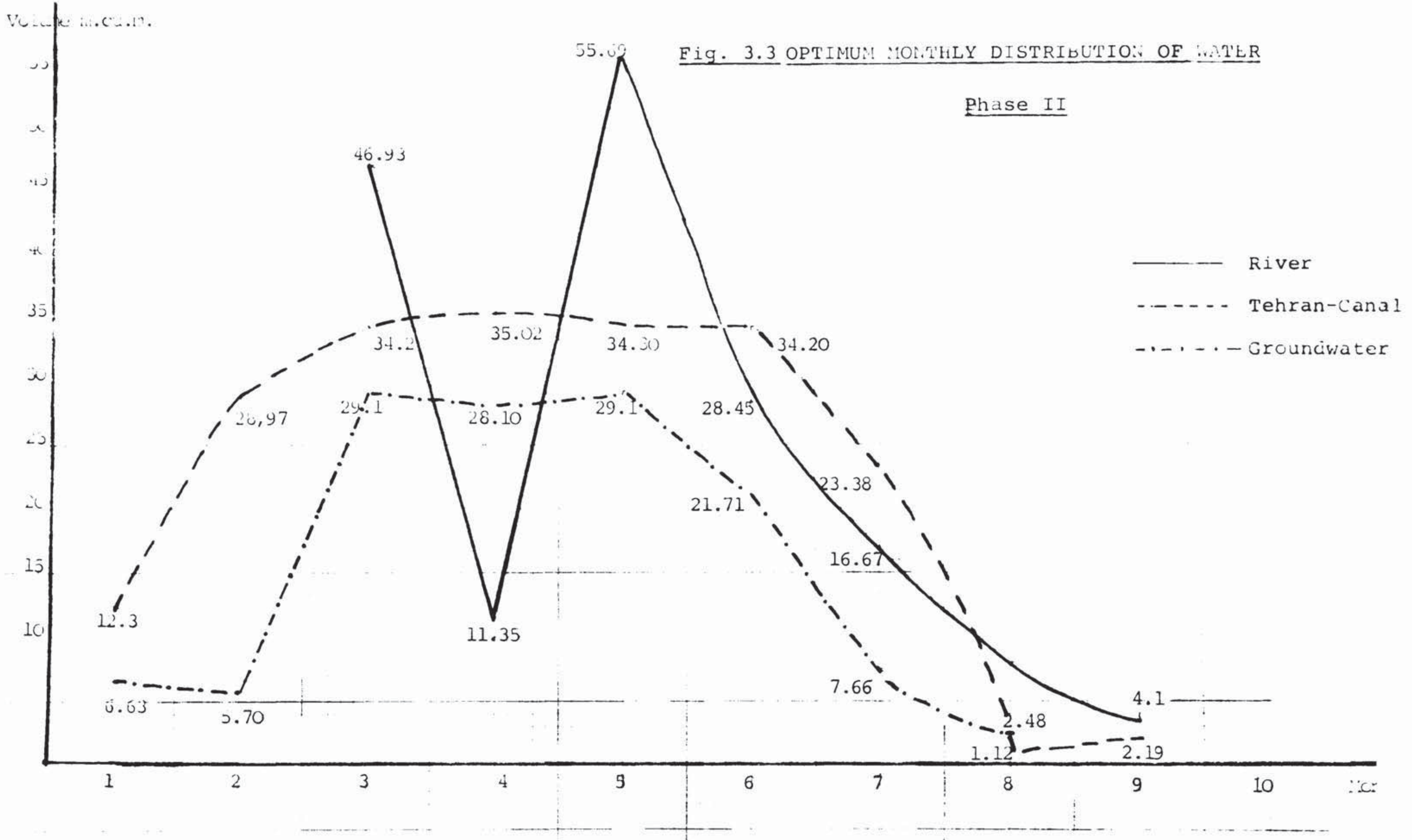


Fig. 3.3 OPTIMUM MONTHLY DISTRIBUTION OF WATER

Phase II



both start during the first month, with a peak during the third and the fifth month. In the second phase, the monthly distribution of water is rather different. No release from the reservoir is required during the first two months of the irrigation cycle. Instead the potentially available water from the reservoir in these periods is accumulated and up to 37 per cent of it is released in the third month. The peak in the third month corresponds to the last month of wheat and the first month of cotton irrigation requirements. The decline in the fourth month is therefore caused by the completion of wheat irrigation. The next peak, in the fifth month, coincides with the heaviest month of cotton irrigation requirement. The pumping of aquifer and the imported water from Tehran however, both begin in the first month, with a peak during the third to fifth months.

The difference in the optimal use of water in the two phases is due to the higher availability of water in the second phase, which has caused the model to generate a rather different cropping mix.

A comparison between the current release from the reservoir, for the purpose of irrigation and the optimal requirement of the system from this source, demonstrates the sub-optimal use of water under the current release policy. Such a non-optimality in the use of river water is basically due to the fact that current releases from the reservoir are based on the natural flow of rivers which have been in use from early times. The use of water now that the dam is constructed and is capable of impounding the streamflow needs revision. For instance, the optimal solution indicates that 65.64 per cent of available water in phase II should be saved during the first two months of irrigation cycle and be released in the subsequent month when the irrigation of a number of profitable crops such as cotton and melons starts. This flexibility in the use of this source of water is attributable to the ways that constraint 3.5.4(ii) is formulated. In fact, a comparison between the value of the objective function of a separate run of the model in which accumulation of river water is not allowed, shows that the above flexibility in the use of river water has resulted in an increase of over eight per cent in the profitability of the entire region during the phase II. The increase in the value of the objective function is achieved through a more profitable cropping mix. The major change in the cropping mix is the substitution of cotton and melon for wheat.

The optimum monthly distribution of water to different sub-regions as we would expect contains the minimum of possible conveyance loss. For this reason, as Figure 3.4 shows, during phase I the entire monthly river water, with the exception of a fraction

Fig. 3.4 OPTIMUM MONTHLY DIVERSION OF WATER TO DIFFERENT SUB-REGIONS (Phase I)

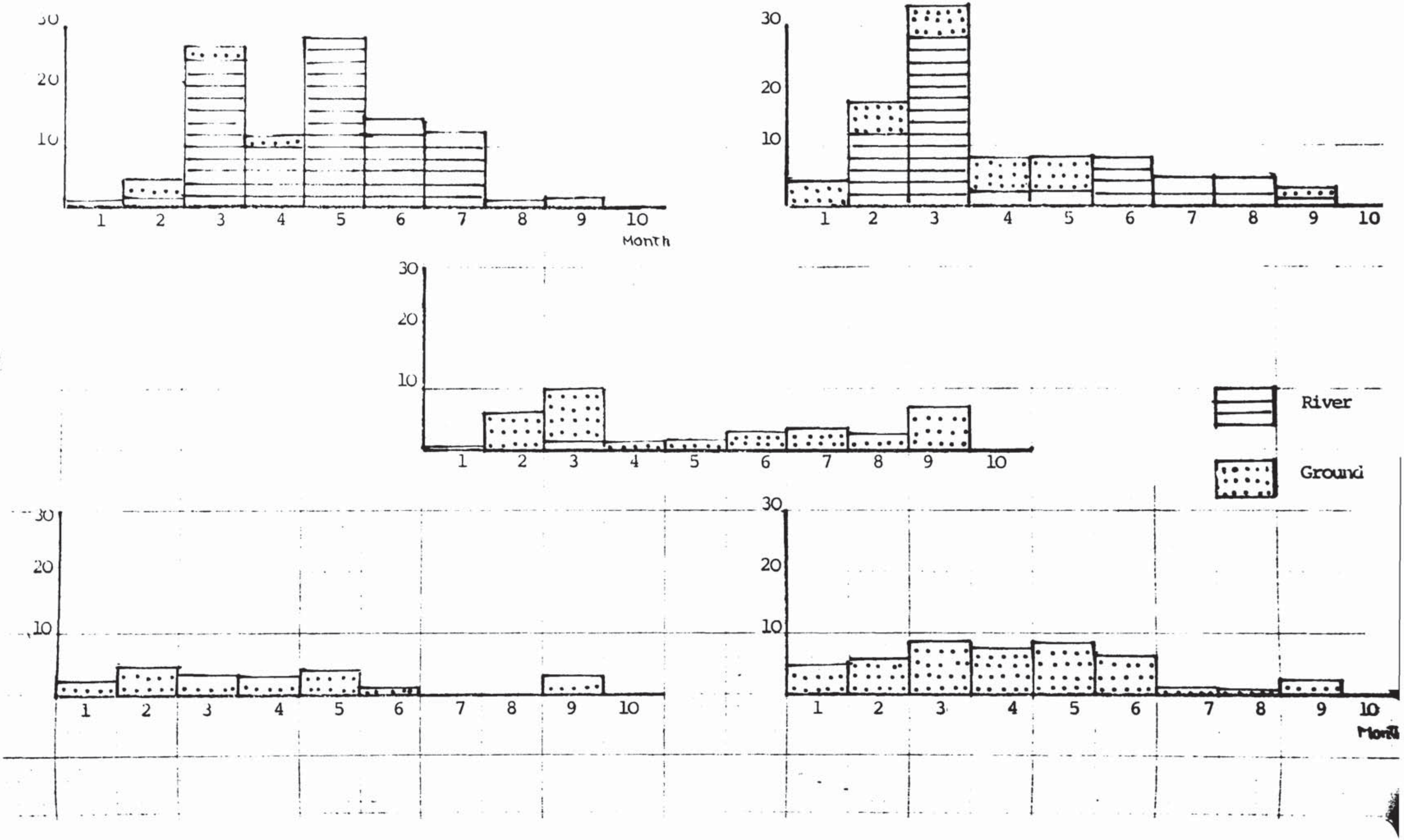
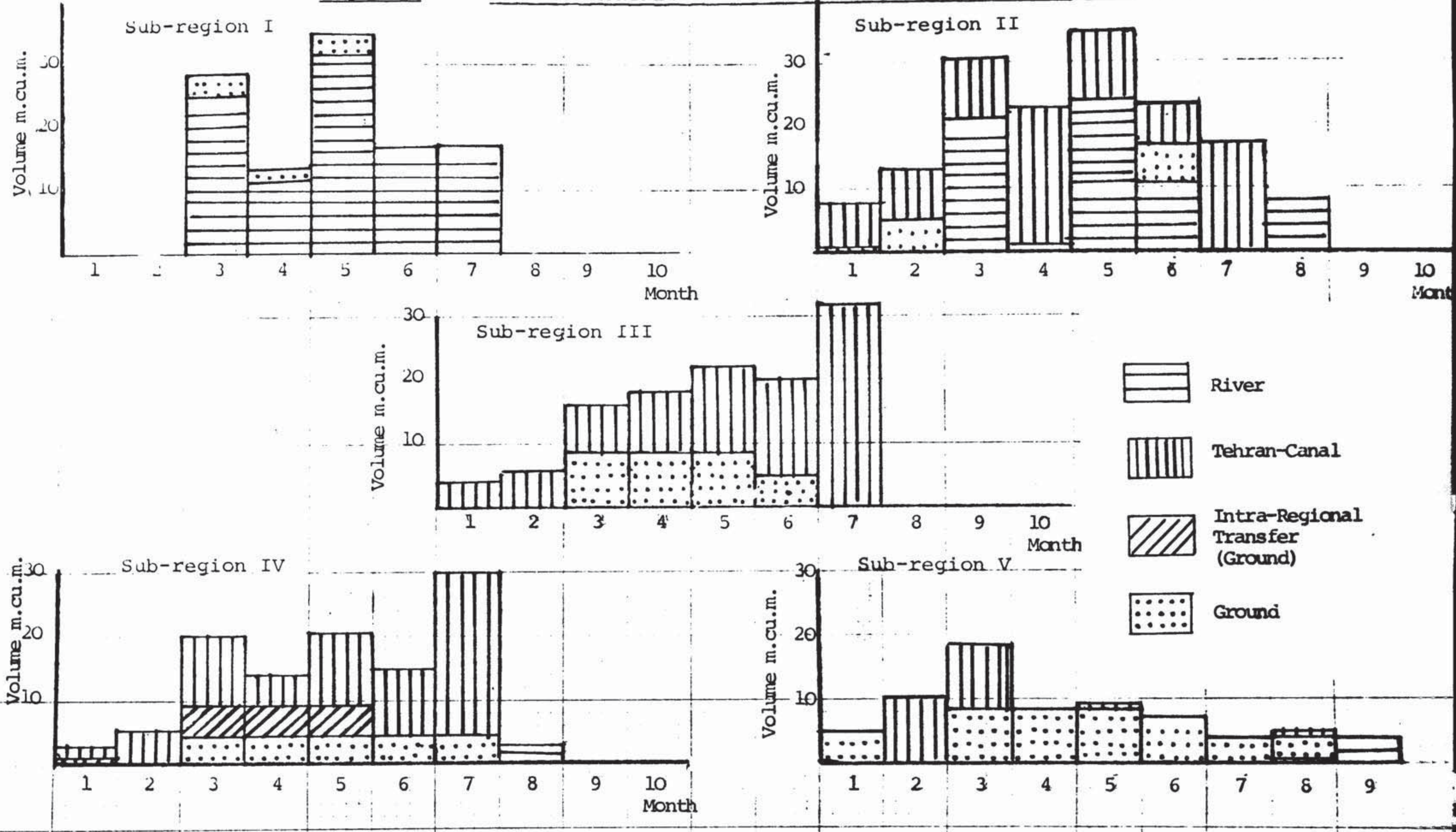


Fig. 3.5 OPTIMUM MONTHLY DIVERSION OF WATER TO DIFFERENT SUB-REGIONS (Phase II)



of the release during the third month in Phase I and during the eigth and ninth months in Phase II is directed to the sub-regions I and II.

As far as the distribution of groundwater is concerned, no allowance during the first phase is made for the intra-regional transfer of water. All the available groundwater in each sub-region is utilised locally. Such a decision by the model is intuitively appealing, because in the presence of uncultivated land in sub-regions III, IV and V, it is more efficient to use the water locally rather than transfer it to other sub-regions and lose a specific proportion of it to evaporation and seepage. In the phase II, however, when the entire plain is fully irrigated, we can observe a rather different monthly distribution of water. The excess, river water from sub-regions I and II, is directed to sub-regions IV and V instead of to the third sub-region which is recommended under the phase I. However, the use of this source of water in the last two sub-regions, which first seems rather odd, is occurred during the months eight and nine when there is no need for water in sub-regions I and III.

In phase II, unlike that of phase I, there is an intra-regional transfer of groundwater from sub-regions II to IV. The transfer, as Figure 3.4 shows, is at a constant level of 3.2 m.cu.m. during the months 3 to 5.

3.8.2 Cropping Pattern

The optimum distribution of cropping mix under the two phases of water availability is presented in Table 3.5 . It is evident from this table that none of the "control crops" have appeared in the optimum solutions. Even among crops with multiple irrigation regimes, only cotton with the highest yield and highest ratio of revenue to the total annual water requirements has appeared in the optimum solution in both phases. During the first phase, wheat appears under the fifth irrigation regime. This particular irrigation regime has the fourth lowest yield among the alternative regimes. In the second phase, however, as a result of higher availability of water this crop is recommended to be grown under the second irrigation regime which generates the highest yield. Alfalfa is another crop which has appeared in the base with an irrigation regime which does not generate the the highest yield.

The optimum cropping mix supports our argument (see 3.4.1) that highest yield or the ratio of revenue to total water requirements alone does not necessarily lead to the best selection of an irrigation regime. What is important is, in fact, the consideration of the value of the marginal opportunity cost of water at a particular point in time which is required by an irrigation regime. It

Table 3.5

OPTIMUM CROPPING MIX - Phase I

(hectare)

Sub- Crop Region	x_{15}	x_{25}	x_{42}	x_{51}	x_{61}	x_{81}	total
I	1165	7000	1334				9500
II	8385		3614				12000
III	4947		39			1386	4986
IV	2210			1622			3832
V	849		11	1377	2000	463	4700

OPTIMUM CROPPING MIX - Phase II

(hectare)

Crop Sub- Region	x_{12}	x_{25}	x_{29}	x_{42}	x_{51}	x_{61}	x_{81}	x_{101}	Total
I		9500							9500
II		5478		6000				521	12000
III						3414		4585	8000
IV	2359		1021		2026			4592	10000
V	4241				3173	585	2000		10000

is only in this way that the best combination of cropping mix can be obtained.

The fallacy of selecting an irrigation regime purely on the basis of yield, or even the ratio of revenue to total water requirement lies in the fact that irrigation engineers in their recommendations look at each crop in isolation, and assign a similar value to a unit of water throughout an irrigation cycle. This misconception can be demonstrated by comparing the opportunity cost of water for an optimal irrigation regime and the one which is recommended by irrigation engineers for a particular crop. In this connection Mahalati (1972), for instance, recommends that alfalfa should be grown under the first irrigation regime. This irrigation regime produces the highest yield. However, the opportunity cost of producing the crop under this regime outweighs the revenue that can be obtained from the crop. To prove this, we know from theory of the linear programming that optimum activities are those which account fully for the costs of the resources which are used in producing them. These costs are the computed marginal values of the scarce resources that the model assign to any resource which is fully utilized. These imputed or accounting costs in the language of mathematical programming are known as shadow prices, or dual values. Considering now, the monthly water requirement of the first irrigation regime for alfalfa and the shadow price of water corresponding to the respective months of water requirement constraint (3.5.4(i)) in a particular sub-region, we can see that the opportunity cost of the resources required to produce one hectare of wheat under the stated irrigation regime outweighs the revenue that this activity generates. The imputed penalty cost of producing wheat under this irrigation regime is 876 Rls/ha, which is the difference between the total opportunity cost of one hectare of the crop (20108 Rls/ha) and its revenue contribution (19232 Rls/ha). Now we can see that for this activity to be recommended by the model, either the water requirement should be reduced or its revenue should be increased or a combination of both.

By carrying out the same sort of calculation it can be shown that the revenue contribution of optimum activities are such that they just cover the cost of the resources used in producing them. For instance, the optimal solution recommends that wheat during the first phase of water availability should be grown under the fifth regime. This regime has a revenue coefficient of 18233 Rls/ha and at the same time requires 1,500, 1,200, 2,400 cu.m of water in the ninth, second and third month of irrigation cycle respectively. The shadow price of water in these months, say, for the fourth sub-region are 3.51; 3.53 and 3.63 Rls/cu.m during the phase I. Therefore, the total cost of water comes up to 18233 which is (ignoring the rounding errors) identical to the revenue contribution of the regime to the objective function.

One thing which the comparison of the optimum cropping pattern, under the two phases of water availabilities strikes us is the unproportional change in the optimum distribution of cropping patterns. This is in contrast to the recommended acreages by Mahab who advocates a proportional increase in the acreages of crops from one phase to the next.

As a result of increase in the supply of water in the second phase, not only the distribution of the optimum cropping patterns related to phase I changes, but two new activities namely X_{29} and X_{101} appear in the optimum solution. A comparison of optimum crops in the two phases, Table 3.5 , shows that for instance, sub-region III which under the first phase is cultivated by crops X_{15}, X_{42}, and X_{81}, has a completely different cropping pattern in the second phase. Crops associated with the phase I are totally phased out. Instead two new crops, namely X_{61}, and X_{101} have been introduced.

Another alteration in the pattern of cropping as a result of increase in the availability of water, is the change in the irrigation regime of wheat. In the second phase, wheat has appeared under the second irrigation regime rather than the fifth one which is optimal in the first phase. Although the total acreage of wheat has decreased quite substantially in the second phase, the higher availability of water supply has enabled the crop to be grown under a more intensive irrigation regime. The new irrigation regime requires six per cent more water in the third month, and generates five per cent more revenue. The disproportionate increase in the revenue, which is about one per cent less than the increase in the water requirement of the crop, implies that water has a lower marginal opportunity cost during the second month in phase II. The lower value of the shadow price of irrigation requirement constraints (3.7.1) in the second month of phase II (tabulated in Table 3.7) is the reflection of this fact.

The practical implication of this result should be borne in mind by the layman when there is a change in the supply of water. An overall increase or decrease in the availability of water does not necessarily imply a similar and proportional change in the cropping pattern. A more efficient utilization of water may require a substantial change in the type, irrigation regime and even location of crops.

Another significant point which the solution to the LP throws up is the substitution of land for water. In the discussion of alternative irrigation regimes (3.7.1) we made the point that in environs where water is a scarce resource in relation to the land, it might be more profitable to adopt a less intensive irrigation regime and employ the excess water in the cultivation of more land. The result clearly indicates this fundamental point for instance in the case of wheat. During the first phase, when the irrigated land in some parts of the plain is slack, wheat appears in the optimum solution under the fifth irrigation regime. This is a relatively low water intensive regime in comparison with the second irrigation regime which has appeared in the second phase.

In this connection, it is interesting to note that; if the "control crop" had been selected in the first place, we would have had 43.80 m.cu.m. less water. Assuming an average annual water requirement of 10,000 cu.m. for a potential crop, the total acreage would have reduced by 4380 hectares. This corresponds to a decline of 19 percent, once it is compared with the current optimal acreages.

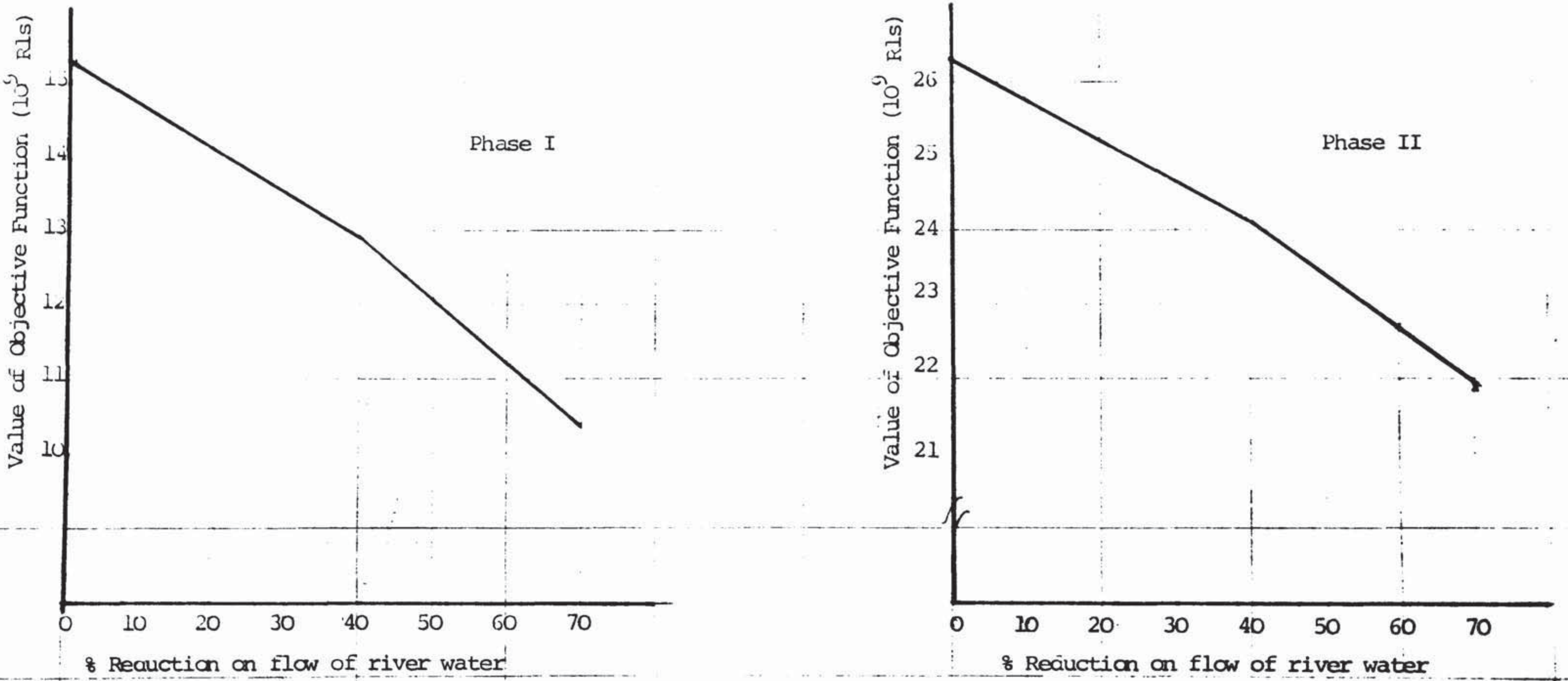
A great advantage of the disaggregation of the Plain into different sub-regions can be seen in the distribution of optimum cropping pattern. For instance, during the first phase, over 63 per cent of irrigated land in sub-region I is planted with cotton, while at the same time this crop has been totally eliminated from other parts of the plain. The location and acreage of each crop is determined by the relative marginal value of water in different sub-regions. This is, in fact, the reason for instance for the elimination of cotton in sub-region II during the first phase, when the land is cultivated by wheat and alfalfa. Now, if we arbitrarily change the location of the crop, we would incur a marginal cost. Depending on the type of irrigation regime, this cost for instance for the shift of the crop from sub-region I to II varies from 38 Rls/ha for X_{252} to 35938 Rls/ha for X_{212}.

3.8.3 Effects of Redirection of Surface Water to Tehran.

To investigate the consequences of the redirection of irrigation water from Varamin to Tehran, two sets of parametric programmings have been carried out.

First, the flow of water to the irrigation region during each month is successively reduced by ten per cent each time. The effects of such a reduction on both the value of the objective function and the total acreages of cropland for the two phases of water availability are respectively depicted in Figures 3.6 and 3.7. The reduction in the flow of water up to 70 per cent during phase I has resulted in a reduction in the value of the objective function by 68 per cent. In other words, on average, for every ten per cent decline in the flow of river water, the profitability of the agricultural sector of the region is reduced by 9.7 per cent. The effects on the total acreage of cropland during this phase is quite pronounced. The optimal cropping acreages, prior to any reduction in the flow of water, as Figure 3.7 shows, is about 37000 hectares. However, after 70 per cent reduction

Fig. 3.6 PARAMETRIC INVESTIGATION ON THE EFFECTS OF REDUCTION OF RIVER WATER ON THE VALUE OF OBJECTIVE FUNCTION



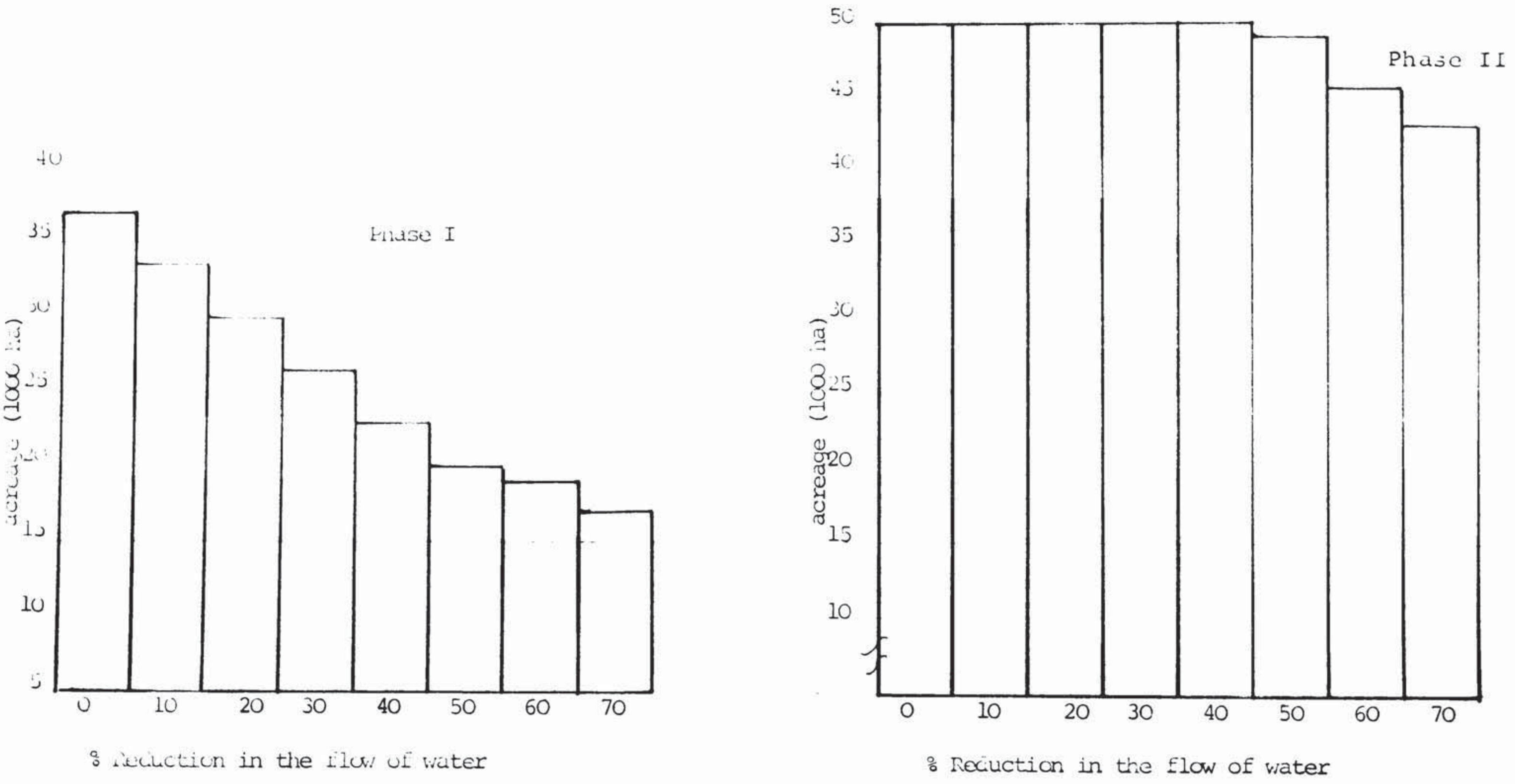


Fig. 3.7 PARAMETRIC INVESTIGATION ON THE EFFECTS OF REDUCTION OF RIVER WATER ON THE TOTAL ACREAGE OF IRRIGATED CROPLAND

in the flow of water, the total acreage shrinks to about 17000 ha., or a reduction of 64 per cent. In phase II, however, the consequence of the reduction in the availability of water on both the value of the objective function and the total acreage of cropland is less severe. After 70 per cent reduction in the flow of water, the profitability and total acreage of the region declines respectively by 15 and 13 per cent. In fact, according to Figure 3.7, the total acreage can be sustained at maximum level after a reduction of even up to 40 per cent in the flow of water. The reason behind such a paradoxical situation in which reduction in the flow of water up to a certain point reduces the value of the objective function, without affecting the total acreage, can be explained by the changes which have occurred in the pattern of optimal cropping mix. As the flow of water reduces, the acreage of activity X_{101} which is a heavy water user during the peak irrigation season, shrinks. The released water instead is used in growing of more wheat which requires substantially less water. In the meanwhile, we can also observe from Table 3.6 a switch-over from more intensive irrigation regimes to less intensive ones. Decline in the supply of water, beyond 20 per cent, which coincides with the disappearance of X_{101}, results in the substitution of a new irrigation regime for wheat, and an increase in the acreage of X_{29} at the expense of X_{25}. Both

TABLE 3.6

PARAMETRIC INVESTIGATION ON THE EFFECT OF REDUCTION ON THE FLOW OF RIVER WATER ON THE PATTERN AND ACREAGE OF CROPS

Phase II (hectare)

Crops **	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{110}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}
0		6600													14978				1021
10		10366													15246				753
20		13517			500										13710				2288
30		13160		959		1197									13134				2865
40		5572		6692											15101				897
50				9141											15800				187
60				5933											9253				5945
70				1956											599				15399

Crops **	x_{210}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{36}	x_{37}	x_{38}	x_{39}	x_{310}	x_{41}	x_{42}	x_{43}	x_{44}	x_{51}	x_{61}	x_{71}	x_{81}	x_{91}	x_{101}
0													6000			5199	4000		2000		9698
10													6000			5199	4000		2000		5933
20													6000			5199	4000		2000		2282
30													6000			5199	4000		2000		-
40													6000			5199	4000		2000		-
50													6000			5199	4000		2000		-
60													6000			5199	4000		2000		-
70													6000			5199	4000		2000		-

X_{13} and X_{29} require relatively less water than x_{12} and x_{25} respectively.

The implication of these results are quite interesting. Redirection of irrigation water to the city, during the first phase of water availability, will have a direct effect both on the profitability as well as on the total acreage of cropland in the region. However, during the second phase, up to 40 per cent in the monthly flow of river water to the irrigation region can be transferred to the city without any effect on the total acreage of croplands. Furthermore, the effect of such an action on the value of the objective function during the second phase is not as severe as in the first phase.

These results can be used as a base for compensating the farmers who lose their "right of use" through redirection of irrigation water to the city. In this connection, the reduction in the value of the objective function caused by the decline in the availability of water is an indication of loss of revenue to the region. Obviously, the degree of hardship in parts of the region where there is a higher conveyance loss is more pronounced. This is because the reduction in the flow of water would first hit the southern sub-region where per hectare of land more water is required than in the northern ones. In other words, the decline in the supply of water would affect sub-region V's acreage first, and it would gradually move to sub-region IV, III, and so on.

Another and perhaps more direct and straight forward way of compensation is through the shadow price of water at each stage of redirection. The shadow prices, as we have already seen, are the marginal value of a unit of water or, in other words, the marginal contribution of an extra unit of water to the objective function. Since the model indicates the exact loss of water to each sub-region, and at the same time generate the appropriate shadow prices for water, the water authority can pay the farmers on the basis of the shadow prices.

As the water becomes more scarce, it becomes more valuable, and as a result the value of the dual increases. For instance, during phase I, after 70 percent decline in the flow of river water, the dual values of irrigation requirement constraints (3.5.4(i)) in general showed an increase of about 57 percent from 3.5 to 5.5 Rls/cu.m. implying that the authority should offer more compensation to rural users as more water is redirected for urban consumption.

However, it should be noted that these shadow prices are representative of the value of water only for one irrigation cycle. Now, if the redirection of water is once and for all, the level of compensation as it was indicated in Chapter 2, should, in fact, be based on the present value of the lost water.

3.8.4 Pricing and Decentralisation

The results of the model can be applied directly to the problem of allocation and use of water by the Varamin Irrigation Authority, who by the virtue of the Nationalisation of Water Resources Act has complete control over the allocation and use of water resources of the plain. However, problems associated with such centralised decision making are quite well known (Marschak, 1959). The water authority, for instance, must be completely informed about all the affairs relating to the allocation and use of water in every single part of the plan. The policy and administration costs of such a system may be so high as to cause additional complications. This problem can be overcome by pricing the water and delegating allocative responsibility to sub-regional managers. In such a decentralized system, the central authority can employ the dual values (Tables 3.7 and 3.8) to price the water. In this respect the central authority announces the monthly prices of water for different sub-regions and leaves the actual use of water to sub-regional managers. The sub-regional managers, who are given the monthly prices in advance, are apt to schedule their cropping mix in such a way to correspond with the aggregate optimal pattern decided for the entire region by the central authority. This is because only the optimal crops decided by the central authority for each region generate sufficient revenue to cover the cost of water. Any deviation

Table 3.6

SHADOW PRICES (DUAL SOLUTION) - Phase I

Rls/cu.m

						Month				
Sub-region		2	3	4	5	6	7	8	9	10
I	3.52	3.52	3.52	3.52	3.47	3.47	3.47	3.47	3.47	0.00
II	3.48	3.53	3.53	3.53	3.48	3.48	3.48	3.48	3.48	0.00
III	3.51	3.51	3.64	3.51	3.51	3.51	3.51	3.51	3.51	0.00
IV	3.51	3.53	3.63	3.51	3.51	3.51	3.51	3.51	3.51	0.00
V	3.51	3.51	3.64	3.51	3.51	3.51	3.51	3.15	3.51	0.00

Table 3.7

SHADOW PRICES (DUAL SOLUTION) - PHASE II

Rls/cu.m

					Month					
Sub-region	1	2	3	4	5	6	7	8	9	10
I	0.00	2.84	3.05	3.05	3.05	1.25	1.25	0.74	0.00	0.00
II	1.25	1.25	3.06	3.06	3.06	1.26	1.25	1.17	0.88	0.00
III	1.25	1.25	3.12	3.12	3.12	1.26	1.25	1.20	1.06	0.00
IV	1.25	1.25	3.18	3.18	3.18	1.26	1.25	1.24	1.24	0.00
V	1.25	1.25	3.21	3.17	3.21	1.25	1.25	1.25	1.25	0.00

would result in a net loss. Assuming that the sub-regional managers are sufficiently informed and rightly motivated, we would expect them to grow those crops which correspond to the pattern recommended by the central planning authorities (Baumol and Fabian, 1964).

So long as the irrigable land constraint in each sub-region is tight, the sub-regional managers do not have any incentive to purchase more water. However, in cases where the land constraint is slack, some physical water supply limitation might be imposed upon the managers (Lane and Littlechild 1972).

3.9 Summary and Conclusion

The purpose of this chapter was to demonstrate the power and usefulness of linear programming as an aid to the allocation and use of water in an irrigation basin. To this end, a linear programming model for the conjunctive use of river, canal and ground water resources of the Varamin Plain was constructed in order to find the most efficient means of irrigating different parts of the plain.

Considering the particular topography of the aquifer, it was felt necessary to partition the basin into a number of sub-regions in order to establish a long-run policy for the extraction of groundwater. To this end the result of a simulation study of the aquifer was used and the plain was partitioned into five sub-regions, each with a specific aquifer field. Conveyance loss as a function of length of canal was introduced in the model to observe the effect of loss of water on the optimum allocation of water. To improve the flexibility of allocation of water, allowance was made for the intra-regional transfer of groundwater.

To demonstrate the current practice among most irrigation engineers of associating a fixed or unique water requirement for a particular crop, alternative irrigation regimes for a number of alternative crops was considered in the model.

The solution to the model, generated the optimum policy for the distribution of different sources of water to different parts of the plain. It also produced the most profitable cropping mix under different conditions of water availability. The outcome of the model, demonstrated a number of interesting points. It showed that in environs of water scarcity, "irrigation norms" do not necessarily lead to the most profitable combination of cropping mix, and that the possibility of substitution of water for land exists.

We also showed that the current release from the reservoir is not optimal. In fact the change in the release policy suggested in our model showed an improvement of about eight per cent in the value of the objective function.

The shadow prices of water indicated the marginal value of water to the farmers. It was suggested that they can be used as a base for compensating farmers who might lose their water as a result of increase in the consumption of water in the city.

The model has a great potential as an aid to the Varamin Water Authority in their planning for the most efficient way of utilising the water resources of the plain. A model of this nature has particularly a direct application to irrigation regions such as Varamin Plain, where all the water resources are under the control of an autonomous body, who, by the virtue of the Nationalization of Water Resources Act, has the power and the authority to implement the allocation and distribution policy suggested by a model of this nature.

However, if the administrative costs of implementing such a centralized decision centre are high the shadow prices can be employed to price the resource and decentralize the system.

In spite of all the possible refinements considered here, the model still suffers from a number of limitations. The limitations are basically to do with simplifying the assumption about the nature of factor supply markets. For instance, supply of labour during harvest may not be perfectly elastic. In fact it might be a limiting constraint. Another limitation which could affect the location of crops could be the transportation costs of perishable crops to the market. For instance, cultivation of vegetables in sub-regions I and II might be more profitable because of accessability to Tehran. Quality of soil, though assumed to be of class I in the entire plain, may vary in texture from one part to the other. As a result some parts of the plain may be more suitable for one particular crop while not for others.

Finally, examination of water resources of the Varamin Plain in isolation might not be entirely satisfactory since the plain competes along with another agricultural region for the available surface water with Tehran. To obtain the optimum allocation of water for urban and rural uses, it is essential to consider the allocation of water within a single model. This is the task of the following Chapters.

CHAPTER 4

ALLOCATION OF WATER FOR URBAN AND RURAL USE

MODEL I

4.1 Introduction

The Varamin region whose water resources allocation was considered in the previous chapter must be viewed as a part of a larger water supply and allocation system incorporating the Greater Tehran Area (GTA) as well as the other agricultural region, viz, Karaj, which competes with Tehran for the available surface water.

In this and Chapter 6 we consider the important problem of urban-rural allocation of water between the Greater Tehran Area and the two surrounding agricultural regions.

The very rapid growth of urban water requirement in recent decades (see Chapter 5), coupled with the comparatively limited supply of water, has created an imbalance in the supply-demand situation. The problem is particularly serious when we consider the fact that the only available source of supply left to the city, at least in the next five years, is the redirection of irrigation water to the city.

The purpose of this chapter is to look at this problem and provide the most economically efficient answer to the allocation and use of water in the entire region. To this end, the technique of linear programming is employed and an integrated model of the system, in terms of the allocation of the available water within each basin for the purpose of irrigation, subject to a given urban water requirement is constructed.

4.2 Short History of Tehran Water Supply

In the past, water requirements of Tehran were provided locally through a network of 26 ghanats and a few private boreholes. However, during 1920 the pressure of population expansion, coupled with a severe drought, necessitated an urgent need for the importation of water from outside. The obvious choice was the unregulated flow of the Karaj River for which the city already had rights. These rights were appropriated during another water shortage spell in early 19th century and were 9/84th of the flow plus a fixed quantity of 53 "sangs" (equivalent to 0.636 cu.m./sec.). By 1929, the construction of the Karaj Canal was finished and the imported water reached the city. This imported water only eased the situation temporarily and after only twenty years the increased growth of the city outstripped the supply of water again and led to a critical situation in water as well as electricity supplies

To this end, various studies with regard to the construction of a storage dam on the Karaj River were initiated and eventually in 1961 the first multi-purpose dam in the country came into operation.

By this time the city was potentially entitled to a total of 184 m.cu.m. from the Karaj reservoir, while the projected requirement for water for the coming decade was in the region of 400 m.cu.m. As a result the idea of constructing the Lar and Latiyan dams and the conveyance of water from Lar and Jajerud Rivers to the city was revived. The position of dams (reservoirs) are depicted on Map 4.1.

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The first stage of the development, which was the construction of a storage dam on the Jajerud River, was approved by the Government and the Plan Organisation. The construction of the dam was started in 1958. Three years later the dam, named Farahnaz Pahlavi (Latiyan) was officially inaugurated (for details see Chapter 3).

4.3 Sources of Water

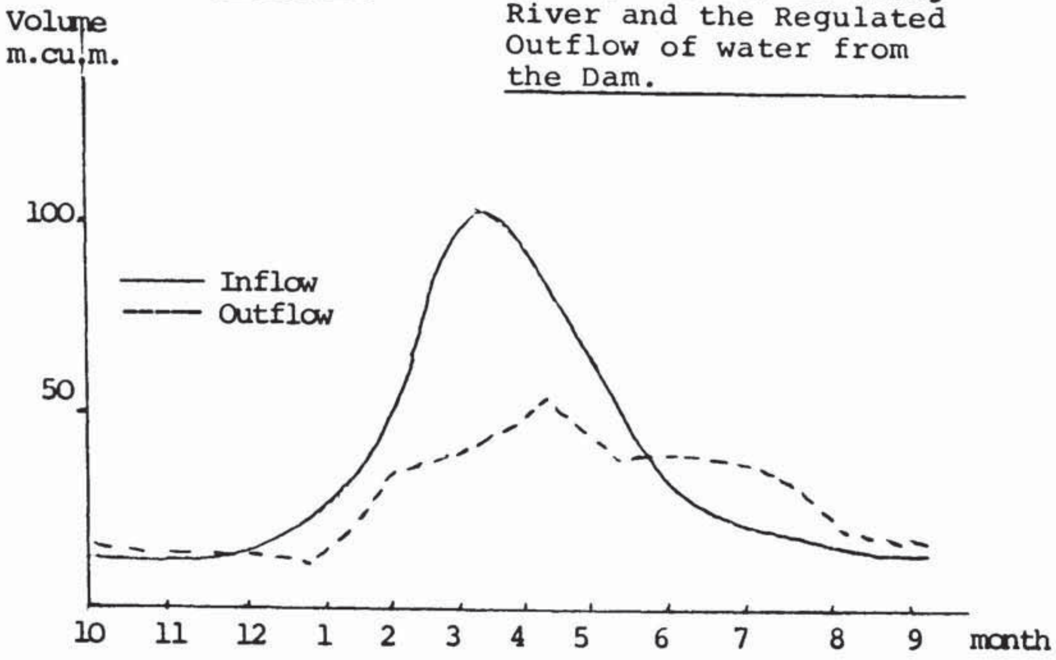
Since the hydrology of the Varamin region has already been described in the previous chapter, this section considers only the water resources of the Karaj region. It should, however, be noted that no detailed information with regard to the hydrology of this plain is available. Our discussion, therefore, is rather brief and covers only the main feature of the water resources.

4.3.1 Surface Water in the Karaj Region

The Karaj River, which is the only perennial river in the plain, derives its discharge, like Jajerud River, from the Alborze range. The total distance from its origin to the Sira gauging station is 66.2 km. and covers a drainage area of about 764 sq. km. On average, 365 mm of precipitation occurs in the drainage area. A substantial portion of it is in the form of snow which starts melting in early spring and the resulting water reaches its peak in mid-summer.

The records of discharge of the Karaj River at the dam site, depicted in the following figure,

Fig. 4.1 Average Inflow of Karaj River and the Regulated Outflow of water from the Dam.



show that the river is in flood in spring and at minimum in autumn and winter. Approximately 68% of total inflow of 425 m.cu.m. occurs between March and June and, since the bulk of the precipitation is in the form of melted snow, it is therefore possible to forecast the annual discharge of the river with some accuracy.

Downstream of the river in the Varian Gorge the Karaj Dam controls the flow of the river.
The primary purpose of this dam is to provide an assured water supply for the city of Tehran. At the same time it regulates the irrigation water for 25,000 ha of land in the Karaj Plain. In doing so it also generates hydroelectricity to meet the peak hours requirements of the capital Tehran.

The average annual release of water from the dam depicted in the above figure is 344 m.cu.m. Out of this 184 m.cu.m. is supplied to the city and the rest is allocated to the downstream irrigation area.

The irrigation water up to 160 m.cu.m. is supplied virtually free of charge. However, for additional release (if any) farmers are charged at a rate of 0.3 Rls/cu.m.

4.3.2 Groundwater in the Karaj Region

Unfortunately, a detailed and comprehensive survey of the groundwater resources of the area is not available. However, according to a general survey of the region (Ministry of Water and Power, Groundwater Division, Vol. 1 1969) which covers an area of 750 square km. the average distribution of wells in the Karaj plain is about one in every 120 hectare of agricultural land. Since the area we are studying covers an area of about 250 square km. the total number of wells based on the above average should be in the order of 208. Considering that the average hourly discharge is 190.40 cu.m./well, the total daily discharge, based on a 22 working hour/day, is 472.019 cu.m./well. With reference to the number of days in a quarter, total quarterly pumping capacity is approximately as follows:

Quarter	1	2	3	4
No. of days	90	90	92	93
Pumping capacity (m.cu.m.)	42.48	42.48	43.42	43.49

However, to keep the water table stable, the average annual pumping in the study area should be limited to

70.162 m.cu.m.

4.4 Previous Works

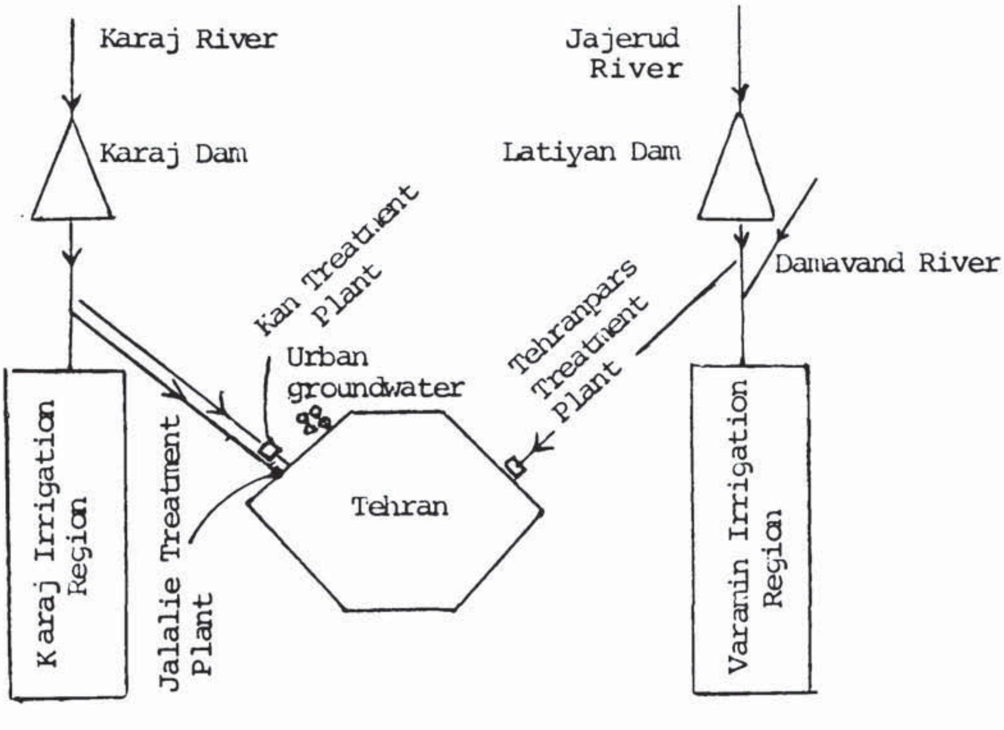
Several recent studies employing mathematical preogramming have investigated the merits of regional water allocation problems within an integrated framework.

Dracup (1966) considers five sources of water and three water users. The supply sources are utilised to satisfy simultaneously the requirements of municipal, industrial and agricultural users of water in Southern California. Heaney (1969) makes a regional analysis of water use in the Colorado River Basin. The objective function in his study includes both tangible benefits (e.g. domestic consumption) as well as more intangible beneficial uses such as water quality, recreation etc. Roger and Schwartz (1973) look at the problem of simultaneous optimisation of investment and allocation of water within an inter-regional context. Moncur (1973) uses both dynamic and linear programming to link the opportunity costs of trans-basin diversion on the Columbia and Snake Rivers in the U.S. Itzhaky et al (undated) develop an integrated short-run and long-run model to provide solutions for an efficient operation of the Israel National Water System. Heady et al (1973) undertake a national study to find the optimum allocation of land and water resources in the U.S. The prime objective of his study is to see whether the U.S. can meet her urban and industrial needs for water in the year 2000. Keith (1974) investigates inter-regional allocation of water in a time frame up to 2020. The object of his study is to show the effects of alternative public decisions on the optimum allocation of water.

4.5 The Model*

The optimisation technique employed in this chapter utilises linear programming teqhniques to make a regional analysis of water allocation and use in Tehran and the surrounding agricultural regions. A schematic representation of the model which indicates the direction of flow is depicted in the following Figure.

Fig. 4.2 SCHEMATIC REPRESENTATION OF THE STUDY AREA



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* Data employed in this model are either given in text or listed in the Appendices to Chapter 4.

The model allocates water supplies over the year in such a way as to achieve the most profitable cropping pattern for fifteen crops in two agricultural regions (Karaj and Varamin) and to meet, in the most efficient way, the seasonal urban water requirements of the city. The regions are denoted by $k=1$ (Karaj) and $k=2$ (Varamin). The hydrologic cycle in this model is divided into four distinct seasons (quarters) $j=1,\ldots,4$. This aggregation has been mainly caused by the non-availability of adequate data for Karaj. However, owing to the seasonal characteristics of demands and supplies, such an aggregation is justifiable.

Three sources of water are considered, namely $h=1$ (surface water, i.e. water from the dam), $h=2$ (water from Damavand tributary). $h=2$ applies only in region $k=2$ (Varamin) and $h=3$ (groundwater).

4.5.1 Activities

Two groups of activities are employed to represent crop production (x_{ik}) and water allocation (W^h_{kj}, S_{kj}, U_{kj}, and V_j) respectively. There are 12 and 13 different crop activities in Karaj and Varamin respectively. Table 4.1 presents a list of candidate crops. According to this table the first 9 crops are common to both regions while the rest can only be grown in one or other of the regions. The total number of water-allocation activities is 28 (8 in Karaj, 12 in Varamin, 8 in the City) which makes the overall number of activities 53.

Table 4.1 CANDIDATE CROPS IN THE STUDY AREA

Notation	Crop	Karaj	Varamin
x_1	wheat	x	x
x_2	barley	x	x
x_3	cotton	x	x
x_4	melon	x	x
x_5	alfalfa	x	x
x_6	sunflower	x	x
x_7	orchard	x	x
x_8	tomato	x	x
x_9	s.cucumber	x	x
x_{101}	sugarbeet	x	
x_{121}	water melon	x	
x_{131}	potato	x	
x_{102}	a.cucumber		x
x_{112}	sorghum		x
x_{122}	maize grain		x

4.5.2 Constraints

There are 10 sets of constraints representing availability and use of water in different parts of the system and 2 sets limiting the capacity of water treatment plants and cropping acreage respectively. They are as follows:

4.5.2 (i) Surface Water availability

$$W_{kj}^{1} + U_{kj} + S_{kj} \leq \bar{W}_{kj}^{1} \qquad \begin{array}{l} k=1,\ 2 \\ j=1,\ldots,4 \end{array}$$

This constraint reflects the quarterly availability of surface water in each region. Surface water from each region can be used in that region or sent to the city but cannot be sent to the other agricultural region. The constraint therefore requires that the total volume of water allocated to irrigation region k and the urban area during the course of season j cannot exceed the available water released from dam k during the same season.

In this constraint, the first term represents the historical water rights which farmers are stillentitled to receive at a zero price. The second term represents the volume of water allocated to the urban area and the third term is what we have called the "would be water". It is the excess of water (if any) over and above the urban needs and the irrigation right which farmers can purchase at a nominal price.

4.5.2 (ii) Urban Requirement

$$\sum_{k=1}^{2} U_{kj} + V_j = \bar{U}_j \qquad j=1,\ldots,4$$

This constraint states that the $\bar{U}_j$, fixed quarterly requirement of the urban area, must be met from the outputs U_{kj} of the two reservoirs plus the V_j urban groundwater. This constraint is in fact a reflection of the hierarchy of the allocation policy which gives the highest priority to the urban use.

4.5.2 (iii) Irrigation Requirement

$$\sum_{i=1}^{I_k} a_{ikj}\, x_{ik} - \left(\sum_{h=1}^{H_k} W_{kj}^{h} + S_{kj}\right) \leq 0 \quad \text{for} \begin{cases} k=1 \begin{cases} I=1,..,13 \\ H=1,\ldots,2 \end{cases} \\ k=2 \begin{cases} I=1,..,12 \\ H=1,2,3 \end{cases} \end{cases} \quad j=1,\ldots,4$$

This constraint matches the seasonal supply of water in each region with the seasonal water requirements of crops in the same region. The irrigation requirement of crop i in region k during season j is $a_{ikj}\, x_{ik}$ cu.m. where x_{ik} is the area of crop in hectares and a_{ikj} is the irrigation requirement in cu.m./ha. The first term thus represents the total water requirements of crops grown in region k during season j. The second term represents the supply of water in each region from that region's dam, groundwater and (in the case of region 2) the river tributary. The third term represents the "would be water".

4.5.2 (iv) Historical Water Rights

$$W_{kj}^{1} \leq \bar{R}_{kj} \qquad \begin{matrix} k=1,2 \\ j=1,\ldots,4 \end{matrix}$$

This constraint is specifically introduced into the model to see whether the historical water rights, which were based on the natural unregulated inflow of water and traditional irrigation techniques are still appropriate to today's circumstances or should be adjusted.

The upper bound on this constraint is the historical water rights.

4.5.2 (v) Tributary Inflow

$$W^2_{2j} \leq \bar{W}^2_{2j} \qquad j=1,\dots,4$$

This constraint represents the quarterly contribution of the Damavand River (h=2) to the Varamin Plain (k=2).

4.5.2 (vi) Groundwater Supply - Rural

There are two sets of constraints, determining the operation of groundwater.

a) $$w^3_{kj} \leq \bar{W}^3_{kj} \qquad k=1,\ 2 \quad j=1,\dots,4$$

This constraint allows pumping to take place during any period j provided it does not exceed the capacity of the installed pumps in the region.

b) $$\sum_{j=1}^{4} w^3_{kj} \leq \bar{W}^3_{k} \qquad k=1,\ 2$$

To keep the groundwater table stable, the annual pumping is restricted to the safe yield of aquifer.

4.5.2 (vii) Groundwater Supply - Urban

$$v_j \le \bar{V}_j \qquad j=1,\dots,4$$

$$\sum_{j=1}^{4} v_j < \bar{V}$$

These two constraints, like a and b in (vi) above limit the seasonal pumping to the capacity of pumps and the annual pumping to the safe yield of aquifer in the urban area.

4.5.2 (viii) Capacity of Treatment Plants

$$U_{kj} \le \bar{T}_k \qquad \begin{array}{l} k=1,\ 2 \\ j=1,\dots,4 \end{array}$$

This constraint limits the conveyance of water from region k during season j to the urban area to the current capacity $\bar{T}$ of water purification plants (Map 4.1). The maximum capacity of the Kan and Jalalie Treatment Plants together which convey the Karaj water to the city is 10.4 cu.m/sec and that of Tehranpars which brings in water from Latiyan reservoir is 4.0 cu.m/sec.

4.5.2 (ix) Crop Limitation

$$\sum_{k=1}^{2} x_{ik} \le \bar{X}_i \qquad i=4,\ 8,\ 9$$

$$x_{ik} \le \bar{X}_k \qquad \begin{array}{ll} k=1 & i=7,\ 11,\ 13 \\ k=2 & i=7,\ 10 \end{array}$$

For the reasons discussed in the previous chapter, the growing of some perishable crops, primarily vegetables, are limited to their present acreages. However, to make the model flexible with regard to the location of these crops, the upper bound represents the aggregated acreage over both regions.

4.5.2 (x) Non-negativity Requirement

Finally all variables are required to be greater than, or at least equal to, zero.

4.5.3 Objective Function

The criterion for the model is the maximisation of crop revenues minus cost of water to the farmers in the agricultural regions. Formally we have

$$\max \sum_{i=1}^{I_k} \sum_{k=1}^{2} r_{ik} x_{ik} - \sum_{k=1}^{2} \sum_{j=1}^{4} (c_k^1 W_{kj}^3 + c_k^2 S_{kj}) \quad \text{for} \begin{cases} k=1, \ i=1,\ldots,13 \\ k=2, \ i=1,\ldots,12 \end{cases}$$

where r_{ik} is the revenue generated from cultivation of one hectare of crop i in region k

c_k^1 is the cost of extracting one cu.m. of groundwater in region k. 0.5 Rls/cu.m. in Karaj and 0.8 Rls/cu.m. in Varamin.

c_k^2 is the cost per cu.m. of "would-be water" which farmers in region k should pay to the water authority. 0.3 Rls/cu.m. in Karaj and 0.5 Rls/cu.m. in Varamin.

4.5.4 Assumptions

Assumptions underlying the model are those which were discussed in Chapter 3. However, in this model due to non-availability of adequate data and also limitation on the use of computer, the level of aggregation, once it is compared with the model of Chapter 3, has been increased. However, the level of aggregations considered in this model should not have a major effect on the general purposes of the model which is set to give an overview of the advantages which could be derived from an integrated approach to the allocation of water resources.

4.6 Discussion of the Model Result

This section appears in two parts. The first part compares the linear programming primal solution with the current allocation* and use of water in rural-urban areas. The second part considers the economic interpretation and policy implication of the dual values corresponding to different sources of water.

4.6.1 Comparison of Optimal Solution with the Current Practice

4.6.1 (i) Urban Requirement - To meet the urban water requirements optimally, the solution requires some changes to be made to the present allocation policy. On balance, the contribution of Karaj reservoir is decreased while that of Latiyan reservoir has gone up. The magnitude of the change is about 15 percent in favour of Karaj agricultural region and 38 percent against Varamin agricultural region. In other words, the annual contribution of Karaj has gone down from 184.6 m.cu.m. to 157.06 while that of Latiyan reservoir

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* The data on the current allocation of surface water, i.e. release for urban and rural uses from Karaj and Latiyan Dams, is obtained from the "Iran's Dams", Ministry of Water and Power, 1973. The data on the average cropping acreages in Karaj are based on the average cropping acreages in the Province of Tehran (Plan Organisation, Vol. 9 1973) and in Varamin are based on the average cropping pattern reported by the Varamin and Garmsar Irrigation Authority (Annual Report 1973).

Table 4.2

COMPARISON OF PRESENT AND OPTIMAL DISTRIBUTION OF URBAN WATER REQUIREMENT

(m.cu.m.)

Quarter	Total Requirement	Sources of Supply					
		Karaj		Latiyan		Ground	
		Current	Optimum	Current	Optimum	Current	Optimum
I	95.68	48.2	47.20	22	31.10	25.48	17.34
II	72.67	30.4	42.00	15	17.00	27.28	13.67
III	81.39	40.1	30.94	19	31.01	19.58	19.33
IV	116.56	65.9	36.92	24	31.79	26.66	48.61
Annual Distribution	366.30	184.6	157.06	80	110.90	99.00	98.95

has increased from 80 m.cu.m. per annum to 110.90. Table 4.2 compares the present and the optimum contribution of different sources of water to the urban area. To produce a better view, the results are diagrammatically depicted in Fig. 4.3. It is evident from the diagram that in the optimal solution the contribution of the Karaj Reservoir to the urban area, during the second quarter, has increased and this in turn has enabled the urban groundwater to be saved for the seasons of high demand for water, when both urban and irrigation requirements are at their peaks. Without such a change we would have had less urban groundwater during the fourth period and consequently a heavier burden on the reservoirs to meet the urban requirements. The result would have presumably been a reduction in the value of the objective function through change(s) in the pattern of optimum crops. In other words, the heavy urban requirements during the fourth quarter which coincides with the peak irrigation period, would have forced the model to choose a less profitable cropping mix which requires less water during this period.

This improvement to a great extent is attributable to the flexible pumping capacity (constraint 4.5.2 (vi)) which has given a great deal of freedom to the model to choose the most efficient pumping schedule.

4.6.1 (<u>ii) Irrigation Requirement</u> - In the case of Karaj, not only all the historical water rights (except the second quarter) have been fully met, but the Plain has

Table 4.3

COMPARISON OF PRESENT AND OPTIMUM CONTRIBUTION OF SUPPLY SOURCES TO IRRIGATION REGIONS

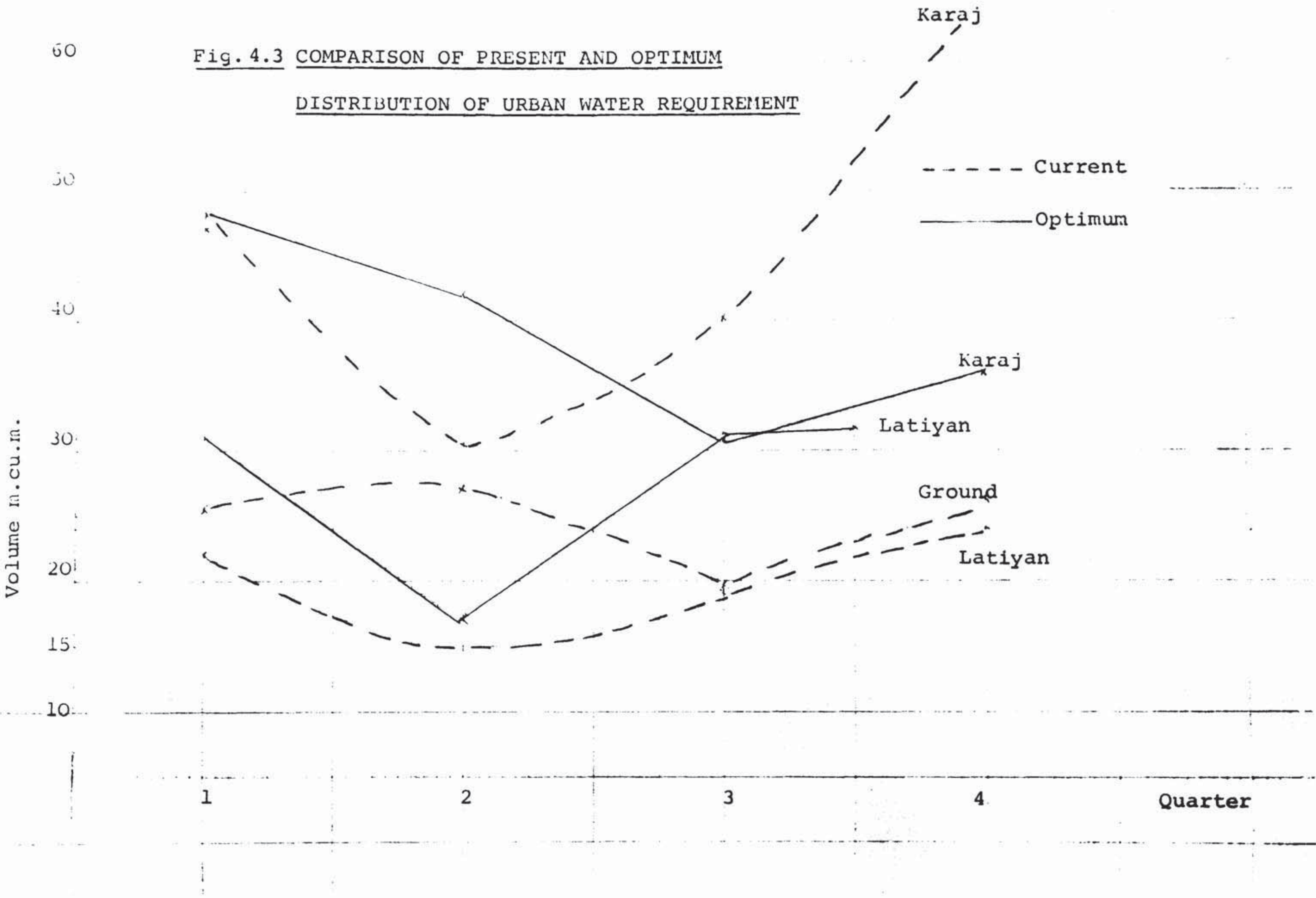
(m.cu.m.)

	Region																			
	Karaj								Varamin											
	Source								Source											
Quarter	Surface		Ground		Excess †		Total		Surface		Ground		Excess †		Tributary		Total			
	*	**	*	**	*	**	*	**	*	**	*	**	*	**	*	**	*	**		
I	31.80	31.79		0		0		31.79	31	21.89		10.77		0	4.53	4.53		37.19		
II	11.60	0		0		0		0	2	0		0		0	8.78	0.82		0.82		
III	48.90	48.90		35.89		9.15		93.94	53	40.89		31.84		0	23.72	23.72		96.95		
IV	69.70	69.70		34.27		28.37		132.34	77	69.98		88.38		0	1.22	1.22		159.58;		
Total	162.00	150.39	70.16	70.16		37.53		258.08	163	132.76	130.1	130.99		0		30.36		294.00		

* Current   ** Optimum   Blank Space - No data available

† Excess is what we referred to as "would be water"

Fig. 4.3 COMPARISON OF PRESENT AND OPTIMUM DISTRIBUTION OF URBAN WATER REQUIREMENT



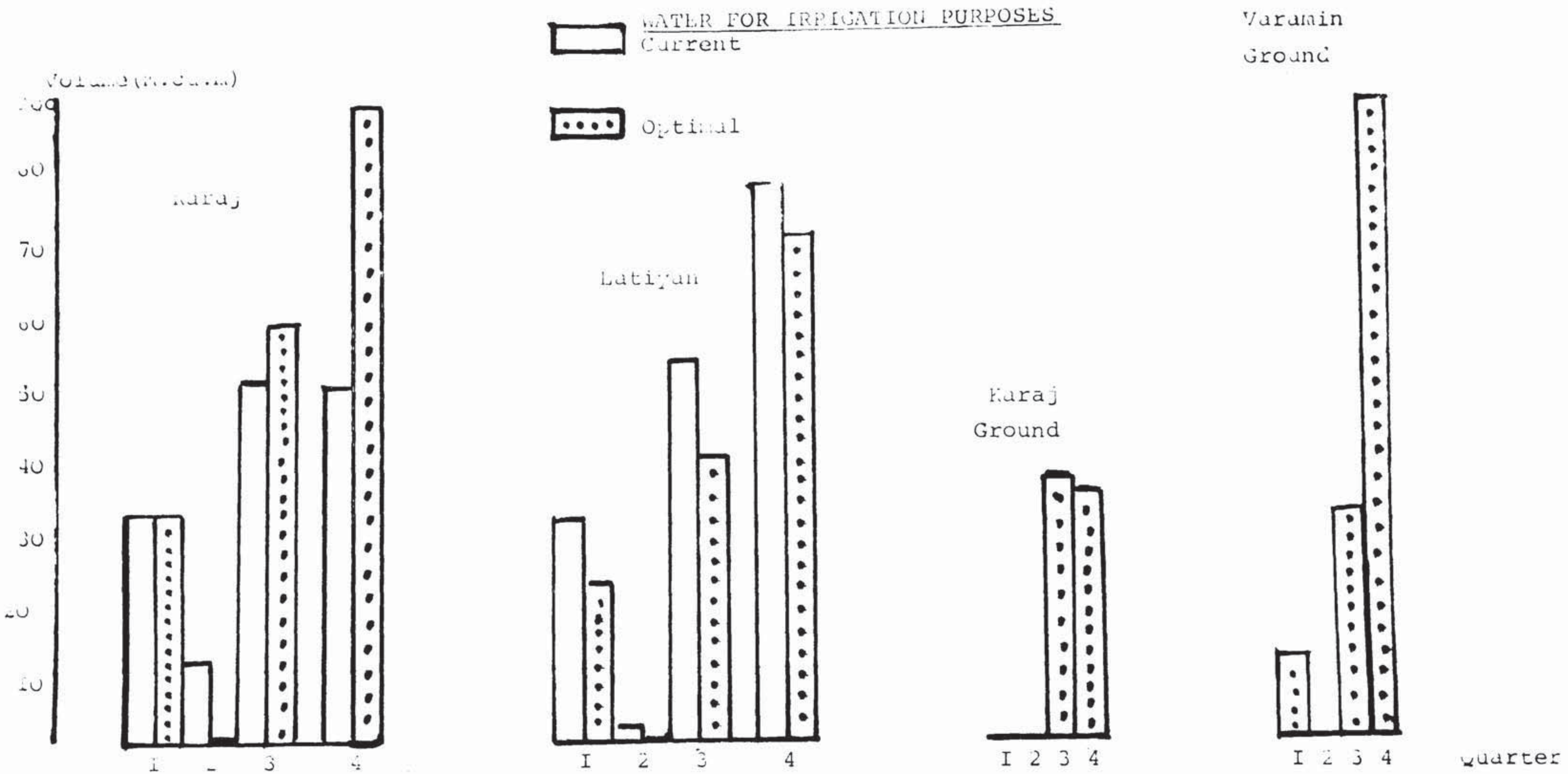
received an additional 9.15 m.cu.m. of surface water in the third quarter and an additional 28.37 m.cu.m. in the fourth quarter. These additional supplies of water are in fact the excesses of urban and rural requirements. With reference to Table 4.3 we could see that, for instance, in the optimum solution the volume of water allocated from Karaj to the urban area is 30.94 m.cu.m. which in addition to the 48.90 m.cu.m. received under the water right leaves 9.15 m.cu.m. free from the total supply of the river. This is the volume of water that farmers are purchasing at a rate of 0.3 Rls/cu.m. from the local water authority. However, as far as the Varamin irrigation region is concerned, not only is there no excess water available for sale, but the actual water rights have been cut from 163 m.cu.m. to 130.99 million. As a result, the irrigated acreage is shrunk by about 8 percent from 30,000 to 27,700 hectare.

The pumping of groundwater in both regions has been fully utilised. In Karaj pumping is evenly distributed between the 3rd and 4th quarters (Fig. 4.4) while in Varamin it is spread over three quarters with a peak during the 4th quarter. In fact this is the only quarter in any of the two regions when the pumping capacity has been fully utilised.

4.6.1 (<u>iii) Cropping Patterns</u> - The optimum cropping patterns (Table 4.5) recommended by the model increases the profitability of the entire irrigation regions by about 54 percent from 1.711 to 2.637 billion rials.

The changes in the crop patterns in both

Fig. 4.4 COMPARISON OF THE CURRENT AND OPTIMAL ALLOCATION OF WATER FOR IRRIGATION PURPOSES



regions, particularly in Karaj, are quite substantial. In Karaj, out of 13 candidate crops only 4 have been selected in the optimal solution. In Varamin, however, the cropping mix has more variety. In fact, those perishable crops with upper limits (constraints (ix)) which potentially can be grown in either of the two regions, are grown only in Varamin.

Cotton is the dominant crop in both regions. In Karaj 85% and in Varamin 41% of the total acreage are allotted to this crop. The rest of the irrigated land in Karaj is planted with water melons (870 ha), potatoes (180 ha), and orchards (2000 ha). In Varamin seven different crops are recommended. They are wheat (2370 ha), cotton (11,330 ha), melon (6,640 ha), orchard (1,500 ha), tomato (2,750 ha) spring cucumber (850 ha) and autumn cucumber (1,320 ha). The acreages of deciduous orchard in both regions have remained unchanged. This is due to their high revenue contribution which is far greater than those of other crops (except melon in Karaj). In fact, their contributions to the objective function are so high that this has made up for the heavy demand which they make on water in the third and the fourth quarters.

4.6.2 <u>Analysis of the Dual</u> - the dual values corresponding to constraints representing availability and use of water have important economic implications with respect to managerial decision making.

A comparison of the value of duals clearly indicates the economic significance of the optimal

Table 4.4 COMPARISON OF CURRENT AND OPTIMUM CROPPING PATTERNS

(1,000 hectare)

Crop	Region			
	Karaj		Varamin	
	Current	Optimum	Current	Optimum
Wheat Barley }	4.00	-	10.00	2.37
Cotton	1.05	18.56	7.00	11.33
Melon	3.29	-	3.20	6.64
Alfalfa	1.21	-	1.50	-
Sunflower	0.04	-	1.00	-
Orchard	2.00	2.00	1.50	1.50
Tomato	1.55	-	1.20	2.75
S.Cucumber	1.00	-	0.85	1.85
A.Cucumber	-	-	1.32	1.32
Sorghum	0.16	-	2.00	-
Sugarbeet	5.00	-	-	-
Water Melon	0.87	0.87	-	-
Beans Peas }	1.06	-	-	-
Potato	0.49	0.48	-	-
Maize Grain	-	-	0.50	-
Totals	21.67	21.921	30.07	27.76

allocation and use of water. It is evident from Table 4.5 below that the absolute value of duals corresponding to the availability of Karaj water (constraints (i)) and urban requirements (constraints (ii)) are equal to each other and are the same for all seasons. At the same time the dual value of Latiyan Reservoir water for the first and the third quarter are relatively smaller. This indicates that water has higher marginal opportunity cost during these periods in the former region (Karaj) and therefore it is worthwhile to supply the city from the region where the opportunity cost of water is smaller (Varamin). In fact, if the treatment capacity at Tehranpars had not been tight, the model would have allocated more water during the first and the third periods from Latiyan to city. The size of the additional supply is determined by the relative value of water and the process of reallocation, in the absence of any restriction, should continue until the opportunity cost of water in both regions for any particular season become the same.

The dual values corresponding to the Tehranpars water treatment plant (constraint (viii) for k=2) in the first and the third quarters are the same, namely 0.9 Rls/cu.m. They represent the marginal cost of withholding water beyond the treatment plant. In fact, by adding these values to the marginal values of water, at the Latiyan dam, for any of the tight periods, brings the total marginal value of water into line with that of Karaj for the same period. This is indeed a sign of

Table 4.5

SHADOW PRICES

(Dual Solution)

Rls/cu.m.

	Quarter				
	I	II	III	IV	Annual
Surface Water					
Karaj	3.7828	3.7828	3.7828	3.7828	
Latiyan	2.8735	3.7828	2.8735	3.7828	
Urban Requirement	+3.7828	+3.7828	+3.7828	+3.7828	
Irrigation Requirement					
Karaj	4.0301	0	4.0828	4.0828	
Varamin	2.8735	0	2.8735	3.7828	
Groundwater					
Urban	0	0	0	0	3.7828
Karaj	0	0	0	0	3.5828
Varamin	0	0	0	0.9093	2.0735
Water Treatment Capacity					
Kan	0	0	0	0	
Tehranpars	0.9093	0	0.9093	0	
DamaVand River	2.8735	0	2.8735	3.7828	

optimality of the allocation of a scarce resource in an integrated system which requires a uniform value of marginal product for every use of the resource in a given period of time (Bain 1966 pp. 597).

In the present model urban water requirements are taken as given and meeting these does not make any positive contribution to the objective function. The duals of the urban demand constraints (4.5.2 (ii)) therefore have a positive sign implying that any marginal reduction in the requirement of the city would have a favourable effect on the overall value of the objective function.

Dual values corresponding to irrigation constraints (except those related to the second quarter) are all positive. This is due to the fact that all the available irrigation water has been fully utilised. There is only 7.9 m.cu.m. of unused water available during the second period. This flows from the Damavand River during the second period and is apparently wasted to the desert.

Groundwater resources in both the urban and rural areas are fully utilised, consequently the dual values corresponding to the safe yield of aquifers are all positive. Among the pumping capacity constraints only the fourth quarter in Varamin has reached the limit while the rest are all slack. For instance, in Karaj 19 percent of the available pumping capacity even during the peak working season (4th quarter) is idle.

The dual values could be interpreted as the cost of constraints. These constraint costs are such that for each activity in the optimal solution, its revenue is equal to the total constraint cost. For example, the tight constraints which are relevant to say activity x_{13} (cotton in Karaj) are water in the first, third and fourth quarters. The dual values of irrigation water for these three quarters are 4.0301, 4.0828 and 4.0828 Rials/cu.m. Since each hectare of this activity requires 1500, 4500 and 6000 cu.m. of water for the quarters respectively, the total constraint cost of one hectare of cotton is therefore (1500 x 4.0301) + (4500 x 4.0828) + (6000 x 4.0828) = 48914.55. This is exactly equal (ignoring the rounding error) to the contribution of this activity to the objective function. This statement, in other words, says that the value of inputs which are used to produce one hectare of cotton, accounts fully for 48,915 Rials of revenue which are yielded by one hectare of this crop. This is obviously the condition for an activity to be in the optimal solution.

In this connection it can be shown that activities that are not included in the optimal solution have higher total constraint cost than their revenue contribution. For example, take melon in Karaj, (a crop which could potentially be grown in any of the two regions). The total imputed cost of water required by this crop is (5000 x 4.0828) + (6000 x 4.0828) = 44910.8. Once the value of dual corresponding to the upper bound of this activity, 25870 Rials/hectare, is added to this the total resource cost would exceed the revenue contribution of this activity (68150 Rls/ha) to the objective function. Consequently, this activity cannot be an optimum one for, as we have seen, the value of resources used to produce one unit of it is worth more than the yield.

4.6.3 Policy Implication - Dual values corresponding to the availability and use of water can be used as a means of valuation and pricing of water.

As far as the urban water requirements are concerned, the model proposes a fixed price for all seasons i.e. 3.78 Rls/cu.m. However, this is the value of water at the source. To this we have to add the conveyance, treatment, etc., cost which is about 5-6 Rls/cu.m. Therefore the price of water to the consumer should be between 8-9 Rls/cu.m. rather than the current price of 7.5 Rls/cu.m. The current domestic water rate is therefore subsidised by as much as 1.5-2 Rls/cu.m. Considering that the diverted water to the city has a positive opportunity cost, it could therefore be argued that the subsidy is in fact coming from the agricultural regions.

Finally, if the market for the sale of water was not prohibited (see Chapter 2), the Varamin Irrigation Authority could use the shadow prices of the Damavand River water as a base for bargaining with farmers in the Damavand

Valley for the purchase of their water.

4.7 Summary and Conclusion

The purpose of this Chapter was to demonstrate the possible economic gains that could be achieved through an integrated approach to the allocation and use of water in Tehran and the surrounding agricultural regions.

Two reservoir systems, viz. Karaj and Latiyan, in conjunction with the available groundwater resources, were considered to serve the urban water requirements of the capital Tehran and two independent irrigation regions.

The two reservoir systems which are currently independently managed were merged into an integrated optimisation model in order to obtain the most economically efficient way of meeting the seasonal urban water requirement of the Greater Tehran Area and the most profitable cropping mix in each of the agricultural regions. The results indicate that the integration of the whole system allows more flexibility and can lead to more efficient allocation of water resources.

The findings in this Chapter could be of benefit to the water authorities who through the Nationalisation of Water Resources Act (see Chapter 2) intend to achieve a more efficient allocation of water resources.

It is, however, recognised that the model in its present form, which optimises the current state of water management, does not provide the 'final answer' to the problem of allocating limited supplies of water. Additional efforts need to be expended in comparing the value of water in rural and urban areas, instead of taking as given the urban water requirement, and in bringing into consideration the stochastic nature of streamflows.

These two points are extremely important for the future as well as day-to-day management of water supplies. The knowledge about the value of water to the beneficiaries in the urban area is needed for it directs the policy maker in his decisions regarding the future investment policies and, at the same time, would provide him with insight towards a more equitable distribution of water among the rural and urban users. In the short run, managerial decisions with regard to the allocation of water should not be based on average release values. This is because streamflows are stochastic in nature and are subject to randomness. Consequently, users of water, in particular farmers in our case, do not receive a firm and regular supply of water. In fact, the current allocation policy which gives a guarantee of average release, is the cause of many anomalies and arguments between farmers and water authorities in the course of years when the streamflows are below average. In this situation, farmers who make their cropping acreages according to the average release, and receive less water, would put the blame on the water authority and accuse them of not honouring their promises.

In the following two Chapters we will first look at the nature of demand for water in the Greater Tehran Area and will try to estimate a functional relationship for water in the city. In Chapter 6 we will return to the problem of urban-rural allocation within a more refined model. It will incorporate a demand function for urban beneficiaries and also consider the stochastic nature of streamflows.

CHAPTER 5

DEMAND FOR URBAN WATER IN THE GREATER TEHRAN AREA

5.1 Introduction

The continuing growth and concentration of population in the Greater Tehran Area (GTA) in recent years, has created a complex of social, economic and physical problems. It is widely accepted that the chief constraint on the future growth of the city is the shortage of water. The problem is so serious that if necessary measures are not taken fairly soon, by the turn of the century, the Capital will be faced with a water famine. The present policy on water resource management appears to treat projected urban water requirements as given and concentrates on developing very expensive and sophisticated water supply systems in order to meet the requirements. Moreover, increasing supply for urban use may be at the expense of water resource development and use for agricultural purposes. Obviously, this policy cannot be pursued for ever. Based on the current trend of water consumption and the present state of demand management, it would be a matter of only a couple of decades before the available source of supply will run short of demand. It is important, therefore, to give particular attention to the demand side in order to examine and analyse the influence and effects of the determinants of the demand and to develop management policies which could bring about an overall balance between supply and demand. It is only a simultaneous approach to the problem of supply and demand which would avoid an economic shortage, and it is the knowledge of the demand behaviour that promotes the achievement of an optimum timing and sizing of new sources of supply.

The motivation for this study, therefore, grows from the realisation that policies hitherto have been oriented towards the supply side. To fill this gap, and to quantify the existing misconception concerning the nature of the demand for urban water, we plan to explore the behaviour and characteristics of the demand in the past and present hoping that the fruit of this investigation will pave the way towards a more rational and efficient policy implication and estimation of future needs.

5.2 Concepts of Requirement and Economic Demand

It is common for water resource planners to employ the "requirement" approach to forecast the demand for water. This procedure in its simplest form, involves the projection of the population for a given year, and then multiplying this estimated future population by a per capita consumption figure. In general, projections of per capita water consumption are based on extrapolation of past trend of water use or, in some instances, an arbitrary figure.

TRWB's approach to water resource planning is along these lines. In its inauguration report in 1955 TRWB states that:

"The average water consumption per person is 250 L/D

> (litres per day) with an upper limit of 300 L/D in the north of the city and 150 L/D in the south. The reason for the variation in the use is that in the north water is required for irrigation of gardens while in the south the use is limited to basic domestic needs ....."

These figures are then used to calculate current as well as future requirements. The main shortcoming of this approach is that it assumes that requirements for water exist independent of other technological and sociological trends in the society and furthermore an implicit zero price elasticity is attached to the use of water. Hanke (1970, pp. 1254) in this regard notes:

> "This forecasting technique therefore assumes that the technical, economic and behavioural characteristics of the community are stable, an assumption that is demonstrably incorrect. The elasticity of demand for water is not zero; consequently, the influences of price on use must also be determined if accurate forecasts and appropriate system designs are to be made."

The requirement approach, in fact, assumes that the marginal value of water is constant and identical in all uses. This fundamental misconception stems from what Milliman (1963) has termed the 'water-is-different' philosophy which fails to recognise that water is a scarce resource and cannot be treated as a free good. The requirement approach to forecasting is appropriate only where water is plentiful and marginal cost of new sources of supply is zero. Under these rare situations, the provisions of all the requirements of inhabitants would add to the overall utility of the community without inflicting any additional cost to the society. But a fundamental difficulty here is that, with the rapid growth of population and urbanisation in Iran, water is becoming increasingly scarce and new sources of supply more and more expensive to exploit.

The role of price as a determinant of demand has traditionally been undermined by planners in the erroneous belief that price elasticity of demand for water is not only very low but the effect of a price increase is eroded rapidly and the consumption will return to its original level. This view can effectively be clarified with the help of the following figure. Let us assume that the per capita demand for urban water in a given year is represented by D_1 D_1 in the following figure. A price increase from P_1 to P_2 would reduce the quantity demanded by $(A_1 - A_2)$. Observation of the demand a few years' later would provide a new function D_2 D_2 to the right of the original one.

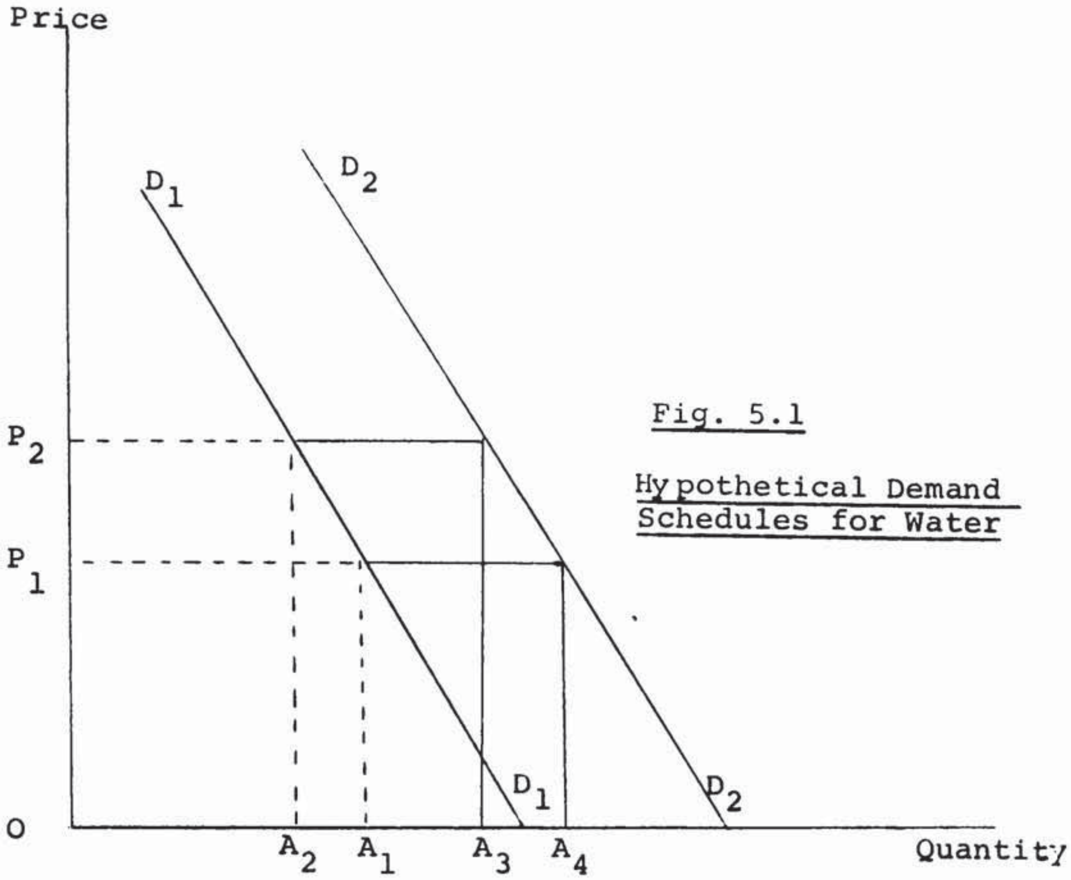


Fig. 5.1

Hypothetical Demand Schedules for Water

The erroneous view of the water design engineers is that they do not distinguish the difference between a movement along the demand curve and a shift in the function. They attribute the increase in the demand to the erosion of the effect of the original price increase. While in fact the increase may have been caused by changes in income, tastes, new technology etc. In fact, if the price had not been changed, the demand would have been at A_4 not A_3. This simply implies that the original price increase has hampered the present demand by an amount equivalent to the difference between A_4 and A_3. The case of Malvern in England where water has been metered, strongly suggests that price is an important determinant of demand. Jackson and Bird (1966)in a study of the effect of price on demand show that the per capita consumption in Malvern has been reduced since the installation of meters by one-third compared with unmetered surrounding areas. The implication of this finding (and many others which we refer to later on) demonstrates the fact that consumers in fact do treat water like any other commodity. They attach a utility value to each unit of it and, in using it, they always try to maximise their utility by balancing the marginal cost and marginal utility derived by the consumption of water. The requirement approach to forecasting implicitly assumes that the relative price of water will not change over the planning horizon and, even if it does change, its effect on the level of demand is assumed to be insignificant. This approach would lead to a misallocation of resources by expanding urban supply probably at a high cost without recognising the value of pricing policy in limiting demand. Milliman (1963) in this respect writes that in the U.S. -

> "In some cases, cities will be forced to pay dearly for additional property rights to water now employed in alternative uses. Because of these factors, it is quite possible that the cost threshold of municipal water supply will double within the next generation for many of our urban growth areas."

The problem is even more acute in Iran when we consider the current political pressure against the redirection of irrigation water to the city.

From the point of view of economic efficiency, such projections are non-optimal, because the same capital could be employed in an alternative investment project which could produce goods and services valued more highly at the margin by the consumer. As a result, the nation or the region will be less well off in the long run than if the more efficient decision on the basis of relative marginal contribution principle were made. This type of analysis requires information regarding factors affecting demand. If, for example, pricing policy is found to have a significant affect on the demand for water in the urban area, it would be inefficient to ignore pricing policy as a tool of water resource management.

5.3 Urban Demand for Water: Some Empirical Evidence

We have already noted the study of responsiveness of demand to price in Malvern, U.K., by Jackson and Bird (1966). However, most of the empirical evidence available is from the U.S.

Among the earliest studies of urban demand for water, one could mention Metcalf's effort (1926) in evaluating the functional relation between the average consumption of water per capita on average price of water. He employs a simple regression on the data for twenty-nine waterworks systems for the period of 1920-24. In this study all uses of water were aggregated and the price was the average of all rates. He used this data to compute the per capita consumption for the study area. Metcalf produced a table which shows the variations in per capita water consumption corresponding to given variations in water rates. No attempt was made in this study to determine the price elasticity of demand. However, an elasticity of -0.65 for a 13 percent change in the level of demand as a result of 20 percent change in the rate can be calculated. Though this study was rather crude and the significance of the statistics doubtful, Metcalf's effort was a breakthrough in statistical analysis of urban water demand.

Much later, in 1958, a somewhat more sophisticated study of residential water demand was presented by Fourt. For forty-four U.S. cities in 1955, Fourt used five variables in deriving a demand function for residential water. They were, the quantity of water used per person, the price, the number of days of rainfall in June, July and August, the average number of persons served per meter and the total population served. The price elasticity of demand per capita at the mean was approximately -0.39. The only determinants which appeared to have a statistically significant influence on the level of per capita demand, were price and the number of persons per household served.

A somewhat similar study was published by Gottlieb in 1963. Gottlieb's study centres on small cities and towns in Kansas, U.S., in the hope of representing the temporal effects of changes in price. The quantities of water used in this analysis were again the aggregate of residential, commercial and industrial uses. Gottlieb supports this aggregation on the ground that commercial and residential uses in most of the study areas account for 80-90 percent of total consumption.

Cross-sectional data (for 19 water systems) in 1952 gave income and price elasticities of 0.45 and -1.23 respectively. The corresponding elasticities for 24 Kansas water systems in 1957 were 0.58 and -0.65 respectively.

Gottlieb also calculated an elasticity of -0.39 for eighteen large cities in 1955. This elasticity corresponds to the one found by Fourt. The conclusion is that the higher price elasticities in small cities are generally attributable to the larger areas of lawns, which implies that the proportion of residential demand used for watering lawns and gardens is more responsive to price changes than other types of residential demand.

Gardener and Schick in a study of behaviour of per capita water consumption in six nothern Utah counties in 1962, extended the previous models a step further by introducing new variables such as value of residence, lot size, percentage of homes with complete plumbing unit and a measure of precipitation and temperature for months of May-October. However, only price, lot size and the percentage of homes with complete plumbing unit were found to be statistically significant. The latter was finally omitted as a high inter-correlation was observed between lot size and plumbing. The price elasticity of demand was -0.76.

Saunders considers the effects of as many as 63 (46 economic-demographic and 13 water usage related) variables, which theoretically could influence the consumption of water. A list of these variables is shown in Appendix 5.1. To isolate those factors which are highly associated with the use of water, he employs the technique of principal component analysis. The selected factors are then fitted in a Least Square Regression Analysis to measure more explicitly the cross-sectional association between the selected variable and water usage.

For an inter-area analysis, 48 different economic and demographic variables in conjunction with 17 water-usage related variables are considered.

To study the actual magnitude of the association of these three groups of variables, 8 variables representing information about the three components were selected and regressed on total water usage. They were: population and value added, representative of the size related component, the median income and income greater than $10,000, representative of the income related component and finally number of housing, cars and land area, to represent the growth component. The result, not surprisingly, showed that population was the variable most closely associated with total water usage, and explained approximately 91 percent of the variation in the consumption among cities. The next important variable was land area, followed by value added and two or more cars. These four variables together explained about 94 percent of the total variation in the use of water.

For the intra-community, Louisville, Kentucky, 22 economic and demographic variables and two water-sales related variables were compiled. The result of the analysis showed a similar result to that of the inter-community analysis. That is, irrespective of size, districts with higher income levels tend to use more water per account. In fact this variable alone explained about 40 percent of the variation in water sales per account.

Saunders makes use of the results in estimation of future water usage in urban areas. Several forecasts are presented with a final water usage estimate for 1975. The formulae used for the projections is

$$\varepsilon 75_i = (W60_i \times 1.19 \times \frac{Y75_i - Y60_i}{Y60_i} + W60_i)\, P75_i$$

where ε = total water use

W = per capita water use

Y = per capita income

P = population

i = index of city.

Two main criticisms of this work are that (a) in spite of the very large number of variables included in the analysis, the final forecast could have been achieved by a regression analysis on a few important variables and (b) effect of price on water consumption is ignored.

The studies reported here, and many others, reveal a set of almost common problems which basically stem from inadequacy of data. The fact is that published statistics are not usually given by category of uses. Residential, commercial, industrial and public demand are lumped into a single aggregate usually called "urban requirement". Consequently, the derived demand function does not in fact represent the behaviour of a particular component but an average response for the four components combined. The problem is more serious where cross-sectional data are compiled from sources where the proportionate importance of each component varies significantly. We have also observed that there is a tendency to use an average price. The range of average prices from cross-sectional observations cited thus far are sometimes quite high. Even within a locality a pronounced discriminating pricing policy can be observed. Appendix 5.2 shows the range of retail price changes and pattern of declining block rates in American cities (Hirshleifer et al, 1969, pp. 107-8). Therefore, the application of an average price serves only as a proxy and the derived price elasticity should be treated with caution. This is particularly true when we consider the fact that the responsiveness of demand to changes in price is most likely to be different for each of the major demand components. For instance, the water bill for a commercial organisation constitutes a very small portion of total expenses. Therefore, it is very unlikely that such an establishment would be prepared to cut its water bill by, for instance, switching-off its air-conditioning system in response to substantial price increases.

The problems of seasonal and, in particular, peak daily or hourly demand, have not been tackled in the studies cited so far. Annual demand is an average concept since wide seasonal and hourly variations in demand are hidden in the mean values. From the design point of view, information about peak demand is extremely important. Such information, once available, may assist the planner to introduce an appropriate measure to control the demand and, in the case of shortages, to correct the imbalance in supply and demand.

Most of these problems have been answered in one of the most comprehensive studies to date carried out at the John Hopkins University. The salient portions of this study, as it related to the impact of price on residential water demand, were incorporated in a paper by Howe and Linaweaver (1967).

The study covered 41 homogeneous residential areas scattered throughout the U.S. during the period of 1961-66. The study areas were selected according to climate and economic level with all other factors that influence water use taken at random. A tremendous improvement in data-gathering technique utilized in this study were: (1) the installation of master meters for each area included in the study area so that accumulated flow could be registered every 15 minutes; (2) the classification of residential areas according to whether they were metered or not, and further whether they were using public sewer or septic tanks for sewage disposal; (3) classification of consumption for indoor and outdoor purposes. In this respect, the demand for outdoor use was estimated by taking the average winter demand as the average demand for indoor uses and subtracting this from the summer demand.

Initially, Howe and Linaweaver expressed domestic and sprinkling demand in the following forms.

$$q_{a,d} = f(v, a, dp, k, p_w)$$

$$q_{s,s} = \beta_o\, b^{\beta_1}\, (W_s - 0.6r_s)^{\beta_2}\, p_s^{\beta_3}\, v^{\beta_4}$$

where: $q_{a,d}$ = average annual quantity demanded for indoor purposes (gpd/du)

v = the market value of the dwelling ($1,000)

dp = number of persons per dwelling unit

a = age of dwelling unit (in years)

k = average water pressure (in PSI)

p_w = the sum of water and sewer charges that vary with water use, evaluated at the block rate applicable to the average residential use in the study areas

$q_{s,s}$ = average sprinkling demand in (ypd/du)

b = irrigation area per dwelling unit

W_s = summer potential evapotranspiration in inches

r_s = summer precipitation in inches

p_s = marginal commodity charge applicable to average summer total rates of use.

The best fitting equations are shown in Appendix 5.3.

Howe and Linaweaver concluded that the factor with highest level of influence, in the case of indoor demand, is number of persons per dwelling followed by market value of dwelling, climate and whether water is metered or not. Finally, at the third level is the price of water.

Sprinkling demand is more sensitive to price and income than indoor demand. In addition the price elasticity of demand is greater in humid areas than in dry western areas. Frequency of billing and regional price index have no significant impact on demand or on price elasticities.

These are the main results of the Howe and Linaweaver study. The great contribution of this research lies in the sub division of municipal demand into major components (residential, commercial etc.) and then into smaller ones (indoor, sprinkler etc.) The problems of price differential have been solved to some extent by considering different rates for indoor and sprinkling demand. The authors have even taken a step further by deriving maximum or peak sprinkling demand according to type of residential area.

For tenants living in apartments where the whole block is metered as a single unit, the price elasticities obtained in the above study may not be appropriate since individual tenants will tend to be unresponsive to the bill for the entire block.

A more serious problem is that of using price elasticities derived from cross-sectional data for forecasting.

Wong (1972) in an analysis of municipal water demand in north eastern Illinois, has shown that both price and income elasticities derived from cross-sectional data are higher than those which have been attributed to time-series data. Houthakker and Taylor (1970) in a study of consumer demand in U.S. are also sceptical about the dynamic implication of elasticities derived from cross-sectional analysis. They indicate that "except under heroic assumptions, cross-section analysis will not provide information on the influence of prices which may be of importance in long-term projection." The reason lies in the fact that cross-sectional studies refer to a particular time period during which the reaction of a particular group of consumers to a change cannot be observed. Instead we make the implicit assumption that the behaviour of each group of customers under the same set of circumstances will be almost identical. This is rather a hard assumption, especially as there are behavioural factors associated with a particular group of people which cannot be statistically measured. Consequently, the consumption or demand within a community may be entirely different from the factors found significant in cross-sectional studies. Therefore, application of such information to a particular locality may produce unsatisfactory results.

The practical implication of these kind of studies are more appropriate for regional or perhaps nationwide planning. At the local level, any reliable planning should be based on intra-community-time-series data (Headley, 1963, pp. 446).

5.4 Demand for Water in GTA

The formulation of an economic model specifically related to urban water demand in Tehran is of utmost importance for the knowledge of the components of such a model would enable the policy maker, in the short run, in his decisions regarding the pricing, allocation and other managerial policy making and, in the long run, given the behaviour of the determinants affecting water utilisation, public officials can design policies and effect decisions in such a manner as to add to the welfare of the inhabitants.

Urban demand for water can be divided into: residential, commercial, industrial and public uses.

5.4.1 Residential Demand - is basically for domestic or indoor uses including drinking, cooking, sanitary facilities, bathing, washing and cleaning and outdoor uses such as irrigation of gardens and lawns, car washing, swimming pools, air-conditioning and so on.

5.4.2 Commercial Demand - is either incidental to the operation of the establishment, e.g. offices, stores, etc.

or an integral input of the service of the firm, e.g. laundries, restaurants, etc.

5.4.3 Public Demand - includes the requirements of the municipality for purposes such as street washing, watering public parks, fire control and so on.

5.4.4 Industrial Demand - like the second category of commercial demand, is usually a variable in the production function, e.g. use of water for generating steam, or as a component of final product such as bottled beverages etc.

The demand for each of these four categories, is subject to a set of rather different variables. For instance, industrial demand may be related to rate of employment or type and growth of industries while commercial demand may be related to the per square metre of the establishment. Further, the price elasticity of demand will almost certainly be different for different demand categories. It would therefore be desirable to estimate separate demand functions for these categories but such disaggregation is not always possible.

Bain, (1966, pp. 180-181) gives the following percentages to each of the above category of use in California:

Domestic	55 - 65	%
Commercial	20 - 30	%
Public	3 - 7	%
Industrial	5	%

In another study Howe, Russell and Young (1970) have found the following percentages to be the average for 206 cities in the U.S.

Residential	41 %
Industrial	24 %
Commercial	18 %
Others	17 %

In the case of Tehran, no detailed published statistics are available. However, a private communication from the TRWB, and the recent water projection published by the Plan Organisation, suggest that the following ratios are fair estimates of total consumption of water in the Greater Tehran Area.

Residential/Commercial	70 %
Industrial	5 %
Forest/Parks	8 %
Others	17 %

In this study it has not been possible to consider different categories of demand separately. This could be a serious problem. We note, however, that industrial component at present accounts only for 5% of total demand and is likely not to exceed this percentage owing to the Prevention of Industrial Development Act which forbids any kind of new industrial investment within a radius of 120 km of the city and is likely to remain in force within the foreseeable future. Forests or the Green Belt receive untreated water. The amount of water supplied for this purpose, according to TRWB, will also remain constant in the foreseeable future.

The category of "other uses" basically accounts for losses due to leakage, illegal connections, main flushing etc. It is common practice in municipal water industry to allow an average of 15-20 percent for this category (Howe et al, 1970, pp. 31-43). A figure of 17% has been suggested by TRWB. This percentage is expected to remain constant. We also note that according to the Iran Statistical Bureau there are about 20,000 commercial establishments registered under the National Insurance Scheme. Assuming that all of them receive water through a connection, the commercial component accounts for only 5% of the total number of connections in the city. Therefore, we would not be too far away from reality by relating total demand for water to factors which are likely to affect residential demand and reflect the economic well-being of the inhabitants.

There are theoretically a myriad of factors which could influence the use of water in urban areas. Saunders, as was noted earlier, investigates effects of up to 63 different economic and demographic variables. However, there are only a handful of factors, as the survey of literature indicates, which have been found to be responsible for the major portion of variation in the consumption of water. Among the most frequently mentioned factors are: population, community size, pattern of housing, climate, income, price, etc. Depending on the method of data collection, some factors may appear to be more important than others. For instance, if the data are based on well diversified geographic locations, climate and location variables may explain a good size of the variation in the use of water. While the same factors in a time-series analysis based on a particular locality usually appear insignificant (McMahon and Weeks 1973).

The focus in this study is on the temporal rather than the spatial causes of the variation in the consumption of water. This approach has been adopted here because we are ultimately interested in the development of a forecasting model. In other words, the objective of the study is to derive a demand function which could explain changes in the consumption of water as a result of changes in the number of population and a set of variables which determine the per capita demand for water over time in GTA. This approach would enable us to observe changes in the absolute value of the variables which are more useful in the prediction of future consumption.

The explanatory variables considered in this investigation are: population of the city, number of premises served by the system, per capita income, number of dwellings and price of water. Therefore, the demand function in algebraic form can be represented as:

$$W_d = f(N, I, H, C, P)$$

where W_d = is the annual residential/commercial consumption of water (million cu.m)

N = population (million)

I = per capita income (rials/year)

H = number of dwellings

C = number of connections (i.e. premises served by the system)

P = water rate (rials/cu.m)

The empirical studies cited above tend to confirm the intuitive feeling that all these variables would have an important influence on water consumption. Number of connections and number of dwellings are included separately in the model since the ratio of number of connections to number of dwellings has been increasing rapidly and is expected to continue to do so. Columns 5 & 6 of Table 5.1 show the number of premises served by the Board and the total number of dwellings in the city. The ratio of dwellings served to the total number of dwellings, according to these figures, has been declining in so much as at present about 85 percent of the total number of dwellings in the city are connected to the mains and receive water from the Board. The rest either purchase water from independent water-tanker companies, who in turn buy the water from the Board, or have their own sources of supply. The gap is, however, planned to be narrowed down and by the early 1990s, 98 percent of the city will be supplied by the treated water (see 5.7.3). Number of connections and dwellings include residential and commercial properties but commercial properties form only 5% of the total.

Population variable represents the total number of population in the metropolitan area. In fact some people live outside the boundary of the city and therefore do not have direct connections. According to a report by the Plan Organisation (Vol. 9, 1973) out of a total population of approximately 4.4 million in 1972, only 3.5 million had direct access to treated water. The Board again hopes to extend its service area so that the total inhabitants of the city will consume treated water by the early 1980s.

The income variable represents the nationwide average per capita income. This is somehow a crude estimate of the actual income of the inhabitants of Tehran. It is well known that Tehranians enjoy a higher standard of living. According to a report by The Plan Organisation, on average the Tehranians are twice as well off as the rest of the country. However, in the absence of any published and viable statistics, the average national per capita income is taken to represent not only the ability to buy, but as a proxy for the influence of increase in the standard of living.

A better surrogate of income used by many researchers, including Howe and Linaweaver (1967), is the value of dwelling because it directly represents the economic level of the household. However, this statistic, with respect to the city of Tehran, is available for four years only which is clearly inadequate.

Finally, the price variable is represented by the domestic rate which has changed only once since the Board came into existence. This would imply insufficient variation in the independent variable. However, a constant price during a time when the general level of prices is rising, implies a declining real price for the relevant commodity. Price, as well as income, have been represented by their real values in our model (deflated at 1973 prices). Apart from providing the variability which facilitates estimates, real price and income are the correct variables for inclusion in a demand function, (Cramer, 1971, Chap. 9).

5.5 GTA Demand Function : Econometric Estimation

Data was available for the dependent and independent variables for the years 1960-73 and are presented in Table 5.1. Simple multiple regression is the most common method employed for estimating demand functions for water in studies reviewed above. A serious objection to this approach in our study, however, is the high degree of collinearity among four of the five explanatory variables, the exception being price. This can be shown by looking at the elements of the correlation matrix.

Correlation Matrix

	Connection	Income	Population	Housing
Connection	1.000			
Income	0.965	1.000		
Population	0.989	0.976	1.000	
Housing	0.950	0.893	0.968	1.000

The high values of the elements of the matrix means that the determinants of the demand function are almost a linear function of one another. The reason behind such a high multicollinearity is the growth of

Table 5.1 DATA EMPLOYED IN THE DERIVATION OF THE DEMAND FUNCTION

Year	Quantity of Water Consumed cu.m.	Water Rate Rials/cu.m.	Population of Tehran	Per Capita Income Rials	Number of dwellings in the city	Number of premises with direct connection
1960	40325230	5.000	2055	12300	218164	112694
1961	47900000	4.930	2193	12370	253679	130000
1962	52000000	4.890	2337	12427	285032	137307
1963	53584250	7.260	2488	12704	316702	155341
1964	60490902	6.960	2644	13399	341116	170257
1965	69016125	6.940	2809	14597	364093	190757
1966	85088938	6.880	2980	15390	390129	228130
1967	106183375	6.820	3159	16425	410312	283544
1968	136493750	6.720	3346	17734	431384	334692
1969	161645688	6.490	3540	18617	445357	372483
1970	191122750	6.460	3743	20460	455807	400301
1971	214284125	6.060	3956	22533	466115	429266
1972	234143563	5.700	4176	24561	476649	453750
1973	252000000	5.430	4404	27274	500000	470000

all the explanatory variables in our model. Such multicollinearity results in very large variances-covariances and hence broad confidence intervals. As a result, the relation between the dependent and independent variables cannot be sensibly investigated (Wonnacott and Wonnacott, 1970, pp. 257-259). In addition, if the present pattern of collinearity changes as one would expect, especially with regard to the number of connections and number of housing, the model would lose its credibility for projection purposes.

We attempted to use Two Stage Least Squares to see whether one of the highly intercorrelated explanatory variables could be shown to represent the remaining explanatory variables. The appraisal, however, led to very low Durbin-Watson statistic implying the existence of serial correlation. The obvious solution lies essentially in the acquisition of additional data which reduce collinearity. In demand studies, the conventional approach to the problem is the combined use of time-series and cross-section data. The traditional approach (Klien, 1962) avoids the problem of collinearity among the explanatory variables by running a regression on the cross-sectional data in which one would expect to observe a wide variation among the variables. The estimated coefficients are then used to correct the quantity demanded for the effects of the variables in the time series analysis. There are, however, difficulties of specification and interpretation (Kuh and Mayer, 1957). Following a more sophisticated approach (Wallace and Hussain 1969) would have required the acquisition of cross sectional data, which was not possible in our case.

An approach, which does not require the acquisition of new data, is the "principal component" method. The core of the theory as Dhrymes (1970) puts it "is one of defining a number of mutually uncorrelated variables exhibiting, in some sense, maximal variance". In fact, what the technique does is to disentangle the complex inter-relationships among the variables and form a new set of variables which are totally uncorrelated with one another but at the same time account for the greatest part of the variance of the original variables. This new set of variables then, which are essentially smaller than the original number of variables, can be used in a regression analysis in order to investigate the functional relationship between the dependent and the new set of components and other variables which were not collinear with the original set of variables.

According to this procedure the original model can be restated as:

$$W_d = f(P, Z_i)$$

W_d and P are as defined before and Z_i are the principal components (or factor scores), representing different linear combinations of the original explanatory variables. Since the examination of cumulative percentage of total variance shows that the first factor score accounts for over 96 percent of total variance it is therefore felt sufficient to consider only the first component in the regression analysis. This component is defined here as an index of prosperity, for it represents a number of variables which could mainly be related to the growth and development of urban areas.

This model is tested in double-log, semi-log and linear form. The linear form with highest R^2 and Durbin-Watson T Statistic has proved to be the best representative of the demand function. That is:

$$
\begin{array}{llll}
 & Wd = 210680.92 & - \; 14389.34P & + \; 75607.65Z \\
 & \quad (18063.12) & (2897.78) & (2429.70) \\
 & & (t_p = -4.96) & (t_z = 31.11) \\
 & & (F_p = 24.65) & (F_z = 968.32) \\
 & R^2 = 0.98 & & DW = 1.31
\end{array}
$$

Both coefficients are significant at 5 percent level of confidence and the signs of coefficients are in accord with the theoretical expectation. That is, there exists a reciprocal relation between the water rate and consumption of water and a direct relation between the prosperity index and consumption.

The analysis of variance shows an F value of 485.41. With (2-13) degrees of freedom, the value of F at 0.01 level of confidence is 6.93. So, we could argue that a highly significant association exists between price, prosperity index and the consumption of water. The value of correlation between the two independent variables is 0.10. Such a low value indicates that no serious problem of multicollinearity exists between price and the prosperity index.

In the time-series studies, as the case with us, one should be aware of a common problem, namely that the error in one period could be related to the error in the previous period. In this situation, one of the crucial assumptions of the standard regression analysis which requires that successive disturbances should be independent of their previous values, breaks down. If the Least-Squares method of estimation is applied to the observation, although the estimated values of coefficients are unbiased, the sampling variances of those estimated may be unduly large. As a result the model would lose its validity from the projection point of view. Testing for serial correlation is usually done by means of the Durbin-Watson Statistic. The computed value of Durbin-Watson statistic is 1.33 which is not significant at 5%. This, in other words, means that the problem of auto-correlation is not important.

Following Surrey (1974), the demand function can be transformed back to include the original variables. In algebraic form the transformation is performed as follows:

$$\hat{D}_W = \hat{\alpha} + \hat{\beta}_1 P + \hat{\beta}_2 Z \qquad \text{estimated demand function}$$

since

$$Z = \sum_{i=1}^{n} a_i \, x'_i \qquad n=1,\ldots,N$$

where

$$x' = \frac{x_i - \bar{x}_i}{S_i} \qquad \text{(standardised value)}$$

therefore

$$\hat{D}_W = \hat{\alpha} + \hat{\beta}_1 P + \hat{\beta}_2 \left(a_i \frac{x_i - \bar{x}_i}{S_i}\right)$$

or
$$\hat{D}_W = \hat{\alpha} + \hat{\beta}_1 P + \sum_{i=1}^{n} \hat{\beta}_2 \frac{a_i}{S_i} x_i - \sum_{i=1}^{n} \hat{\beta}_2 \frac{\bar{x}_i}{S_i}$$

or

$$\hat{D}_W = \left(\hat{\alpha} - \sum_{i=1}^{n} \hat{\beta}_2 \frac{\bar{x}_i}{S_i}\right) + \hat{\beta}_1 P + \sum_{i=1}^{n} \hat{\beta}_2 \frac{a_i}{S_i} x_i$$

Upon the substitution the demand function with the original variablesis is as follows:

$$\hat{D}_W = 59465.21 - 14389.34P + 0.147C + 3.87I + 25.90N + 0.213H$$

where:

x_i = original variables

$\bar{x}_i$ = mean value of i^{th} variable

S_i = standard deviation of i^{th} variable

a_i = regression coefficient of i^{th} variable in the first component

$\hat{D}_{W,P,C,I,N,H,Z}$ as defined before

The significance of price variable in the model indicates a "demand" rather than a "requirement" function. This in other words implies that people are price conscious and do respond to changes in the water rates.

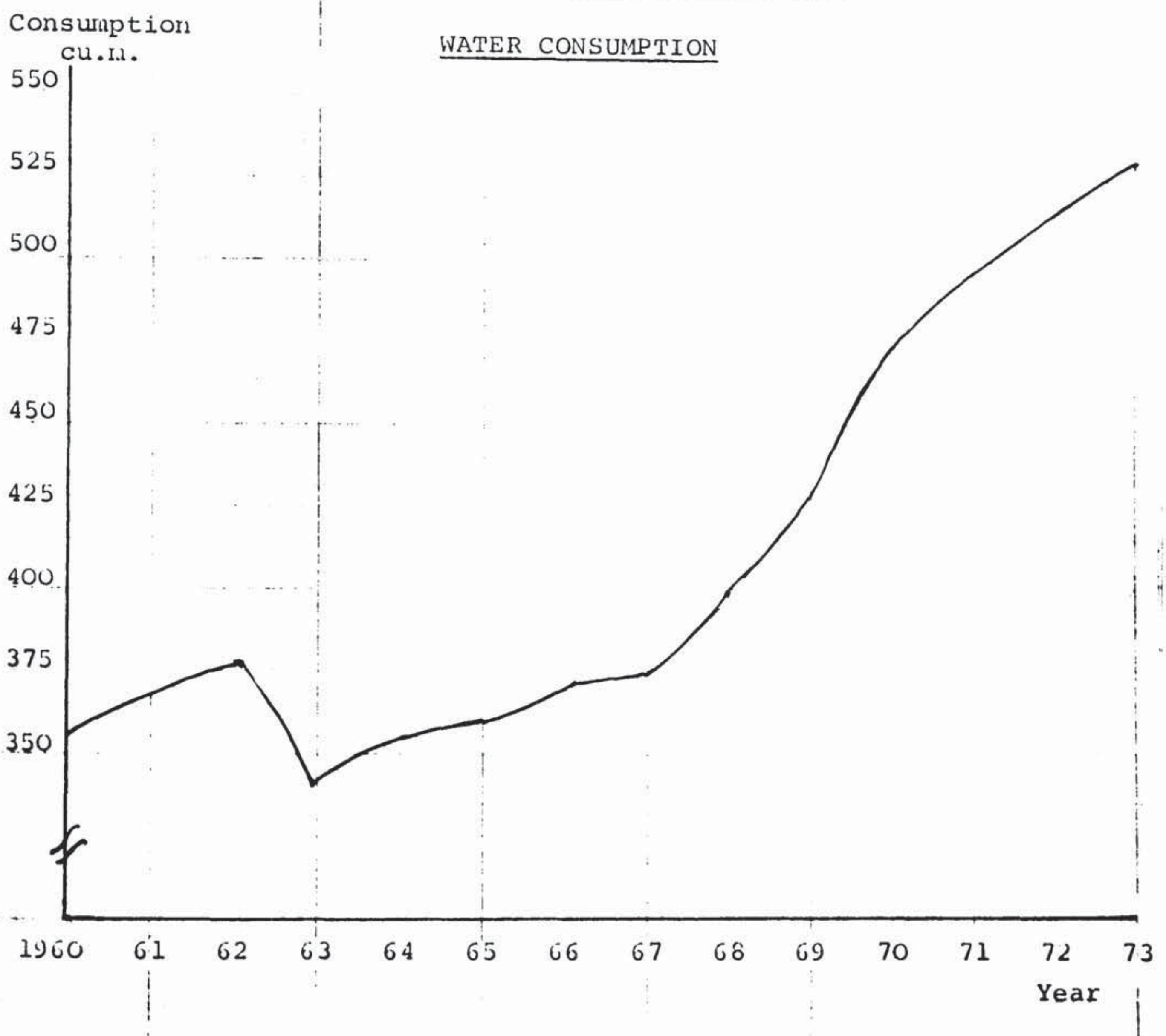
By computing the average percentage changes in water purchases associated with a given percentage change in the price of water, an estimate of the price elasticity (the degree of responsiveness) of demand for residential water is derived. The resulting statistic measured at the mean is -0.72. This elasticity indicates that as a result of, for instance, 10 percent price increase, the consumption of water is likely to be reduced by 7.2 percent. Considering the nature of the data, in which all uses of water are aggregared, the derived price elasticity appears to be quite reasonable. The survey of empirical studies, shows that the elasticity of demand for out-door purposes, in particular sprinkler demand, is around 1 and for indoor uses between 0.1 - 0.5. Therefore, the estimated elasticity in our model which falls between these two extremes, is reasonable and, in fact, reveals that the response of consumers to changes in water rates are somehow similar to that of Americans.

Examination of the changes in the level of demand in the third year of observation, 1962, and the subsequent year, 1963, when the actual water rate increased by 50 percent, shows a fall of 10 percent in the level of consumption per connection (Fig.5.2). This

Fig. 5.2

GROWTH OF PER CAPITA CONNECTION

WATER CONSUMPTION



represents an arc price elasticity of 20 percent. Considering the fact that during this period (1962-63) the per capita income is not substantially changed (only by 2 percent), and considering that the effect of increase in the number of population and housing to a great extent has been removed by computing the per connection consumption rather than the total consumption, the drop in the consumption could, to a great extent, be attributed to the increase in the water rate.

During this period, mainly the central and the southern part of the city, where the population and housing density is high had direct connection. This, in other words, means that water was used mainly for indoor purposes. Therefore, the computed low elasticity of -0.20 is in fact the representative of the price elasticity for indoor demand at that period. Such a low elasticity is in line with other empirical investigation and also theoretical expectation. This is so because at relatively low level of income, water is basically consumed for bare necessities, drinking, washing, etc. Under these circumstances, the demand is very inelastic to changes in price. The movement of price in an upward direction could not affect the level of demand by a sizeable measure because the possibility of substitution for these categories of uses are almost non-existent. This, in other words, implies that the marginal utility of water remains substantially above the water rate.

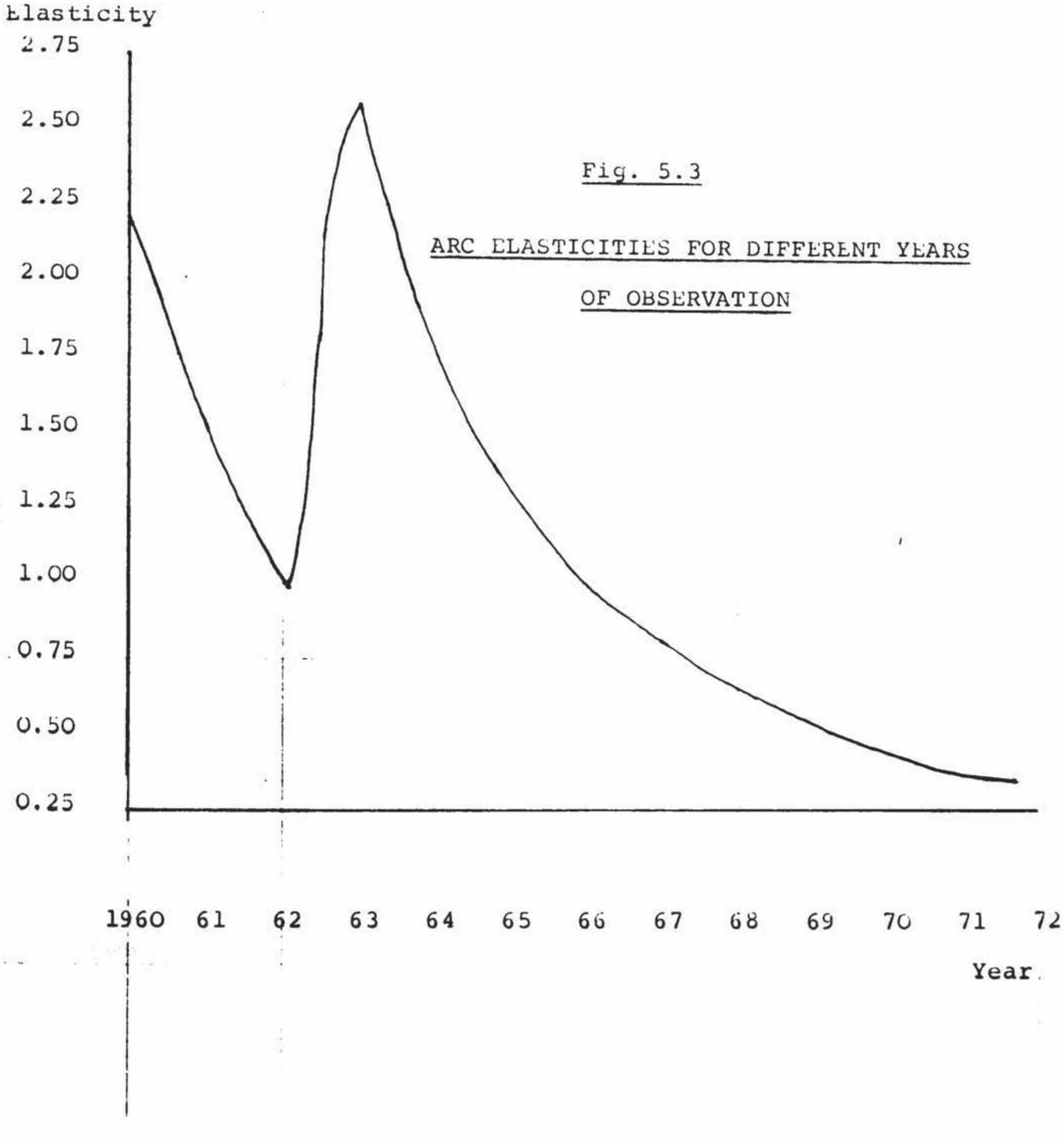


Fig. 5.3

ARC ELASTICITIES FOR DIFFERENT YEARS OF OBSERVATION

However, with the growth in the overall standard of living, we would expect an increase in the consumption of water. Dieterich and Henderson (1963) point a per capita consumption as low as 5-20 L/c/d for underdeveloped countries using public hydrants to as high as 180 L/c/d in U.S. for 1959. Darr et al (1975) have found separately an income elasticity of 0.92 and over 1 for the Jerusalem and San Francisco-Oakland areas respectively. This means that there is strong relationship between standard of living and consumption of water.

The resulting relationship in this study with highly significant "T" statistic for the "prosperity index" indicates that a rather high degree of confidence can be placed for this coefficient.

Theoretically, we would expect to observe a higher price elasticity of demand, cet par, with the growth in the per capita consumption. But the reason that we observe a declining elasticity, Fig.5.3, is that the proportion of the budget devoted to expenditure on water as a result of increase in per capita income and effective decline in the water rate, has been diminishing. This implies the existence of a negative income-price cross elasticity.

5.6 Seasonal Demand for Water

In the discussion of demand function so far, the quantity of water consumed is expressed as the aggregate of annual demand. This annual single value hides the seasonality aspects of demand which is of paramount importance to the policy maker, both from the design and control points of view. Considering the records of monthly supply of treated water to the city for the period of 1969-72, it is evident that the average monthly demand is at minimum during winter and reaches a maximum during June through September. Since precipitation is at minimum for about 5-6 months (April-September) and the temperature reaches its maximum in the same period, the difference between summer and winter demand is basically attributable to the use of water for sprinkling and other outdoor uses. This, follows the procedure adopted by Howe and Linaweaver (1967) in their famous research on the residential demand for water. They take the average winter demand as the volume of water consumed for indoor purposes and further assume that the demand for indoor water is constant throughout the year. They then deduct the total summer demand from this to obtain sprinkling demand for water. Strictly speaking, the difference between summer and winter should not be solely attributed to the sprinkling uses as it is suggested by Howe and Linaweaver, because by doing so we ignore the water which is used for air-conditioning and more frequent car washing. Furthermore, this procedure should be adjusted to allow for higher consumption of water during the summer for indoor uses such as more frequent bathing, higher drinking consumption etc. For these reasons we have taken the early spring level of demand as the representative of demand for indoor consumption.

Following this procedure, the estimated outdoor water demand based on Figure 5.4 is presented in Table 5.2. According to this Table the outdoor demand starts in April, reaches its peak in June through September and then continues to fall, in so much as after October it totally disappears. According to Table 5.3 the total monthly demand (April-October) for the four years of observation has increased from 102.3 to 149.2 million cu.m. or a growth of over 45 percent; while at the same time the outdoor demand shows an increase of about 66 percent. The proportion of water used for outdoor purposes in the peak months according to Table 5.4 is up to 34 percent of total monthly consumption.

The components of outdoor demand basically consist of lawn and garden irrigation, swimming pools. To this, the air-conditioning use of water should be added, for water-coolers are operated during the hot season (mainly for an average of 5-6 months a year) which coincide with the peak demand period. The available statistics do not provide any information regarding the outdoor uses of water. However, a rough estimation is possible by calculating the air-conditioning use of water and taking this value from the total outdoor demand to arrive at the sprinkler use of water.

According to the Credit Bank of Iran there are about 750,000 air coolers in the country. More than 2/3 of these appliances are sold in Tehran, therefore at the

Fig. 5.4

MONTHLY CONSUMPTION OF WATER IN TEHRAN 1969-73.

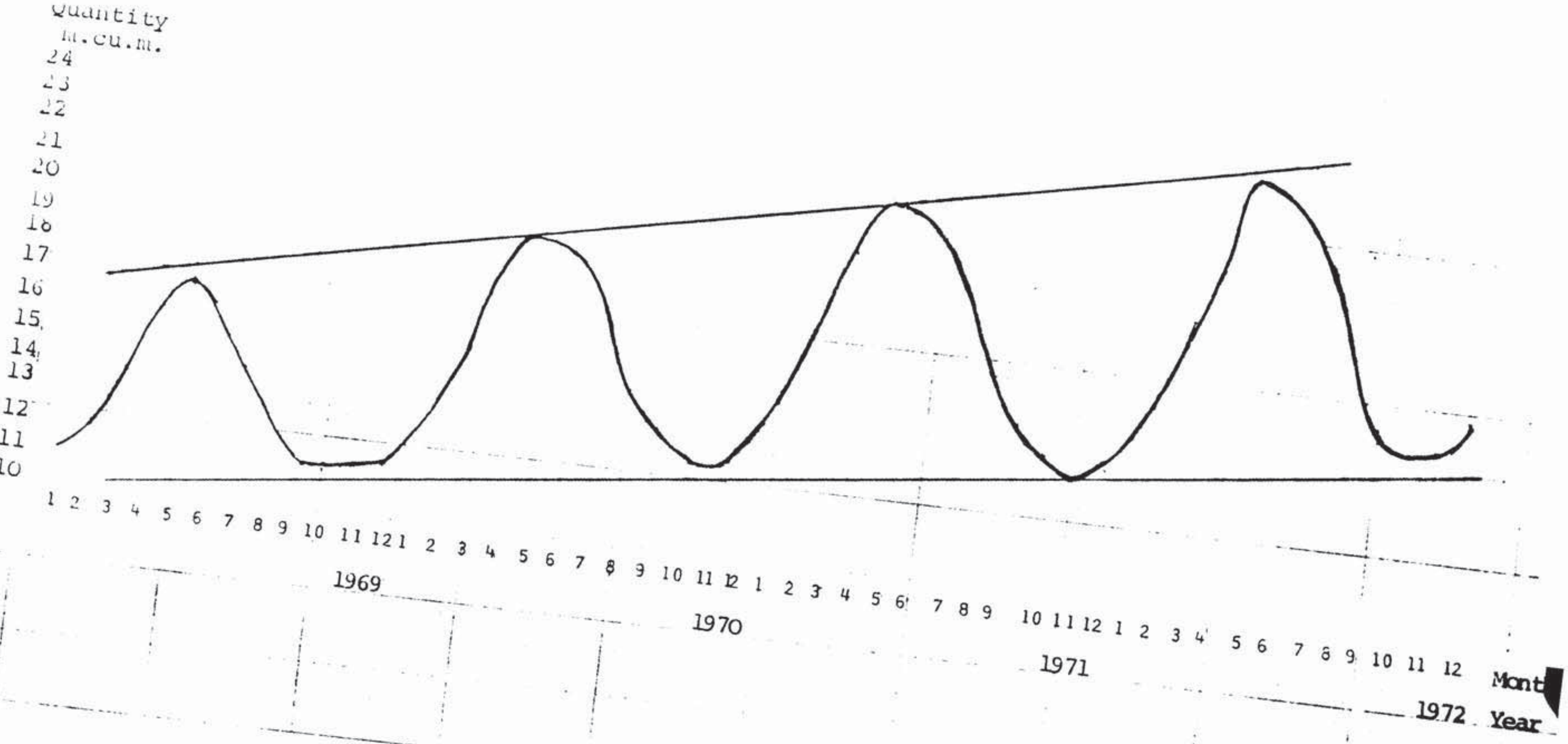


Table 5.2

ESTIMATED OUT-DOOR USE OF WATER

(m.cu.m.)

Year / Month	1969	1970	1971	1972	Percent growth over the 4 year period
4	1.0	1.0	2.0	2.2	120
5	2.7	4.5	4.7	4.4	63
6	5.1	5.0	6.7	8.2	61
7	5.7	5.6	6.8	8.0	40
8	4.2	5.1	6.0	7.0	67
9	3.2	2.8	3.5	5.2	63
10	1.4	0.7	0.7	2.2	57
Σ	23.3	25.5	29.8	37.2	60

Table 5.3

MONTHLY CONSUMPTION OF WATER

(m.cu.m.)

Year / Month	1969	1970	1971	1972	Percentage Growth over the 4 year period
4	12.2	14.9	17.8	18.2	49
5	14.0	18.6	20.5	20.4	46
6	16.4	19.7	22.5	24.2	48
7	17.7	19.5	22.0	24.0	41
8	15.5	19.0	21.8	23.0	48
9	14.5	16.7	19.3	21.2	46
10	12.7	14.6	16.5	18.2	43
Σ	103.0	121.1	140.40	149.2	39.8

Table 5.4

ESTIMATED OUT-DOOR USE OF WATER AS A PERCENTAGE OF TOTAL MONTHLY CONSUMPTION

Year / Month	1969	1970	1971	1972
4	7	0.7	11	12
5	19	24	23	22
6	31	29	30	34
7	34	29	28	33
8	67	27	28	30
9	22	17	18	25
10	11	0.4	0.4	12
Percentage of total	23	21	21	25

present there are about half a million units installed in the city. The water consumption of this type of cooler has been estimated by Withford (1970,pp.75) to be about 18 litres per hour for a two ton refrigeration capacity. Since most of the units produced in Iran are of one ton capacity, the average consumption is about 9 litres per hour. Assuming a 10 hours working day for 5 months, the total air-cooler consumption of water is:

$$9 \times 10 \times 150 \times 500{,}000 = 6.5 \text{ million cu.m.}$$

According to this estimation, the sprinkling demand for water in 1972 is in the order of 30 million cu.m.

5.7 Future Water Demand- Projection of Explanatory variables

We have reached the stage now to assemble the available data and make an estimate of future water demand. However, it may be well at this point to state that in this study we are concerned with the "projection" of future water demand depending to a great extent on the behaviour of the market in the past. In other words, forecast of water demand is based on the understanding that the set of econometric estimates regarding the effects of various variables will hold to be true and that no major catastrophic events such as depletion of oil fields or a nuclear war would happen.

The analysis of aggregate demand indicates that almost total variations in demand can be explained by the explanatory variables included in the model. Therefore, assuming that the behavioural characteristics of the coefficients remain reasonably unchanged over the period of forecast, a set of projected values for the independent variables would produce a reliable measure of the future demand for water. Our task is now to make a forecast for the set of independent or explanatory variables.

5.7.1 Population (N)

An estimate of the future size and composition of the population is critical in any water demand forecast. Forecasts of future population on a national level is much simpler than composition of rural and urban population especially within the boundaries of each part of the country. This is particularly a difficult task in a country such as Iran where the pattern of the economy is rapidly moving away from agriculture to industry. Under this circumstance a mass migration of peasants to towns and cities in search of work is inevitable. The problem becomes more acute once the changes in the boundaries of localities are brought into consideration. The increase in the population and improved infrastructural facilities change the feature of nearby villages, and gradually make them a part of the city. This is a common phenomenon in the Greater Tehran Area where many parts of the city once were individually identified with their own public utilities but now are an integral part of the city with a common source of utilities.

The forecast of immigration into cities, in particular Tehran, by itself is a challenge. Within the two national censuses of 1946 and 1956, the rate of population growth in the rural area was about 2.1 percent, while that of the nation as a whole was estimated at 3.1 percent. During this period, the annual rate of population growth in the urban area was 5.1 percent which was 2.5 times that of rural area.

Table 5.5 shows the composition of the population based on the census of 1956 and 1966. According to this Table the population of urban and rural areas increased by 64 and 18.6 percent respectively, while at the same time the overall increase of country population was 32.5 percent.

According to this Table, over a period of 10 years (between the two censuses) the average annual rate of population growth in urban area, was 0.72949 percent (38.03760 - 30.74270). On the basis of this proportion, the share of each component of the population could be worked out according to the following equation:

$$\begin{aligned} S_u &= 30.74270 + 0.72949t \\ S_r &= 69.25730 - 0.72949t \end{aligned} \qquad (1)$$

Since the average annual rate of population growth for the country as a whole has remained constant at 2.857 percent, it is possible to calculate total population at year T according to this following equation:

$$P_t = P_o (1 + r)^t \qquad (2)$$

Therefore the share of urban and rural area at T would simply be the product of (1) and (2). They are:

$$S_u \cdot P_t = (30.74270 + 0.72949t)\ P_o\ (1.02857)^t$$

$$S_r \cdot P_t + (69.25730 - 0.72949t)\ P_o\ (1.02857)^t$$

During the same period, the population of Tehran went up from 1.561 to 2.980 m respectively. The percentage share of Tehran was accordingly 8.02 for 1956 and 11.55 for 1966. This implies that average annual rate of population growth was 0.35 percent. Therefore, the share of Tehran at year T could be found according to the following equation:

$$S_{Teh} + S_u \cdot P_t \cdot (8.0236 + 0.3533t)\ \ (30.74 + 0.72949t)$$

On the basis of these calculations Tehran will have a population of over 10 m by 1990 (Table 5.4). Such high rate of population for the reasons to be discussed shortly is very hard to be materialised.

TRWB forecast of population for the year 1991 is 5.5 million. This is based on the Urban Master Plan Population projection which, according to the statistics of Plan Organisation, is grossly underestimated (Plan Organisation Vol. 9, pp. 77). The annual rate of growth for this projection, according to Table 5.5, reaches a peak of 4.19 percent in 1976 and suddenly drops by over 50 percent to 1.09 for 1977 and continues to decline to under 1 percent for the latter part of the eighties. Such a low rate of population growth apparently requires in the first instance a total stoppage of immigration to the city and also an eventual decline of about 47 percent in the fertility rate.

Considering that Tehran currently absorbs about

Table 5.5

COMPOSITION OF THE POPULATION IN 1956 AND 1966

	1956		1966	
	Population (thousand)	Distribution (per cent)	Population (thousand)	Distribution (per cent)
Tehran	1,561	8.02360	2,980	11.55710
Nine large cities	1,682	8.64560	2,530	9.81190
22 small cities	673	3.45930	975	3.78130
Other cities	2,065	10.61420	3,323	12.88730
All urban areas	5,981	30.74270	9,808	38.03760
Rural areas	13,474	69.25730	15,977	61.96240
Total population	19,455	100.0	25,785	100.0

Table 5.6

Total Population Projection and Share of Tehran on the Basis of Past Trends

Year	Total Population	% share of Urban areas	Urban Area	% share of Tehran from Total	Tehran Population
1970	28,861	40.948	11,818	12.965	3.743
71	29,686	41.677	12,372	13.318	3.953
72	30,534	42.406	12,948	13.671	4.174
73	31,406	43.142	13,549	14.024	4.404
74	32,303	43.864	14,169	14.377	4.643
75	33,226	44.593	14,816	14.730	4.894
76	34,175	45.322	15,488	15.083	5.154
77	35,152	46.051	16,187	15.436	5.425
78	36,156	46.780	16,913	15.789	5.708
79	37,189	47.509	17,668	16.142	6.003
80	38,252	48.238	18,451	16.495	6.309
81	39,344	48.968	19,265	16.848	6.628
82	40,468	49.697	20,111	17.201	6.960
83	41,625	50.426	20,989	17.554	7.306
84	42,814	51.155	21,901	17.907	7.666
85	44,037	51.884	22,407	18.260	7.885
86	45,295	52.613	23,831	18.613	8.430
87	46,589	53.342	24,851	18.966	8.835
88	47,920	54.071	25,910	19.319	9.257
89	49,289	54.800	27,010	19.672	9.695
90	50,697	55.599	28,151	20.025	10.151

Table 5.7

TRWB Forecast of Tehran Population

Year	Population	Rate of Growth
74	4,200	3.83
75	4,340	3.33
76	4,530	4.19
77	4,620	1.99
78	4,700	1.73
79	4,780	1.67
80	4,870	1.88
81	4,950	1.67
82	5,000	1.01
83	5,060	1.20
84	5,120	1.19
85	5,170	0.97
86	5,230	1.16
87	5,280	0.96
88	5,340	1.12
89	5,390	0.94
90	5,440	0.93
91	5,500	1.10

60 percent of total immigrants, it would be very dubious indeed to envisage a sudden stoppage of migration of peopole to the city.

Tehran, as the biggest and most important industrial and commercial centre in the country, does in fact provide the best employment opportunities in the country. At present about 70 percent of industries are either in or around the city. In addition the centralization of public and government services in Tehran aggravate the problem. In 1956, 23 percent of total government employees were working in the city while this figure was 37.7 percent in 1967. Considering that the population of Tehran counts for 11 percent of total, clearly the concentration of government employees in Tehran is twice as much as it should be. Another reason for the concentration of population in Tehran is the availability of social as well as cultural facilities. For example, more than 70 percent of university students are in Tehran. These are only a few examples of a number of reasons for the presence of such a high rate of population growth in Tehran. According to these arguments, the probability that the population of the city would grow as low as the rate suggested by the Board is very remote.

However the objectives of government policies regarding the control of population in Tehran is considered, we can strongly envisage a decline in the growth of population in the city. The policies are:

1. Decentralization of government as well as the public services. This is done through the delegation of more responsibilities to the local government offices. It is planned to reduce the number of this category of employees in Tehran by half.
2. The low of prevention of the establishment of new industries in the first 120 km radius of the city of Tehran.
3. Promotion of mass media such as a national television network, establishment of more local universities and technical colleges etc.

For these and other reasons such as the policy for a more equitable distribution of income, provision of cheap housing facilities in other parts of the country, it is likely that the rate of growth of population in Tehran would decline and reach a rate which would be in line with that of other major cities.

In this respect Statistical Bureau (1973) produced three national population projections for the year 1991. Each projection is based on a set of hypotheses and contains the overall population of the country as well as the breakdown of rural and urban population. Taking the projected rate of population growth for the major cities, the population of Tehran under three alternative hypotheses is presented in the following Table 5.8.

Table 5.8

Population Projection Based on Different Rate of Growth

Year	Population in 10^6	Rate of Growth	Population in 10^6	Rate of Growth	Population in 10^6	Rate of Growth
1974	4,593	4.3	4,588	4.2	4,597	4.8
75	4,790	"	4,781	"	4,800	"
76	4,996	4.2	4,982	4.1	5,011	3.8
77	5,206	"	5,186	"	5,200	"
78	5,424	"	5,399	"	5,399	"
79	5,652	"	5,620	"	5,604	"
80	5,884	"	5,851	"	5,816	"
81	6,137	4.1	6,091	3.9	6,037	3.2
82	6,388	"	6,328	"	6,231	"
83	6,650	"	6,575	"	6,430	"
84	6,923	"	6,832	"	6,636	"
85	7,207	"	7,098	"	6,840	"
86	7,502	4.0	7,375	"	7,067	2.5
87	7,802	"	7,640	3.6	7,244	"
88	8,114	"	7,915	"	7,425	"
89	8,438	"	8,200	"	7,611	"
90	8,776	"	8,496	"	7,801	"
91	9,127	"	8,800	"	7,996	"

Considering the growing awareness of the Government with regard to matters concerning the control of population growth, the third alternative, i.e. a population of just under 8 millions which is more in line with that of the Plan Organisation's Projection (App. 5.4) is considered in our projection equation.

5.7.2 Per Capita Income

The projection of per capita income here is based on the work published by The Plan Organisation under "The Prospects of the next twenty years of Iran's Economy and the Future of Oil". In this report, four different projections of per capita income, among others, on the basis of different sets of assumptions are made (Table 5.9).

The report investigates the possible effects of the alternative economic policies on the economy of the country and comes up with the fourth possibility. This alternative has been favoured, the report states, because;

- the pattern of growth is more stable
- the balance of payment problem is less serious
- the inflationary effect is less problemsome
- the capital stock is higher
- the investment policy provides a saving for the future generation.

Accordingly, the fourth alternative is adopted in our projection model.

Table 5.9

Per Capita Income Projection

Year	Per Capita Income	Rate of Growth	Per Capita Income	Rate of Growth	Per Capita Income	Rate of Growth	Per Capita Income	Rate of Growth
1974	31,626	15.96	31,626	15.96	31,626	15.96	33,356	12.2
75	36,674	"	36,674	"	36,674	"	40,794	"
76	42,527	"	42,527	"	42,527	"	49,891	"
77	46,414	9.14	46,414	9.14	47,009	10.54	61,017	"
78	50,657	"	50,657	"	51,964	"	64,294	10.5
79	55,287	"	55,287	"	57,441	"	67,747	"
80	60,340	"	60,340	"	63,495	"	71,385	"
81	65,855	"	65,855	"	70,187	"	75,218	"
82	70,557	7.14	69,088	4.91	76,455	8.93	79,258	"
83	75,594	"	72,480	"	83,283	"	83,839	10.6
84	80,992	"	76,039	"	90,720	"	88,685	"
85	86,775	"	79,773	"	98,821	"	93,811	"
86	92,970	"	83,689	"	107,646	"	99,233	"
87	99,794	7.34	88,870	6.19	115,493	7.29	104,969	"
88	107,119	"	94,371	"	123,913	"	104,970	
89	114,982	"	100,212	"	132,946	"	110,061	
90	123,422	"	106,416	"	142,638	"	115,399	
91	132,481	"	113,003	"	153,036	"	120,996	

5.7.3 Number of Connections

TRWB projection of number of connections is based on an overall population of 5.5 million by 1991 (Table 5.6). On the basis of this assumption, the Board plans to increase the number of connections to a total of 678,000 by 1991.

In another report, the Plan Organisation assumes a population of 7.5 million for 1991 (Appendix 5.4) and further assumes that almost the entire city from 1980 onwards will receive water through direct connection. According to the same report, in 1972 for a total population of 4.5 million (including 600,000 outside the city limit) there were just over 450,000 direct connections. The ratio of population to the number of connections in that year is 9.56 persons per connection. Based on the TRWB statistic, the same ratio for 1991 will be 8. Assuming that the current ratio would eventually reach a figure of 8 by 1991, as proposed by the Board, the number of connections based on the forecast of population is presented in Table 5.10

5.7.4 Number of Dwellings

The projected number of dwellings here is based on the long-run housing objective of the government. The objective as it is stated in the outline of the Fifth Economic Development Plan is to reduce the density of 8.7 percent per dwelling to 7.7 by the end of the plan in 1977.

From 1978 onwards it is postulated that the rate of housing density would decline by about 0.24-0.26 percent annually. Accordingly in 1990-91 the density would reach a figure of 5 which will be equivalent to

Table 5.10

Projection of Number of Connections

Year	TRWB Plan based on a 5.5 million population	Based on the average population growth
1974	500	508
75	520	537
76	535	574
77	550	600
78	560	600
79	570	637
80	579	668
81	588	709
82	597	739
83	606	791
84	615	804
85	624	829
86	633	874
87	642	896
88	651	918
89	660	941
90	669	965
91	678	989

Table 5.10

Projection of Number of Dwellings

Year	1	2	3	4	5	6
	GNP at 1972 Prices (Rls 10^9)	GNP allocated to building industry	Share of Tehran from (2)	Number of dwellings built in Tehran	Accumulated number of dwellings	Density Rate
1974	1847.05	139.31	35.19	20837	520837	8.83
75	2325.43	175.39	55.77	33023	553860	8.67
76	2926.72	221.30	70.37	41668	595528	8.41
77	3686.00	278.84	88.67	52503	648031	8.02
78	3997.10	199.86	63.56	37634	685665	7.87
79	4334.46	216.72	68.92	40807	726472	7.71
80	4700.44	235.02	74.74	44252	770724	7.55
81	5097.16	254.86	81.05	47988	818712	7.37
82	5527.36	276.37	87.89	52037	870749	7.16
83	6014.32	300.72	95.63	56619	927368	6.93
84	6544.18	327.21	104.05	61604	988972	6.71
85	7120.72	356.04	113.22	67033	1056005	6.48
86	7748.06	387.40	123.19	72935.85	1128940	6.26
87	8430.66	421.53	134.05	79365.62	1208305	6.00
88	9041.88	452.09	143.76	85114.52	1293419	5.74
89	9697.42	484.87	154.19	91289.70	1384708	5.50
90	10400.48	520.02	165.37	97320.28	1482628	5.26
91	11154.50	557.73	177.36	105019.90	1587647	5.04

the assumed average size of a family.

On the basis of this assumption, forecast of number of dwellings as a function of GNP is presented in Table 5.11.

5.8 Projected Demands as a Function of Price

Assuming that the projected values of the explanatory variables derived in the preceding section will hold their values in future, and assuming further that the behaviour of the estimated demand function will remain unchanged over the projected horizon, a set of projected demand function for water as a function of price can be obtained by substituting the projected values of the explanatory variables in the estimated demand function. These projected demand functions for the period of 1976-1991 are presented in Table 5.12.

Based on these functions, Tehran Regional Water Board can decide on an appropriate price (water rate) in order to match the demand with the available supplies.

We should, however, be aware of the fact that the required increases in the water rate may fall outside the range of the water rates which were observed in the estimation of the demand function. In these higher price ranges the demand schedule may behave differently. In other words, the demand at these high price ranges may not be linear. In this situation, the price elasticity might well change and, as a result, the responsiveness of consumer to changes in price may

Table 5.12

Projected Demand Function for Water in Tehran (1976-91)

Projected Demand Function

$$W_{dt}^{\dagger} = \alpha^{*} - \beta^{**} P$$

$W_{d1976} = 474.623 - 14389.34P$

$W_{d1977} = 537.579 - 14389.34P$

$W_{d1978} = 563.431 - 14389.34P$

$W_{d1979} = 596.235 - 14389.34P$

$W_{d1980} = 629.791 - 14389.34P$

$W_{d1981} = 666.590 - 14389.34P$

$W_{d1982} = 702.743 - 14389.34P$

$W_{d1983} = 742.396 - 14389.34P$

$W_{d1984} = 784.457 - 14389.34P$

$W_{d1985} = 827.527 - 14389.34P$

$W_{d1986} = 876.544 - 14389.34P$

$W_{d1987} = 923.481 - 14389.34P$

$W_{d1988} = 949.522 - 14389.34P$

$W_{d1989} = 996.866 - 14389.34P$

$W_{d1990} = 1046.832 - 14389.34P$

$W_{d1991} = 1099.432 - 14389.34P$

- * 1000 cu.m.

** Rls/cu.m.

† To obtain the value of W_d the derived value should be multiplied by 1000.

be different.

However, in the absence of any empirical evidence to the contrary, it is fair to assume that the function remains linear beyond the ranges which were observed in our study.

5.9 Summary and Conclusion

In this Chapter attempts were made to develop a demand function for urban water in Greater Tehran Area. To this end, the concept of 'demand' and 'requirement' with regard to the management of urban water supply were discussed. Considerations were then given to the components of demand and it was found that residential component account for a major proportion of total consumption in Tehran. In the next section, the technique of principal component analysis and multiple regression analysis were employed to identify a functional relationship between the consumption of water in the city and a set of explanatory variables. The result of the econometric study established that price, along with other explanatory variables influence water consumption. After forecasting values of the explanatory variables and substituting them in the estimated demand function, a set of projected demands as a function of price for the next 15 years were made.

The implications of the results in terms of management of urban water supply are quite significant. For an effective planning and development of water resources, the water authority must identify major factors which influence the consumption of water. They must dislodge themselves from the conventional 'requirement' approach and instead they must replace demand management through the instrument of pricing policy if efficient investment and management of water supplies is to be forthcoming. This should not, however, be interpreted as meaning that there is no longer need for concern about the task of supplying water. Undoubtedly engineering work must continue. What in fact we are saying is that pricing policy is a powerful tool that is available to the policy makers. Pricing policy, combined with supply management, provides planners with the means to ensure a more efficient utilization of the scarce resource and further a more equitable distribution of the cost incurred in providingwater services.

A task of the next Chapter is to incorporate the projected demand functions in an optimization model in order to obtain a socially optimum distribution of available water resources between the city and the agricultural regions. As a by-product, the optimum water rates will also be generated.

CHAPTER 6

ALLOCATION OF WATER FOR URBAN AND RURAL USE

MODEL II

6.1 Introduction

Although the deterministic approach to the optimisation problem presented in Chapter 4 was quite appropriate as a means of testing the economic efficiency of the current allocation policy, in reality the reservoirs are operating in a stochastic environment where the flow of water is subject to uncertainty. For this reason, the average release employed in Model 1, although rational as an approximation, cannot produce a reliable operating solution to the problem.

The point of departure in this Chapter is therefore to develop a mathematical programming model which permits an explicit consideration of the stochastic nature of water flows. In addition the model disregards the current priority of urban use and instead introduces the demand for urban water as a function of price in order to allocate the available supply among the competing users according to their marginal opportunity costs.

6.2 Sources of Water

The main water resources which are considered in this Chapter are Karaj, Latiyan and Lar. Since descriptions of the first two systems have already been given in Chapters 3 and 4, in this Chapter we therefore describe only the Lar Dam and its downstream irrigation network.

6.3 The Lar Dam and Mazandran Irrigation Region

6.3.1 Background

The broad aims of the River Lar project are to increase the supply of water to the city of Tehran and to provide assured supplies of water for irrigation in Mazandran. The possibility of transferring water from the River Lar to Tehran was first conceived by the Government in early 1900. However, lack of finance and technical know-how postponed the implementation of the project until late 50's when growing demand for water in Tehran necessitated the construction of an embankment on the Lar River and conveyance of some of the stored water to Tehran.

Following international tendering, contracts were awarded in 1974 for the construction of Lar Dam, the Lar Diversion work for the diversion of water to the Latiyan Dam and the Mazandran Irrigation Works to transfer water between the River Haraz, Babol and Talar (see Map 6.1). These works are scheduled for completion in 1980.

6.3.2 Surface Water

6.3.2(i) The Lar River

The Lar River is the major and by far the most reliable source of surface water in the Mazandran basin. It derives its discharge in the form of melted snow from the Alborze Mountains. This particular hydrological characteristic of the stream flow provides a useful forecast of water supply, since farmers in the basin of this river can observe the snow on the mountain peaks and judge the flow of water during the irrigation period. Nevertheless, years of serious crop failure do occur.

Downstream of the Lar River at the Lar Gorge (Map 6 .1), Lar Dam with a gross capacity of 960 m.cu.m. and a live storage volume of 860 m.cu.m. is under construction. The dam, which will be completed by 1980, will regulate the flow of the Lar. In doing so it will provide a regular supply of water to the Mazandran irrigation network and through a diversion tunnel system transfer Lar water to Latiyan (Farahnaz Pahlavi) reservoir for onward conveyance to Tehran. The conveyance tunnel is in two sections each with a tunnel terminating in a hydro-electric power station. The mean seasonal discharge of the Lar River along with those of Karaj and Jajerud Rivers for a period of up to 13 years and the technical characteristics of the three dam systems considered here are respectively presented in Appendices 6.1 and 6.2

6.3.2 (ii) The Babol and Talar Rivers

In addition to the Lar, the plain receives water from Babol and Talar Rivers. However, the flow of water from these two rivers is dependent on rainfall rather than melted snow. Consequently, the streamflows are not as reliable as that of the Lar. In fact the discharges of Babol and Talar reach their peak during the spring when there is a shortage in the Lar. For this reason in Mazandran, a series of weirs and canals will link the Lar, Babol and Talar Rivers, the interconnection between the three rivers would enable the transfer of surplus Talar and Babol water to the downstream of Lar irrigation network.

Average monthly discharge of these rivers during the six months of irrigation season are presented in Appendix 6.3.

6.3.3 Groundwater

Groundwater is extracted in three different ways in the region; first, the natural spring and ghanat systems with a total discharge of over 400 m.cu.m. Obviously, since the discharge of these sources cannot be controlled, under half of the overall inflow is used for irrigation purposes. Second, is a series of artesian aquifers which are tapped by deep wells (70-170 m. deep). Due to lack of control, currently over half of the total discharge is spilled to the sea. Finally, there are a substantial number of shallow wells in the plain with a total discharge of 145 m.cu.m. Presented in Appendix 6.3 are the quantities of water from the above sources which are available for agricultural use during an average irrigation year.

6.3.4 Irrigation in Mazandran

The study area in Mazandran is bounded by the Caspian Sea in the North and the foothills of the Alborz Mountains in the South. It covers a gross area of 2310 square km. between the Alesh Rud and the Siah Rud.

The texture of soil in the plain varies from loams and silt loams in the higher ground with silty clay loams and silty clay on the lower land. These soils are well suited for rice cultivation. Cultivation of rice is in fact the predominant crop in the project area, about 58% of the total cultivated area, and has been practiced for many centuries. Due to the humid nature of the climate in the region irrigation is almost exclusively directed to rice. Other crops such as cotton, wheat, etc. though grown, are usually rainfed.

There are a number of varieties of rice grown in the region. However, based on the period of maturation, they are divided into long and short varieties. Although the long variety produces higher yield, it is more vulnerable to water shortages which usually occur during the late season. Furthermore, since the harvesting time of the two varieties do not coincide, farmers can spread their labour. For these reasons, the land is uaually divided in roughly equal proportions between the long and short varieties.

6.4 Application of Stochastic Programming in the Field of Management of Water Resources

Consideration of the stochastic nature of streamflow has long been a preoccupation in the optimisation models dealing with design and operation of reservoirs. Broadly speaking, allowance for uncertainty in the field of reservoir management can be made either indirectly through what Roefs (1969) calls "simulation-deterministic optimisation-regression approach" or, directly, through stochastic optimisation techniques. In the former case, a number of stream flows are (depending on the desired degree of statistical confidence) simulated first, the results of simulations are then individually optimised. The outcome of the optimisation models are then treated as data in a regression analysis which produces functional relationship between optimum release policies and stream flows (Roefs 1968, Chap. 3). In the latter case, on the contrary, no repetitive simulation is involved and a more exact solution to a problem is obtained through an explicit representation of probabilistic nature of stream flow in an optimisation model.

Application of direct stochastic optimisation models to multiple reservoir systems could be accomplished either by linear programming under uncertainty (Dantzig 1963) or Chance Constrained programming (Charnes and Cooper 1963). Practical applications of the former technique in many cases is limited due to the sheer size of the problem. For instance, for a two linked reservoir system each with 20 different probabilities of stream flow and 10 levels of storage for a 4 season model, the number of rows is:

$$20 \times 20 \times 10 \times 10 \times 4 = 160,000.$$

This is computationally infeasible on available Linear Programming packages. Another practical difficulty of linear programming under uncertainty of a water resource system is the calculation of a loss function for violated constraints (Mass et al 1963, pp.524-538).

An alternative to linear programming under uncertainty which could be extended to a multi reservoir problem is chance-constrained linear programming. The essence of this approach is that it allows for violation of constraints a certain percentage of the time. In other words, it does not require that constraints should always hold but one will be satisfied if they hold in a certain proportion of time. The technique as will be shown in the course of the development of the model, permits for the transformation of a stochastic constraint into an equivalent deterministic statement.

Chance constrained programming was originally developed by Charnes and Cooper in 1963. Six years later Revelle et al (1969) introduced the technique to the field of reservoir management and ever since it has occupied a dominant position in the relevant literature. Revelle et al (1969) first applied the technique to the design and operation of a single reservoir system. Joeres et al (1971) found an optimum operating rule for a system of two reservoirs in conjunction with a firming supply from a Susquehanna pipeline for the Baltimore water supply in the U.S. Nayak and Arora (1971) extended Revelle's model to a four reservoir system in the Minnesota River Basin. Eisel (1972, a,b) used the same technique but with a non-linear operating rule for a single purpose, one season reservoir to determine the capacity of an irrigation reservoir and in a separate investigation to determine the optimum management of a hypothetical wild land basin.

In this connection we could also mention other related works by Revelle and Kirby (1970), Eastman and Revelle (1973), Nayak and Arora (1974), Gundelach and Revelle (1975) and Loucks and Dorfman (1975) who have extended and refined the linear chance constrained approach to a variety of reservoir management problems.

However, in spite of extensive research in the application of linear chance constrained models, the majority of studies have been preoccupied with the problem of minimisation of reservoir capacity. No attempts have been made to extend the technique to the maximisation of the benefits of inter-regional allocation and use of water when the capacity of reservoirs is given.

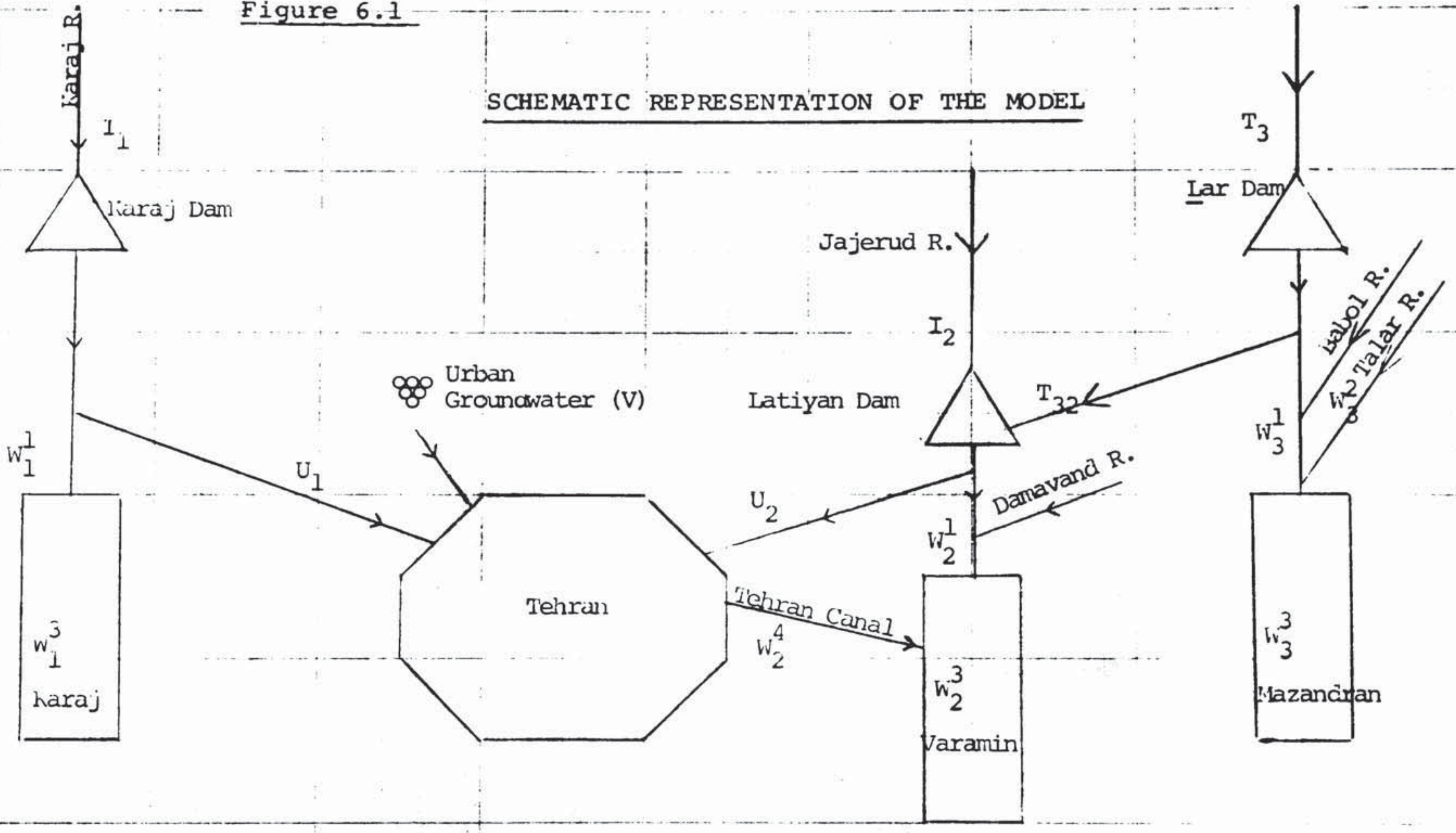
Our model therefore extends the state of the art in this field by considering a complex inter-regional as well as intra-regional allocation and use of water for a system of reservoirs and local groundwater resources with the objective of maximising consumers' plus producers' surplus in the urban area and crops revenue in the irrigation regions.

6.5 Model Formulation - A Chance Constrained Approach

Fig. 6.1 illustrates all the water resource systems considered in this Chapter. According to this Figure, there are three reservoirs namely Karaj (k=1), Latiyan (k=2) and Lar (k=3), controlling respectively the random flows I_k of Karaj, Jajerud and Lar Rivers. Water released from each reservoir R_k can either be used in the downstream irrigation region W_k^1 namely Karaj (k=1), Varamin (k=2) and Mazandran (k=3) or transferred to the city for urban consumption U_k (for k=1,2). In the case of Lar, however, direct conveyance of water to Tehran is not possible but it could be done indirectly through transferring water T_{32} to Latiyan. In addition to the flow of water from the reservoirs, there is the flow W_k^2 of uncontrolled rivers which are available to Varamin W_2^2 and Mazandran W_3^2 irrigation regions. The third source

Figure 6.1

SCHEMATIC REPRESENTATION OF THE MODEL



of water is groundwater W_k^3 and V_u (for agricultural and urban use) which could be locally pumped and used. A certain amount of the water consumed in the city can be reclaimed and transferred to Varamin W_2^4 for irrigation purposes.

The problem can now be formally stated as finding an optimum operating policy for the water resources of the systems, some with probabilistic behaviour, which maximises consumers' plus producer's surplus in the urban area and crops revenue in the agricultural regions.

The mathematical representation of the system could well be partitioned into two parts: constraints with stochastic elements and those which are assumed to be completely deterministic.

6.5.1 Stochastic Constraints

Constraints with random variables, in our model, are those which limit the permissible range of reservoirs storage volume and others which link the releases from reservoirs to the point of use. Formally they are:

(a) $S_{kj} \leq S_{k\,\max}$ $\qquad k=1,\ldots,3$; $j=1,\ldots,4$

(b) $S_{kj} \geq S_{k\,\min}$

(c) $R_{kj} \geq U_{kj} + W_{kj}^1 + T_{kj}$ $\qquad k=1,\ldots,3$; $j=1,\ldots,4$; $U=0$ for $k=3$; $T=0$ for $k=1,2$

Constraints (a) and (b) limit the content of reservoir k in season j to prespecified levels defined by the upper (max) and lower (min) bounds on the capacity of each reservoir. Constraint (c) requires that water released from reservoir k during season j for urban U, rural W^1 and inter-basin transfer T purposes should not exceed the optimum volume of release R determined by the model.

Constraints (a)-(c) in their present form do not permit for an explicit consideration of the stochastic nature of S and R. In reality, the content of a reservoir or the release are influenced by the randomness of the natural streamflows and, as a result, we cannot be assured that release will always exceed the demand or that the content of a reservoir falls within the capacity limits.

This difficulty can however be overcome by restructuring the model within the framework of a chance constrained programme which limits the violation of the constraints to a prespecified probability (Pro). Formally they can be stated as follows:

a' $\quad \text{Pro}\left[S_{kj} \leq S_{k\,\max}\right] \geq \alpha_1$

b' $\quad \text{Pro}\left[S_{kj} \geq S_{k\,\min}\right] \geq \alpha_2$

c' $\quad \text{Pro}\left[R_{kj} \geq U_{kj} + W^1_{kj} + T_{kj}\right] \geq \alpha_3$

Constraints a' and b' specify that the content of reservoir k at the end of period j should be within the upper and lower capacity limit respectively at α_1 and α_2 percent of the time. Constraint c' requires that urban, rural and transfer supplies should be within the volume of release with the probability of at least α_3.

Although we have so far taken a step forward and have limited the possibility for violation of constraints to a prespecified percent of the time, our ignorance about the probability distributions of S and R would stop us from finding a deterministic equivalent for the constraints.

This difficulty can be removed by replacing S and R by a function of the streamflow variable whose distributions are known. For this reason we impose the following linear decision rule for the operation of reservoirs:

$$R_{kj} = S_{kj-1} - b_{kj} \qquad (1)$$

where R and S are as defined before and b is an unknown deterministic variable which can be positive or negative. According to this rule, release during each period is a function of the stock of water at the beginning of the period and a decision variable.

Substituting the release rule into the following equation of continuity (2) which links the state of each reservoir from one season to the next

$$S_{kj} = S_{kj-1} + I_{kj} - R_{kj} \qquad (2)$$

yields

$$S_{kj} = I_{kj} + b_{kj} \qquad (3)$$

Substituting a similar equation for S_{kj-1} into the release rule (1) we obtain:

$$R_{kj} = I_{kj-1} + b_{kj-1} - b_{kj} \qquad (4)$$

The substitution of (3) into the reservoir capacity constraints a' and b' and (4) into the release requirement c' yields

a'' $\quad \text{Pro}\left[I_{kj} + b_{kj} \geq S_{k\ min}\right] \geq \alpha_1$

b'' $\quad \text{Pro}\left[I_{kj} + b_{kj} \leq S_{k\ max}\right] \geq \alpha_2$

c'' $\quad \text{Pro}\left[U_{kj} + W_{kj} + T_{kj} - b_{kj-1} + b_{kj} \leq I_{kj-1}\right] \geq \alpha_3$

Note that the only random variable in a'' - c'' is the streamflow I_{kj} which has a known probability distribution. Knowledge of the distribution of this random variable would enable us to convert these constraints into legitimate linear programming constraints.

A simulation study of Jajerud streamflow by FAO shows that the inflow in this water-shed is normally distributed. Distributions of Karaj and Lar streamflows have also shown similar properties. The reduction of a'' - c'' on the basis of this fact, to deterministic equivalents, therefore can be performed as follows.

Let the cumulative distribution for the inflow into reservoir k during the jth season be given by:

$$\text{Pro}\left[I_{kj} \leq i_{kj}\right] = 1 - F_{I_{kj}}(i_{kj}) \qquad (5)$$

where i_{kj} is a known quantity, I_{kj} is the random natural inflow into reservoir k during season j and $F_{I_{kj}}(i_{kj})$

is the cumulative probability distribution function of streamflows for the same reservoir and the same season (Mood and Graybill, 1963, pp.85-87).

Using (5), we can reduce a'' - c'' to

a''' $F_{I_{kj}} (S_{k\ min} - b_{kj}) \leq 1 - \alpha_1$

b''' $F_{I_{kj}} (S_{k\ max} - b_{kj}) \geq \alpha_2$

c''' $F_{I_{kj}} (U_{kj} + W_{kj} + T_{kj} - b_{kj-1} + b_{kj}) \geq 1 - \alpha_3$

By reference to the cumulative distribution function for the random inflow I_{kj} equation a''' - c''' can also be stated as follows:

$$S_{k\ min} - b_{kj} \leq F^{-1}_{I_{kj}} (1 - \alpha_1)$$

$$S_{k\ max} - b_{kj} \geq F^{-1}_{I_{kj}} (\alpha_2)$$

$$U_{kj} + W_{kj} + T_{kj} - b_{kj-1} + b_{kj} \leq F^{-1}_{I_{kj}} (1 - \alpha_3)$$

where $F^{-1}_{I_{kj}}$ is the inverse of the distribution function whose value can be obtained. Thus the probabilistic constraints a'' - c'' are replaced by the equivalent deterministic constraints a''' - c''' (Vajda,1972, Chap. III, Hillier and Lieberman,1969,ppp.536-542).

Considering a reliability level of 90 percent for α_1, α_2, α_3 we could write (5) as

$$F^{-1}_{I_{kj}} (1 - \alpha) = F^{-1}_{I_{kj}} (0.10) = i_{kj}^{0.10}$$

$$F^{-1}_{I_{kj}} (\alpha) = F^{-1}_{I_{kj}} (0.90) = i_{kj}^{0.90}$$

where $i_{kj}^{0.10}$ is the value of streamflow in region k during season j that is exceeded 90 percent of the time;

$i_{kj}^{0.90}$ is the value of streamflow in region k during season j which is exceeded only 10 percent of the time.

The deterministic equivalent could alternatively then be written

$$S_{k\,min} - b_{kj} \leq i_{kj}^{0.10}$$

$$S_{k\,max} - b_{kj} \geq i_{kj}^{0.90}$$

$$U_{kj} + W_{kj} + T_{kj} - b_{kj-1} + b_{kj} \leq i_{kj}^{0.10}$$

6.5.2 Deterministic Constraints

The rest of the constraints in our model are either deterministic in fact or are assumed to be deterministic. This is a limitation of the model, particularly with regard to the flow of Babol and Talar. However, considering the magnitude and importance of these two rivers in Mazandran, in relation to the available water in the entire system, their stochastic nature could only have a minor effect on the irrigation of paddies. The amount of water in the aquifer is also random. In practice, however, the stochastic rate of recharge does not have an immediate effect on the extraction rate in a basin where pumping is restricted by the safe yield of aquifer. Lowering of water table in one year, as a result of inadequate recharge, can be replenished in subsequent years without influencing the pumping rate by any considerable amount.

The deterministic constraint c'' can now be linked to the urban demand and irrigation requirement constraints.

6.5.2 (i) Urban Demand

$$q_j = \sum_{k=1}^{2} U_{kj} + V_j \qquad j=1,\dots,4$$

The optimum quantity of water determined by the model for urban consumption in each season q_j should be met by reservoirs 1 and 2, U_{kj}, and the urban groundwater resources V_j.

6.5.2 (ii) Irrigation Requirement

$$\sum_{i=1}^{I_k} a_{ikj}\, x_{ik} \le \sum_{h=1}^{4} (1-f_k^h)\, w_{kj}^h \qquad \begin{array}{l} j=1,\dots,4 \\ k=1,\dots,3 \end{array}$$

$$\text{for} \begin{cases} k=1, & I=13 \\ k=2, & I=12 \\ k=3, & I=5 \end{cases}$$

The net sum of water from source h, reaching irrigation region k, during season j, should be sufficient to meet the water requirements a_{ikj} of crop i grown in region k during season j. In this constraint f_k^h represents the proportion of water from source h which is lost to seepage and evaporation during conveyance in region k.

Unlike the constraint on the urban demand an inequality sign has been assigned to this constraint in order to allow for the possibility of spillage in cases where excess water is available.

6.5.2 (iii) Tributary flows

$$w_{kj}^2 \le \bar{w}_{kj}^2 \qquad \begin{array}{l} k=2,3 \\ j=1,\dots,4 \end{array}$$

The flow of the Babol and Talar Rivers in Mazandran and the Damavand River (discussed in Chapter 3) in Varamin are not controlled by the reservoirs. Consequently, their flows are treated separately in the model. The flow of the Babol and Talar, in addition to the supply of water from artesian and natural springs in the Mazandran Plain, are aggregated and represented as a single source in the model.

The flow of water from these sources is stochastic in nature but for reasons already discussed and also due to lack of any detailed information about their distributions they are taken as deterministic. The upper bounds in the respective constraints represent the mean quarterly flows.

6.5.2 (iv) Groundwater supply

a) Agricultural Regions

$$W_{kj}^{3} \leq \bar{W}_{kj}^{3} \qquad k=1,\ldots,3 \quad j=1,\ldots,4$$

$$\sum_{j=1}^{4} W_{kj}^{3} \leq \bar{W}_{k}^{3} \qquad k=1,\ldots,3$$

b) Urban Area

$$V_j \leq \bar{V}_j \qquad j=1,\ldots,4$$

$$\sum_{j=1}^{4} V_j \leq \bar{V}$$

The description of these sets of constraints is given in Chapter 4. The first sets of constraints in both agricultural and urban areas represent the quarterly pumping capacity of wells and the second sets represent the annual safe yield of aquifers. In the case of Mazandran Plain, however, information with regard to the number and types of wells is not available. Consequently, there is only one constraint for the extraction of groundwater in this region which represents the quarterly quotas for the pumping of aquifer.

6.5.2 (v) Tehran-Varamin Canal

$$W_j^4 \leq \bar{W}_j^4 \qquad j=1,\ldots,4$$

$$\sum_{j=1}^{4} W_j^4 \leq \bar{W}^4$$

These two sets of constraints represent the capacity of the Tehran-Varamin Canal (about 12 litres per second) and the annual available water which it is potentially possible to pump and treat in the Southern part of Tehran and convey by gravity to Varamin.

6.5.2 (vi) Capacity of Lar-Latiyan Canal

$$T_j \leq \bar{T} \qquad j=1,\ldots,4$$

This constraint limits the maximum volume of water which is potentially possible to transfer from the Lar reservoir to the Latiyan reservoir during any season. This amounts to 145.856 m.cu.m.

6.5.2 (vii) Crop Limitation

For reasons discussed in Chapters 3 and 4 an upper bound is imposed on the acreages of the following crops.

$$\sum_{k=1}^{2} X_{ik} \leq \bar{X}_i \qquad i=4,\ 8,\ 9$$

$$X_{ik} \leq \bar{X}_{ik} \qquad \text{for} \begin{cases} k=1 & i=7,\ 11,\ 13 \\ k=2 & i=7,\ 10 \\ k=3 & i=3 \end{cases}$$

6.5.3 Objective Function

The criterion for the model is the maximisation of consumers' plus producer's surplus in the urban area and crops' revenue net of irrigation costs in the irrigation regions. Formally, the objective function is as follows:

$$\sum_{j=1}^{4} \left(\int_{o}^{q_j} \acute{f}_j(Q_j)\, d\,Q_j \right) + \sum_{i=1}^{I_k} \sum_{k=1}^{3} r_{ik} X_{ik} - \sum_{j=1}^{4} \left\{ \left(\sum_{k=1}^{2} c_k U_{jk} + c\, V_j \right) + \sum_{h=1}^{H_k} \sum_{k=1}^{3} c_k^h W_{jk}^h \right\}$$

where

$\acute{f}_j(Q_j)$	is the inverse of seasonal urban demand function
r_{ik}	is the revenue generated from the cultivation of one hectare of crop i in region k
c_k	is the cost of one cu.m. of water reaches the urban area from region k
c	is the cost of one cu.m. of urban groundwater
c_k^h	is the cost of one cu.m. of irrigation water from source h in region k.

Urban demand as a function of price is considered in the objective function in order to determine the optimum urban-rural allocation on the basis of the marginal opportunity cost of water rather than administrative "requirement" approach which was dealt with in Chapter 4. In other words, in this model the available water is allocated between urban and rural consumers in such a way that the marginal value of water in the optimum solution for both uses is the same.

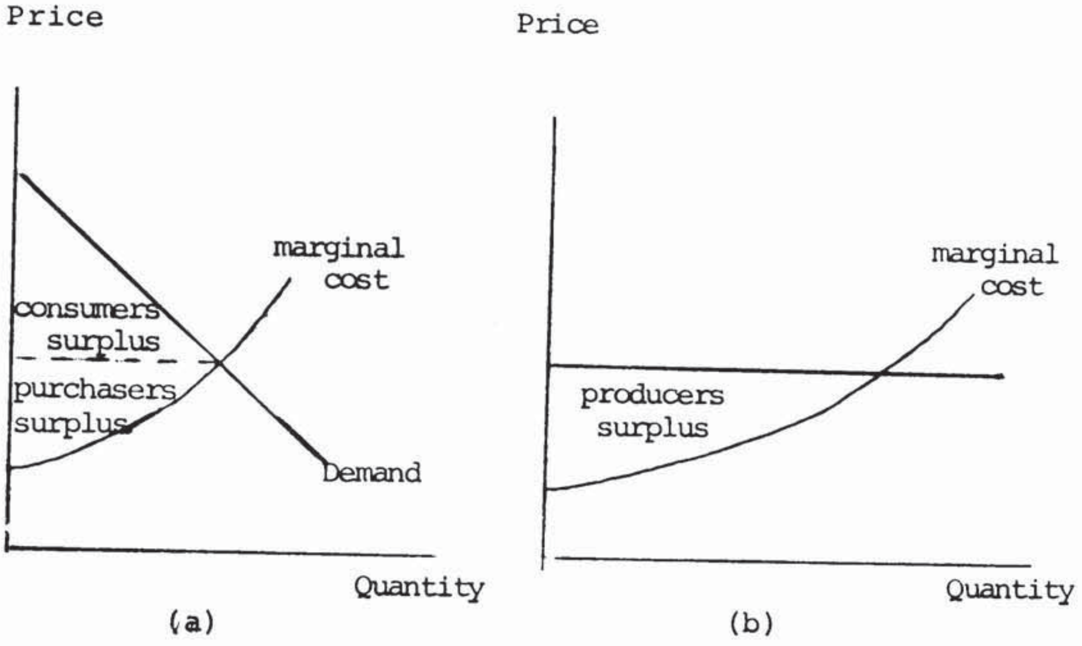
It is important to note that though the urban demand functions do not appear in the constraints of this model, the optimal price and quantity obtained will nevertheless satisfy the demand functions. The reason is as follows: The shadow price corresponding to the constraint (6.5.2(i)) i.e., seasonal demand = seasonal supply can be interpreted as the benefit to be obtained from meeting one more unit of demand without having to increase the supply . But this marginal benefit is simply equivalent to the marginal price that urban consumers are willing to pay for an additional unit of water. This fact is implicit in the objective function, since the marginal benefit from an additional unit of consumption is

$$d\left(\int_0^{q_j} f_j(Q_j)\,dQ_j \right)/dq_j = f_j(q_j) = P_j$$

It follows immediately that if we substitute the optimal quantity q_j given in the solution to the model, back into the demand function, then the price we obtain is also the shadow price on the urban supply equals demand constraints - and vice versa. In other words the optimal price and quantity satisfy the demand function.

Ideally we should have had demands as a function of price for all the agricultural activities in the objective function. However, considering that the market price for major crops such as cereal, grain, cotton, sugarbeet etc. is determined nationally, rather than at local level, the demand for these crops is perfectly elastic. Under these circumstances, the consumer surplus, that is the area under the demand curve, above the price level, as the following figure (b) shows, is zero. Consequently, the crops' net revenue which is considered in the objective function is equivalent to the remainder of the area under the demand curve i.e. the producers surplus.

Fig. 6.2 Representation of Consumers and Producers Surplus



(a) (b)

Formulation of the model in this manner enables us to refrain from allocating supplies on the basis of a requirement approach which tries to meet the requirements irrespective of the value of water in alternative use. The appropriateness of the higher priority of use which is assigned to the urban beneficiaries under the 'Nationalisation of Water Resources Act' (see Chapter 2) can thus be reappraised.

The application of Marshallian concepts of consumers and producers surplus to the optimum allocation and pricing of water resources is used by authors including

Flinn and Guise (1970) who employ the concept to generate a pricing policy for a multi-purpose reservoir system serving a hypothetical urban, industrial and irrigation region; Mobasheri and Grant (1973) also consider a similar objective function in a temporal study of conjunctive operation of a surface and groundwater system serving a residential water region; Crew and Roberts (1970) have also a similar objective function in a model of seasonal pricing and investment policy for a water supply system.

6.6 Seasonal Urban Demand Schedules

The seasonal urban demand schedules are derived by weighting the annual demand function, estimated in the previous Chapter, by the proportion of seasonal consumption during 1969-73. The average seasonal proportion of demand according to Fig. 5.5 of Chapter 5 is approximately as follows

Season	1	2	3	4
Proportion of Consumption	26.12	19.84	22.22	31.82

Formally, the seasonal demand functions are

$$f_j\ (p_j) = d_j f(p)$$

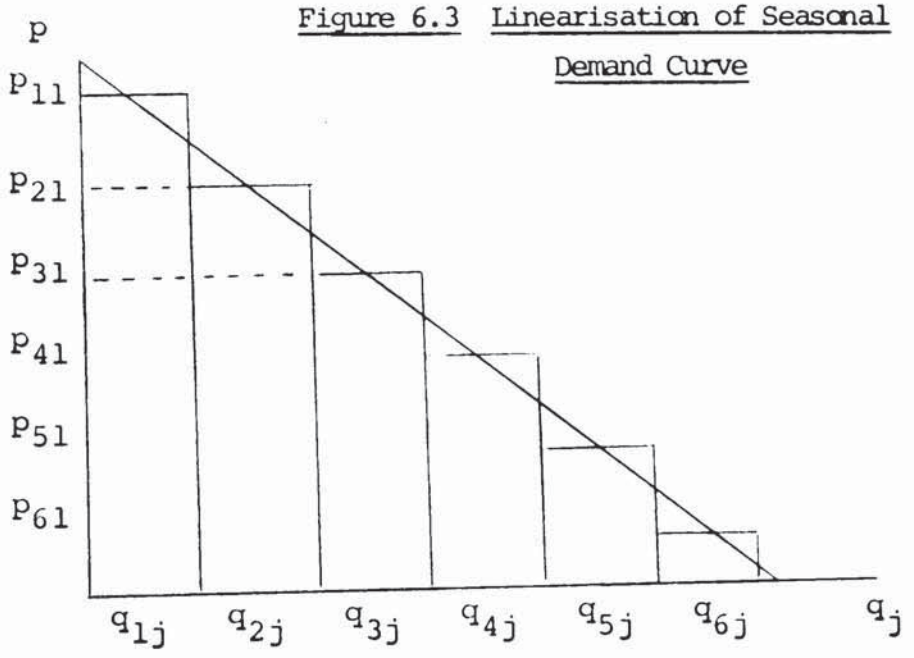
where f(p) represents the estimated annual demand, $f_j(p_j)$ seasonal demand and d_j is the proportion of water consumed during season j.

The value of the intercept of the linear seasonal demand functions obtained from the projected annual demand function (see Chapter 5) for the period 1975-85 is given in Table 6.1.

6.7 Linearisation of the Seasonal Urban Demand Schedules

The seasonal demand schedules, when integrated, produce quadratic functions. In order to avoid the problem of non-linearity and be able to use the available linear programming package (ICL 1900 LPMK 3) the urban seasonal demand schedules are linearised. In this connection, the seasonal demand functions are replaced by a step function of 6 steps as shown in the following figure.

Figure 6.3 Linearisation of Seasonal Demand Curve



For any volume of water demanded between

$$\sum_{i=1}^{I-1} \bar{q}_{ij} \quad \text{and} \quad \sum_{i=1}^{I} \bar{q}_{ij} \qquad I=6$$

TABLE 6.1

PROJECTED SEASONAL DEMAND FOR URBAN WATER AT ZERO PRICE $(d_j b = u_j)$

(m.cu.m)

Quarter / Year	1	11	111	1V
1974	97.767	74.261	83.163	117.510
1975	109.608	83.255	93.242	133.527
1976	123.970	94.164	105.460	151.023
1977	140.414	106.655	119.449	171.056
1978	147.167	111.764	125.194	179.283
1979	155.735	118.292	132.482	189.721
1980	164.501	124.950	139.939	200.399
1981	174.112	132.251	148.115	212.108
1982	183.555	139.342	156.148	223.611
1983	193.912	147.290	164.959	236.229
1984	204.898	155.635	174.305	249.612
1985	216.149	164.181	183.876	263.318

consumers are represented as being willing to pay a price p_{ij} and we define a set of variables q_{ij} ($i=1,\ldots,6$ and $j=1,\ldots,4$) such that $0 \leq q_{ij} \leq \bar{q}_{ij}$ for all i and j and no member of the set can take a positive value unless all preceding members are at their upper bounds, i.e.

$$\text{if } q_{ij} > 0 \text{ then } q_{(i-1)j} = \bar{q}_{(i-1)j}$$

then demand for season j is given by

$$q_j = \sum_{i=1}^{6} q_{ij} \qquad j=1,\ldots,4$$

and the consumer surplus, i.e. the area under the step function, is given by;

$$\Sigma_i \, p_{ij} \, q_{ij} = \int_0^{q_j} \acute{f}_j(Q_j) \; dq_j \qquad j=1,\ldots,4$$

In order to obtain p_{ij}, i.e. the height of step i in season j, take the annual demand function for urban water to be $Q = b - ap$ where a and b are constants

hence $q_j = d_j(b - ap_j)$ $\qquad j=1,\ldots,4$

Let f_i be the width of step i as a fraction of $d_j b$, the intercept on the q_j axis, so that

$$\sum_{i=1}^{I} f_i = 1$$

and $$\bar{q}_{ij} = f_i(d_j b) \qquad \begin{array}{l} i=1,\ldots,6 \\ j=1,\ldots,4 \end{array}$$

The mid point of step i in season j is thus

$$\left(\sum_{n=1}^{i} f_n \, d_j b\right) - (\tfrac{1}{2}) f_i \, d_j b \qquad \begin{array}{l} i=1,\ldots,6 \\ j=1,\ldots,4 \end{array}$$

and the height p_{ij} of step i for season j can be obtained by substituting the above mid point into the demand function thus

$$\left(\sum_{n=1}^{i} f_n d_j b\right) - (\tfrac{1}{2}) f_i d_j b = d_j b - d_j a p_{ij}$$

therefore

$$p_{ij} = \left(d_j b + (\tfrac{1}{2}) f_i d_j b - \sum_{n=1}^{i} f_n d_j b\right) / d_j a$$

The d_j all cancel out, giving,

$$p_{ij} = ({}^{b}/_{a})\ (1 + {}^{f_i}/_{2} - \sum_{n=1}^{i} f_n) \qquad \begin{array}{l} j=1,\ldots,4 \\ i=1,\ldots,6 \end{array}$$

Since d_j has disappeared from the right-hand side of the equation, therefore the height of step i is identical for all four seasons j.

Following this procedure, the height of step i for i=1,...,6 for 10 levels of projected demand are presented in Table 6.2.

6.8 Assumptions underlying the Model

The chance constrained model of this Chapter is based on a number of assumptions in addition to those considered in Chapters 3 and 4. First, the model is conditional in the sense that, at any given time period j, all the constraints with stochastic elements in the previous j-1 periods are assumed to be satisfied. This assumption is essential, since otherwise a failure at any time period j may disrupt the operation of the system in subsequent time periods. To elaborate, if for instance the streamflow during period j, instead of falling in the assumed α percentile region of the distribution

TABLE 6.2

LINEARISATION OF SEASONAL DEMAND SCHEDULES

(HEIGHT OF STEPS)

(Rls/cu.m)

Year	Step (p_i)					
	1	11	111	1V	V	V1
1974	23.84	19.51	15.17	10.84	6.50	2.17
1975	26.73	21.88	17.01	12.15	7.29	2.43
1976	30.23	24.74	19.25	13.75	8.25	2.75
1977	34.24	28.02	21.79	15.57	9.34	3.12
1978	35.69	29.37	22.84	16.32	9.79	3.27
1979	37.98	31.08	24.17	17.27	10.36	3.46
1980	40.11	32.82	25.52	18.24	10.94	3.65
1981	42.46	34.75	27.02	19.31	11.58	3.86
1982	44.76	36.63	28.49	20.36	12.21	4.07
1983	47.28	38.69	30.06	21.50	12.90	4.30
1984	49.96	40.89	31.79	22.72	13.36	4.54
1985	52.70	43.13	33.53	23.96	14.37	4.79

function, falls in the (1-α)percentile region, the constraints with this random variable could be violated. As a result, the demand in the urban area or crops' water requirement could not be met.

Second, farmers and other beneficiaries can plan better and act more efficiently when they are assured of a supply of water with a high probability of incidence than a release which is based on average streamflow and is therefore subject to high fluctuations. Third, the economic and political loss resulting from the more frequent failure which is likely under the average release policy in meeting the urban-rural demand outweighs the monetary loss which may result from the less than average, but more secure, availability of water under the new system.

6.9 Discussion of the Model Result*

The chance constrained milti-reservoir model which is developed in this Chapter is run under two states of water supplies. The first run optimises the allocation and use of Karaj and Latiyan water supplies, while the second run extends the sphere of water resources and integrates the Lar Dam with its associated downstream irrigation region to the existing systems.

6.9.1 Operating Rules

The solution to each run of the model generates a set of optimum operating rules for each reservoir. The derived operating rules are presented in Table 6.3. By following these rules, the system can meet the optimum level of urban demand and irrigation requirements with

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* Data used in this model are listed in Appendices to Chapters 4 and 6.

TABLE 6.3

RELEASE RULE FOR THE OPTIMUM OPERATION OF RESERVOIRS

(m.cu.m.)

1976-80		1980-85		
Karaj	Latiyan	Karaj	Latiyan	Lar
$R_{11} = S_{14}$	$R_{21} = S_{24}$	$R_{11} = S_{14}$	$R_{21} = S_{24}$	$R_{31} = S_{34} - 60.99$
$R_{12} = S_{11} - 40.69$	$R_{22} = S_{21} + 22.06$	$R_{12} = S_{11} + 40.69$	$R_{22} = S_{21} + 22.38$	$R_{32} = S_{31} - 72.64$
$R_{13} = S_{12} + 60.01$	$R_{23} = S_{22} + 122.67$	$R_{13} = S_{12} + 8.42$	$R_{23} = S_{22} + 122.27$	$R_{33} = S_{32} - 100.00$
$R_{14} = S_{13} + 106.45$	$R_{24} = S_{23} + 8.25$	$R_{14} = S_{13} + 10.64$	$R_{24} = S_{23} + 60.23$	$R_{34} = S_{33} + 6.98$

a probability of 90 percent. This is in fact the principle advantage of the model which comes to grips directly with the impossibility of ensuring a specific performance from a system which is fed by random streamflows. Unlike the constant average release policy of Chapter 4 which arbitrarily provides assurance with regard to the future flow of water, without due consideration to the stochastic nature of streamflow, the optimum release policies of this model give no absolute guarantees about the exact magnitude of future release. It only attaches a statement of reliability to the future commitments within a given probability of occurrence. Under this system, the degree of uncertainty, which the beneficiaries under the average release policies are faced with, is substantially reduced. Farmers who are given an undertaking, under the average release policy, with regard to a safe supply of water, would not turn up to the water authority complaining about the insufficient supplies as they quite often do at present. Instead they could plant their crops knowing in advance that their requirements would be satisfied not always but at a prespecified percentage of the time.

6.9.2 Effects of Growth of Urban Demand on the Distribution of Water

To investigate the effects on the optimal distribution of water resulting from increase in the level of urban demand, two runs of parametric programming each containing five levels of projected demand functions are carried out. The first run considers the effect of quarterly growth of urban demand (1976-80) on the allocation and distribution of existing sources of supplies, i.e. Karaj and Latiyan. While the second run analyses the effects of projected demand during 1980-85 on the allocation and distribution of water commencing on the completion of the construction of the Lar Dam and Mazandran Irrigation Network. Fig. 6.4 presents the contribution of different sources of supplies to the optimum level of demand in the urban area. According to this figure the contribution of the reservoirs to the urban area during the first five years of analyses have not proportionally increased. The flow of water from Karaj to the urban area has mainly been increased during the fourth quarter, while the entire extra urban demand during the third season has been satisfied by the Latiyan reservoir. In order to meet the extra demand during the first two quarters, when the contribution of the reservoirs have almost remained unchanged, the extraction of urban groundwater during the fourth quarter has continuously declined so that the extra pumping could take place during the first and second seasons. It should, however, be noted that the annual pumping capacity of urban groundwater has been increased by 20 m.cu.m. during the second year of observation. This increase can be seen from comparing the general shift in the pumping of the first and second years of observation.

In the second five years of analyses (1980-85), which coincide with the commencement of Lar Dam and Mazandran Irrigation Network, the contribution and distribution of water, as a result of extra availability of water through inter-basin transfer of water from Lar to Latiyan, has changed. Karaj, which was supplying the

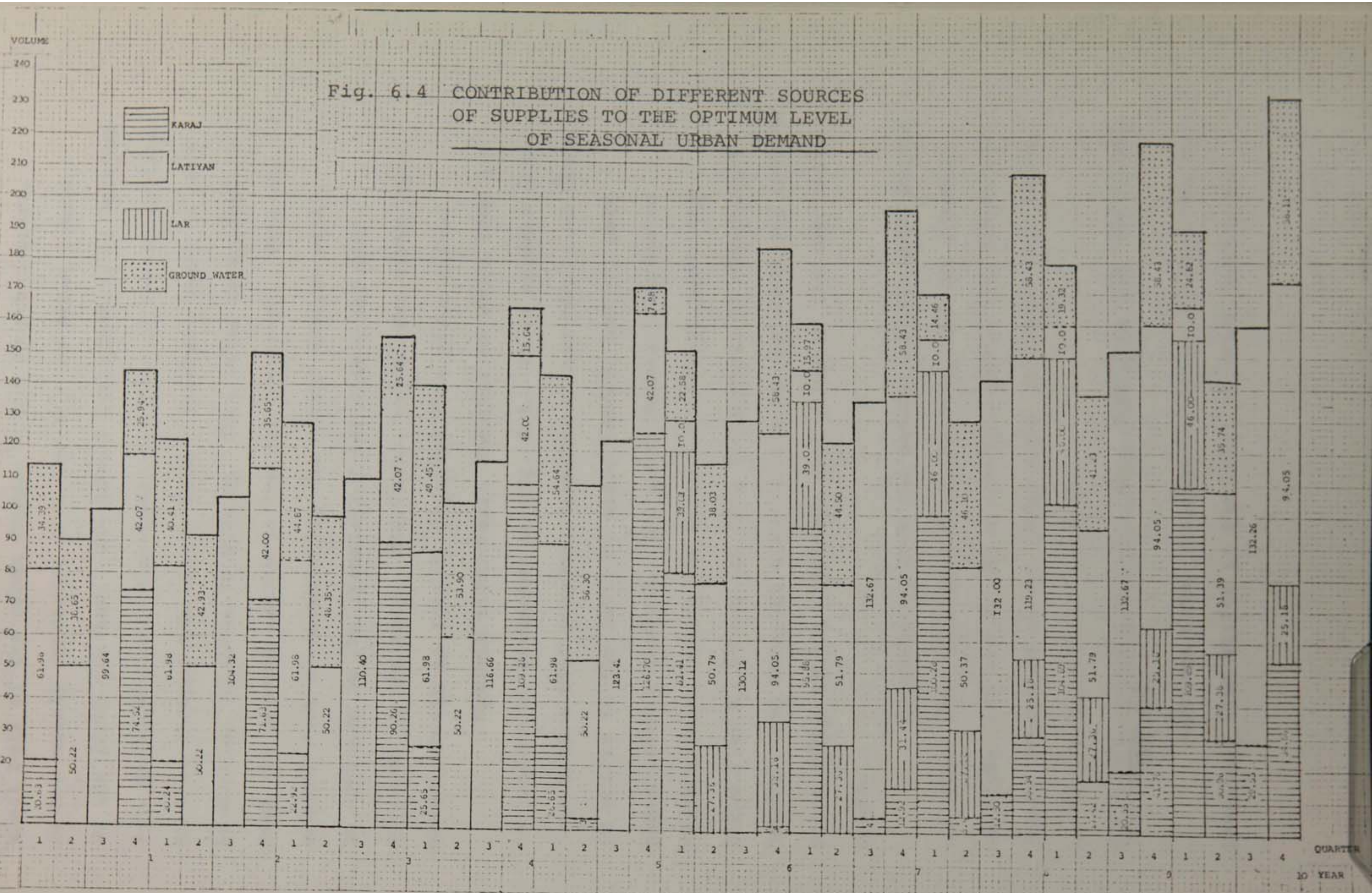


Fig. 6.4 CONTRIBUTION OF DIFFERENT SOURCES OF SUPPLIES TO THE OPTIMUM LEVEL OF SEASONAL URBAN DEMAND

great bulk of the urban demand in the fourth quarter, is now mainly concerned with meeting the urban demand in the first quarter. The direct contribution of Latiyan, i.e. excluding the inter-basin transfer of Lar to Latiyan, in this quarter has shrunk from a constant level of over 61 m.cu.m. to about 10 m.cu.m. This water is shifted to meet the growing demand in the third quarter. From the seventh year of observation the entire Latiyan water, in addition to the transferred Lar water, has been directed to the city. Therefore, beyond the sixth year, Varamin Plain is totally deprived from river water.

Optimim inter-basin transfer of water from Lar to Latiyan is presented in Fig. 6.5. It is evident from this Figure that seasonal transfer of Lar water, in spite of shifts in the level of urban demand, has not been significantly changed. The total annual transfer is 97.82 m.cu.m. during the sixth and seventh years and 98.50 m.cu.m. during the last three years of observation. However, the seasonal distribution in the sixth and seventh years are a little different from those of the last three years.

Considering that the entire Latiyan water beyond the sixth year is directed to the city, and the transfer of water from Lar is at a constant level, the additional growth of demand in the urban area, as Figure 6.4 shows, is met by the Karaj reservoir.

6.9.3 Effects of Growth of Urban Demand on the Irrigation Regions

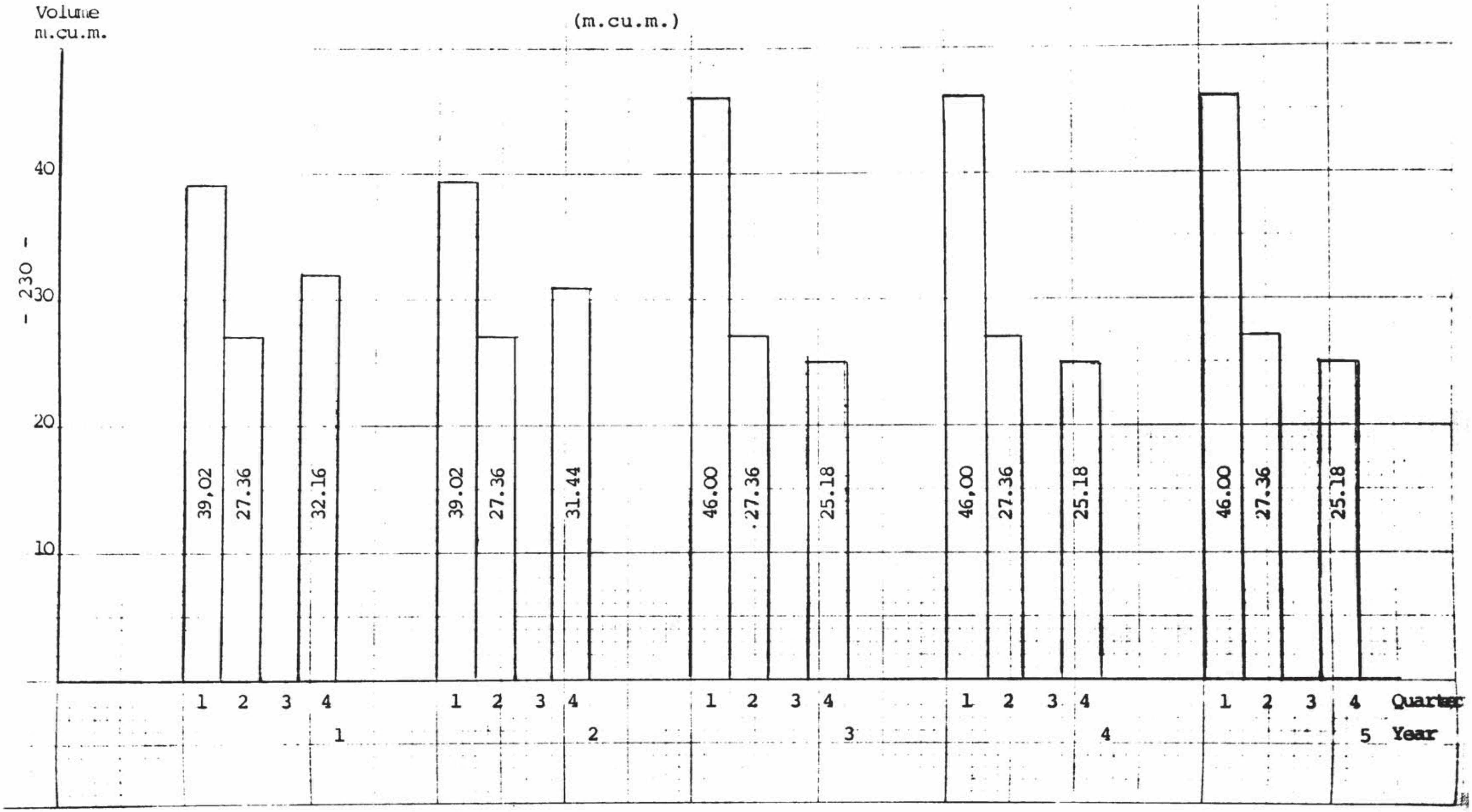
Optimum total irrigated acreages in each region resulting from shifts in the level of urban demand are

Figure 6.5

OPTIMUM INTER-BASIN TRANSFER OF WATER

LAR TO LATIYAN

(m.cu.m.)



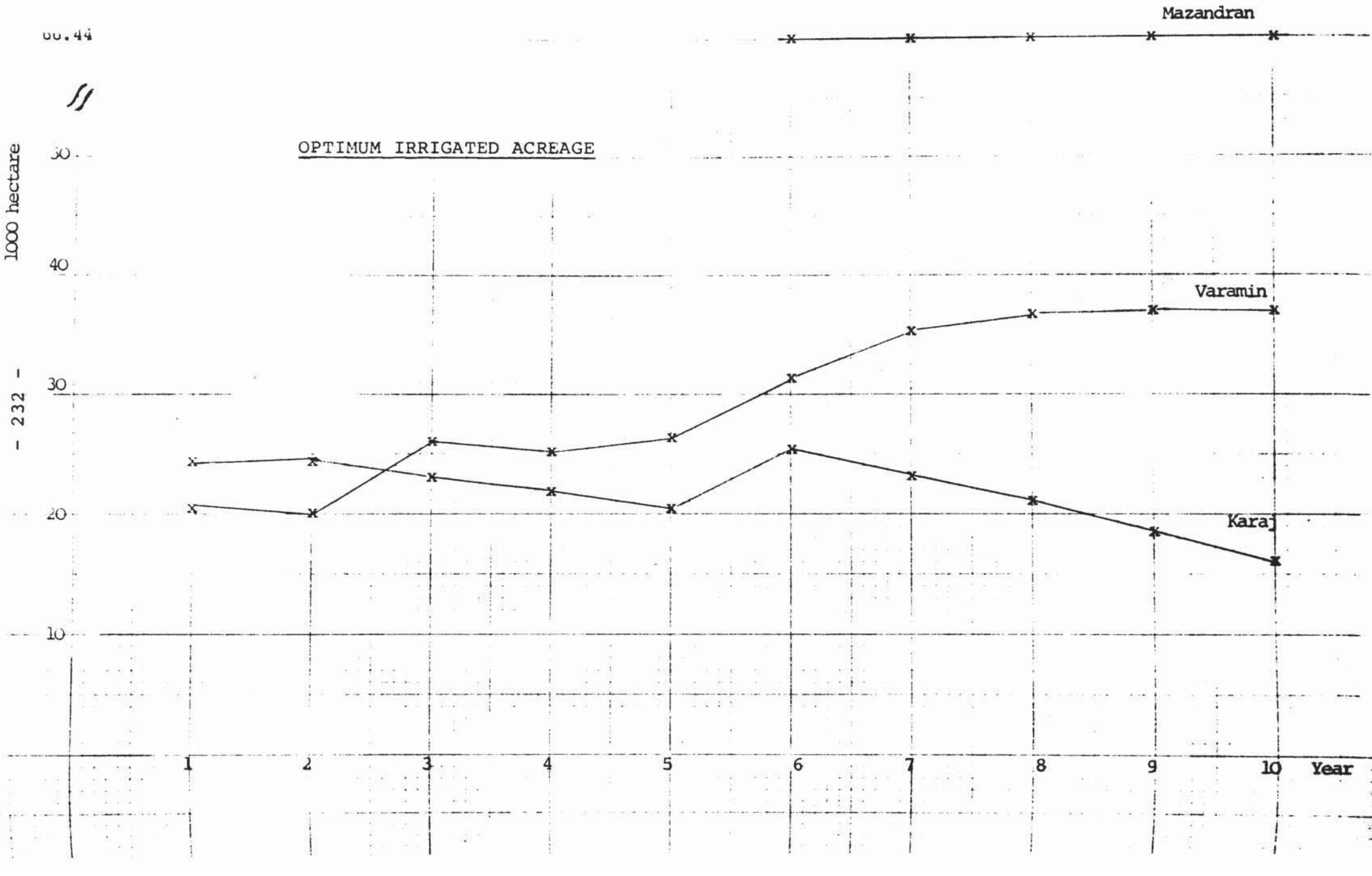
presented in Fig. 6.6. Acording to this figure total acreage during the first five years of observation in Karaj has declined from about 25,000 ha to just over 20,000. In the sixth year when the flow of Lar reaches Latiyan, and as a result there is more water available to be sent to the city, the flow of water to the Karaj irrigation region according to Table 6.4 increases from 171 to 230 m.cu.m. As a result, the acreage under irrigation in this region moves up to over 25,000 ha. However, from the sixth year onwards, as we saw earlier, the extra demand in the urban area has to be met from the Karaj reservoir. The result is a continuous decline in the acreage of irrigated crop land in this region so that by the final year of observation, the available surface and local groundwater is only able to irrigate a total area of about 16,000 ha.

In the Varamin region, most of the irrigation has been carried by the local groundwater in the first five years of observation. The increase in irrigated acreage in the third year has been caused by increase in the pumping of aquifer (Table 6.5). In the second five years, the Tehran Canal gradually comes into the opration and as a result, the irrigated acreage increases in as much as by the tenth year it reaches a level of 37000 hectare.

In the Mazandran region, as the straight line in Figure 6.6 shows, irrigated acreage remains at a constant level of about 66,500 ha.

The actual effects of different levels of irrigation water availability on the cropping mix

Figure 6.6



OPTIMUM IRRIGATED ACREAGE

TABLE 6.4

OPTIMUM CONTRIBUTION OF RESERVOIRS TO THE AGRICULTURAL REGIONS (m.cu.m.)

		Year									
Region	Season	1	2	3	4	5	6	7	8	9	10
Karaj to Karaj	1	9.65	9.96	7.87	5.73	3.39	37.03	34.04	30.60	27.07	23.09
	2	-	-	-	-	-	-	-	-	-	-
	3	106.30	107.13	100.82	94.38	87.31	65.99	56.96	46.61	36.00	24.03
	4	104.93	106.34	98.12	89.70	80.47	127.29	115.48	101.90	87.90	72.26
Total		220.88	223.43	206.81	189.81	171.17	230.31	206.48	178.11	151.06	119.38
Latiyan to Varamin	1	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-
	3	26.51	22.68	17.82	12.85	7.40	20.45	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-
Total		26.51	22.68	17.82	12.85	7.40	20.45	-	-	-	-
Lar to Mazandran	1						-	-	-	-	-
	3						-	-	-	-	-
	4						155.82	155.82	155.82	155.82	155.82
Total							155.82	155.82	155.82	155.82	155.82

TABLE 6.5

OPTIMUM SEASONAL EXTRACTION OF GROUNDWATER IN THE AGRICULTURAL REGION

(m.cu.m.)

		Year									
Region	Season	1	2	3	4	5	6	7	8	9	10
Karaj	1	26.26	26.26	26.26	26.26	26.26	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	43.42	43.42	43.42	43.42	43.42
	4	43.89	43.89	43.89	43.89	43.89	26.73	26.73	26.73	26.73	26.73
Total		70.16	70.16	70.16	70.16	70.16	70.16	70.16	70.16	70.16	70.16
Varamin	1	18.08	16.42	27.92	25.81	28.07	23.56	25.77	24.28	19.61	14.03
	2	-	-	-	-	-	-	-	-	-	-
	3	24.53	26.18	51.59	53.70	64.43	73.95	75.73	78.23	73.85	68.38
	4	88.38	88.38	110.48	110.48	110.48	110.48	110.48	110.48	121.52	132.57
Total		131.00	131.00	190.00	190.00	203.00	208.00	212.00	213.00	215.00	215.00
Mazandran	1						1.91	1.91	1.99	1.99	1.99
	3						48.32	48.32	48.32	48.32	48.32
	4						72.48	72.48	72.48	72.48	72.48
Total							122.71	122.71	122.71	122.71	122.71

presented in Table 6.6. It is evident from this Table that the only crops whose acreage has been adversely affected are cotton in Karaj and wheat in Varamin.

6.9.4 Effect of Reliability Levels on the Value of the Objective Function

Figs. 6.6 and 6.7 present the results of parametric programming analyses of the effect of changes in the level of reliability level (α)* on the value of the objective functions. Increasing the level of certainty for meeting the stochastic constraints, from 4 out of 5 times to 19 out of 20 times, would reduce the value of the objective function by 0.18 billion rials for the first run (Karaj and Latiyan) and 0.32 billion rials under the second run (Karaj, Latiyan and Lar). The reduction in the value of the objective function is solely attributable to the reduction in the acreage of crop lands. In other words, this implies that urban beneficiaries value water to such an extent that their demand should be met prior to making any commitments to the rural beneficiaries. This benefit reduction does, however, ignore the economic benefits to farmers resulting from a more reliable supply of irrigation water. Irrigation authorities must work out costs of probable failure of the systems in meeting the requirements and decide whether benefits from increased reliability outweight the costs.

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* See App. 6.10 for the values of streamflows at different level of reliabilities.

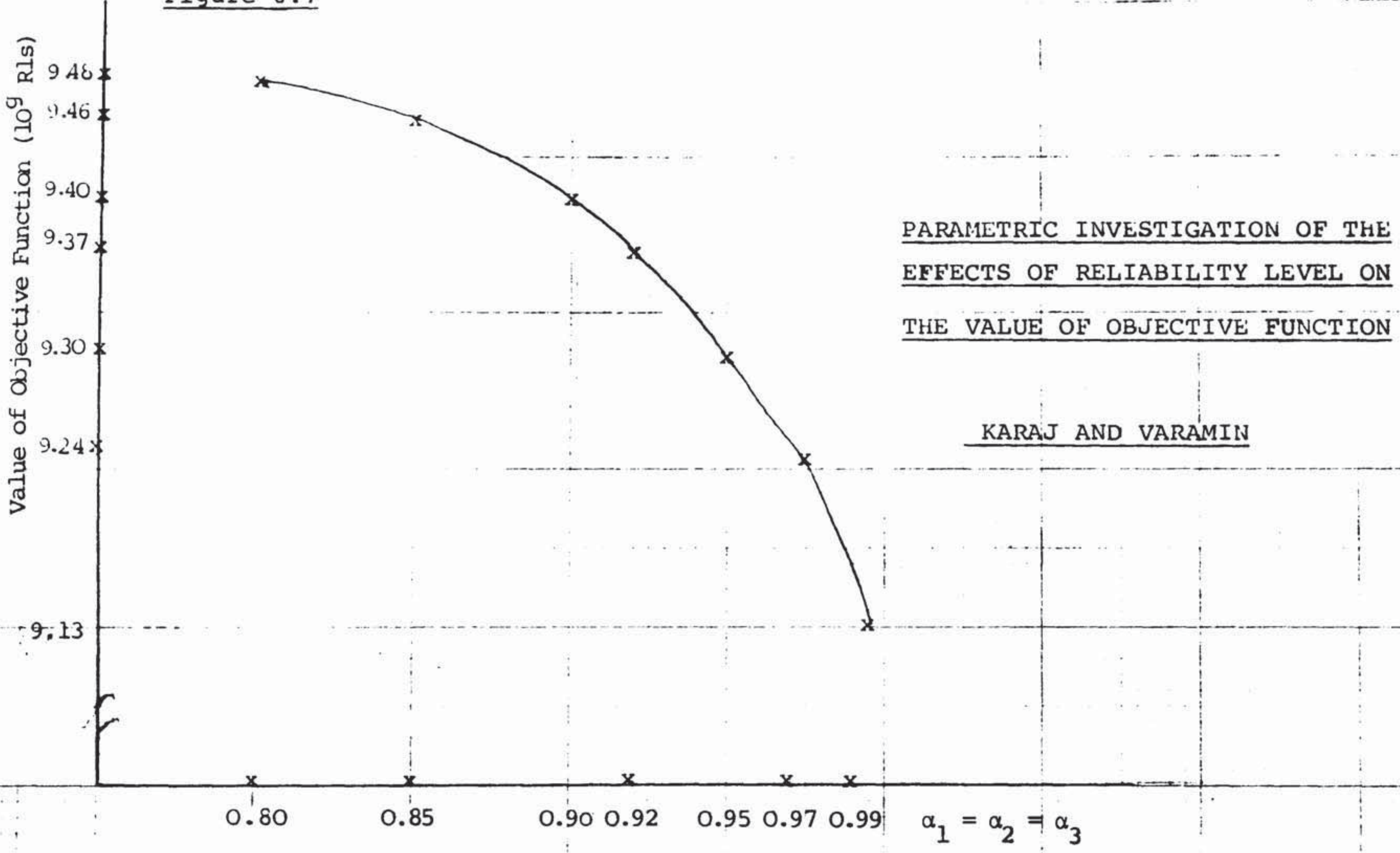
TABLE 6.6

OPTIMUM CROPPING PATTERN

(hectare)

		Year									
Crop	Variable	1	2	3	4	5	6	7	8	9	10
Karaj											
Cotton	x_{13}	21307	21392	19932	18439	16809	21665	19585	17214	14786	12054
Orchard	x_{17}	2000	2105	2160	2216	2273	2332	2392	2454	2518	2584
Water Melon	x_{111}	870	890	910	930	950	970	1000	1030	1060	1090
Potatoes	x_{113}	480	490	500	510	520	530	540	550	560	570
Total		24657	24677	23502	22095	20552	25487	23517	21248	18924	16298
Varamin											
Wheat	x_{21}	4767	3842	7436	6276	7813	10779	14017	15255	12636	9733
Cotton	x_{23}	1934	1843	3899	3840	3348	4749	4640	4934	7194	9589
Melon	x_{24}	6640	6810	6990	7170	7360	7550	7750	7950	8160	8370
Orchard	x_{27}	1500	1579	1620	1662	1705	1746	1791	1838	1886	1935
Tomato	x_{28}	2750	2790	2860	2930	3010	3090	3170	3250	3330	3420
Spring Cucumber	x_{29}	1850	1900	1950	2000	2050	2100	2150	2210	2270	2330
Autumn Cucumber	x_{210}	1320	1350	1390	1430	1470	1510	1550	1590	1630	1670
Total		20761	20114	26145	25308	26756	31524	35068	37027	37106	37047
Mazandran											
Rice	x_{32}						43000	43000	43000	43000	43000
	x_{33}						19551	19551	19551	19551	19551
	x_{34}						3896	3896	3896	3896	3896
							66447	66447	66447	66447	66447

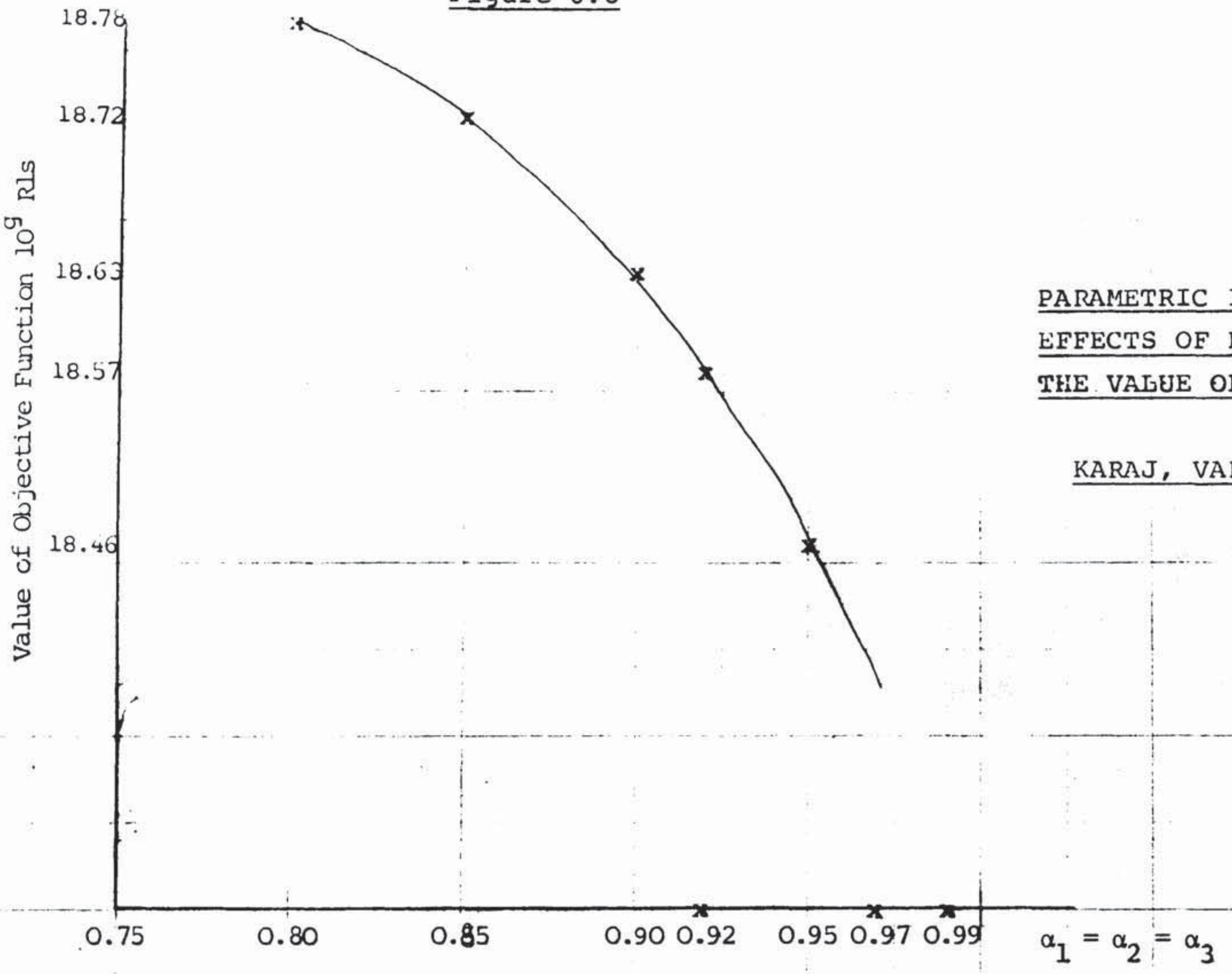
Figure 6.7



PARAMETRIC INVESTIGATION OF THE EFFECTS OF RELIABILITY LEVEL ON THE VALUE OF OBJECTIVE FUNCTION

KARAJ AND VARAMIN

Figure 6.8



PARAMETRIC INVESTIGATION OF THE EFFECTS OF RELIABILITY LEVEL ON THE VALUE OF THE OBJECTIVE FUNCTION.

KARAJ, VARAMIN, MAZANDRAN

6.9.5 Analysis of the Duals

The shadow prices corresponding to the constraints on the flow of water, upper bound on the seasonal urban demand, seasonal irrigation requirements, groundwater and tributary flows are presented in the following Table.

Considering that the cost of storage from one season to the next is assumed to be zero, the model has equalised the marginal values of water among all seasons by saving water in periods of high inflow for those periods when the demands are high and inflow is relatively low. However, in the case of Latiyan, the shadow price during the third quarter, as a result of high inflows is lower than for other periods. The constraint corresponding to the upper bound on the storage capacity of this reservoir is tight in this period. The value of shadow price corresponding to this constraint is 0.94 Rls/cu.m. which is just equal to the difference between the marginal value of water in this and other quarters.

Considering that the reservoirs are linked to each other, the marginal values of water for all reservoirs should be the same. This is in fact what the analysis of the duals shows. The apparent differences are, however, caused by the difference in the marginal cost of water. For instance, once the marginal conveyance cost of water from Lar to Latiyan (0.47 Rls/cu.m.) is added to the shadow price of water from the Lar reservoir, we get a value of 3.09 which is equal to the marginal value of

DUAL SOLUTION

(Shadow Prices)
Rs/cu.m.

	Season				Annual
	I	II	III	IV	
Water in the Reservoir					
Karaj	3.07	3.07	3.07	3.07	
Latiyan	3.09	3.09	2.15	3.09	
Lar	2.62	2.62	2.69	2.62	
Urban Demand	8.64	8.64	8.64	8.64	
Irrigation Requirements					
Karaj	4.07	0.00	4.07	4.07	
Varamin	2.87	0.00	2.87	3.78	
Mazandran	0.12	-	0.18	3.69	
Groundwater					
Urban	0.00	0.00	0.00	0.00	3.01
Karaj	0.00	0.00	0.00	0.00	3.84
Varamin	0.00	0.00	0.00	0.90	2.67
Mazandran	0.00	-	0.06	3.57	0.00
Tributary					
Varamin	2.87	0	2.87	3.78	
Mazandran	0.07	-	0.13	3.64	
Tehran-Canal	0	2.70	2.70	3.61	

water in the Latiyan reservoir. The difference between the shadow prices of water in Karaj and Latiyan reservoirs (0.02 Rls/cu.m.) is likewise attributed to the difference in the marginal cost of water from these two sources.

The shadow price of water for urban consumption as the Table shows is 8.64 Rls/cu.m. for all seasons. It has already been explained in Section (6.5.3) above that if we substitute this shadow price back into the seasonal demand functions, then the quantities obtained should be equal to the optimal quantities given in the solution of the model. This, in other words, implies that optimal prices and quantities should satisfy the demand functions. We find, however, that the prices and quantities obtained only approximately satisfy the demand functions. These errors of approximation are due to the fact that we had to replace the estimated seasonal demand functions by piecewise linear approximations in order to incorporate them in the objective function of the linear programming problem.

In the irrigation regions, however, we observe a distinct seasonal variation in the shadow prices of water. The variation is particularly pronounced in the case of Varamin and Mazandran. The shadow price of irrigation water in different regions is determined by the degree of scarcity of water available from different sources. For instance, shadow price of water in Karaj is determined by the constraint on the annual safe yield of aquifer. The marginal value of this source of water is 3.84 Rls/cu.m., while in Varamin and Mazandran they are determined by the availability of water from the tributary sources. By adding the marginal cost of irrigation water to the appropriate value of the duals we arrive at the corresponding shadow price of irrigation water. For instance, by adding the marginal irrigation cost of water in Mazandran (0.05 Rls/cu.m.) to the value of tributary duals, we get the shadow prices of irrigation water in the plain. Considering that no irrigation is required during the third quarter, the dual values are obviously zeros.

It is interesting also to note that during those periods where water from the reservoirs are directed to both urban and irrigation regions, the dual values as we would expect are identical. For instance, the difference between the marginal cost of water to the urban area and the corresponding dual values (8.64-5.57 Rls/cu.m.) is just equal to the value of dual 3.07 Rls/cu.m. (net of cost) in the Karaj irrigation region.

The variation in the value of shadow prices corresponding to the tributary constraint suggests the possibility of storing water in periods of high inflow for those periods which make make higher contribution to the objective function. If the long-run marginal cost of constructing reservoirs is less than these values, it would be economically desirable to control the flows of these rivers.

6.10 Summary and Conclusion

In this Chapter attempts were made to develop a mathematical programming model representing optimum allocation and use of water in an environment surrounded by uncertain streamflows. To this end, an integrated chance constrained linear programming model in terms of the existing as well as the future water resources was formulated.

The solution to the model provided a set of simple operating rules for each reservoir. By following these rules, the beneficiaries of water could expect to receive a supply at a prespecified probability of occurrence. Such a supply is more reliable than the existing release policy which gives guaranteed supply in an environment surrounded by random streamflows.

The optimum distribution of water was carried out on the basis of the value of the marginal product of water in alternative use, implying that the allocations were carried out without giving any priority to any of the beneficiaries. The increase in the supply of water to the urban area is recommended because the urban users in aggregate generate more value in terms of the objective set for the model than the agricultural activities.

It should however be noted that, in spite of continuous shifts in the level of urban demand, no allowance was made for the possible increase in the revenue contribution of agricultural activities. In other words, the effect of growth in the level of urban demand observed without due consideration to the increase in the level of demand for agricultural products. As the demand for food grows, the demand for agricultural crops would inevitably move upwards. In this situation, the forces of competition between urban and rural beneficiaries may recommend a different allocation policy which could be more favourable to the irrigation regions than the current solution.

In this connection, in a separate run of the model in which crop limitations were relaxed, it was found that the demand for urban water was reduced by 1/6th, once compared with the current optimum level. The reduction was obviously caused by the higher value of water in the agricultural regions. Shadow price of water went up from the current level of 8.64 to 12.5 Rls/cu.m. in the urban area. This is a clear indication of the sensitivity of the model to the change in the revenue contribution of the crops.

The solution indicates the opportunity cost of water in different agricultural regions. Among the three agricultural regions, Varamin would be most affected by the increase in the urban demand followed by Karaj and Mazandran.

What this result indicates is that, if the projected demand for urban water materialises, Varamin region would suffer most. This result repudiates the current government policy which arbitrarily attaches a higher value to the use of water in Varamin and superficially allocates any excess water which might be available as a result of inter-basin transfer of water (Lar to Latiyan) to the Varamin Plain. Such an inefficient policy decision, stems from the fact that decision with regard to the allocation of water is carried out in isolation without due regard to the opportunity cost of water. The allocation policy which is recommended by our model indicates that water has a higher productive use in Karaj and therefore is more efficient to send any excess water to this region rather than Varamin.

CHAPTER 7

SUMMARY AND RECOMMENDATION

7.1 Review of Findings

Since each Chapter of this project contains its own summary and conclusion, we therefore present here an overview of our major findings and propose areas in which further research could be carried out.

The purpose of this study was to bring into focus the need for the consideration of economic efficiency criteria alongside the engineering and other considerations in the management of water resources in Iran.

Considering that the efficiency of any industry depends, to a great extent, on the legal framework within which each economic unit operates, the study was started by looking at the effects of institutional and legal frameworks of the water industry on the allocation and use of water. Attention was then focused on the possible effect of the Nationalisation of Water Resources Act on the future efficiency of the allocation and use of water. In the course of analysis of the Act it was noted that in spite of its development oriented nature many clauses of it conflict with established principles of economic efficiency. Our major objection was to the outright rejection of the market mechanism and rationality of farmers as independent decision makers. We point out that the new law, which has rested all the decisions with regard to the development and use of water resources of the country in the hands of a central body, would put too much pressure and responsibility on the administrators. Instead we proposed a "mixed system" under which the water authorities would be concerned with the major policy decisions and act as regulatory bodies in solving problems arising from commonalities.

With this background, and in view of a request by the World Bank to the TRWB, we focused on the problems of management of water resources in Tehran and the surrounding agricultural regions. To this end, a detailed linear programming model for the allocation of existing as well as planned water resources of the Varamin Plain was developed (Chapter 3). The solution to the model demonstrated a number of important factors which are usually neglected but have a pronounced effect on the efficiency of allocation and use of water. For instance, we demonstrated that the current belief among the majority of irrigation engineers who usually ascribe a fixed water requirement, i.e. "water norm", for crops may lead to an inefficient allocation of the resource. In this respect, it was shown that it is more efficient, in terms of generating higher revenues, to look at the value of water in alternative crop production and grow those crops which are least costly in terms of the opportunity cost of the resource. In this way, we may not necessarily always choose those irrigation regimes which correspond to the highest point in a production curve. This is a particularly important phenomena where water is scarce in relation to the available land. In this connection it was shown that the current supply of water from the rivers can be reduced by up to 40 percent without affecting the total acreage of irrigated cropland in the region. We also disaggregated the entire region into a number of sub-regions to investigate the effect of loss of water due to evaporation and seepage during conveyance, the possibility of intra-regional exchange of groundwater and the optimum extraction of groundwater in different parts of the plain.

It was suggested that the results are not only valuable as a mechanism for the allocation of water supplies by the water authority, who by virtue of the new water law are in full control of water resources of the plain, but also with the inevitable future redirection of surface water to Tehran they can be used as a base for compensating those farmers who lose their "right of use". In addition, we recommended the use of shadow prices to decentralise the process of decision making.

We then focused on the problem of inter-regional allocation of water resources (Chapter 4). To this end, an integrated linear programming model was developed to determine the optimum contribution of the existing sources of supply to a predetermined level of urban requirement. The results of this model brought to light the current mis-allocation of water resources and demonstrated the potential economic gains which could be achieved by considering the entire system as a whole, rather than dealing with each part of the system in isolation. The findings of this Chapter and those of the preceding ones, suggested that the current release policies, which are decided in isolation for each area and are greatly influenced by past water rights established prior to the construction of dams on the rivers, do not conform with the most efficient operation of the systems.

The subject of Chapter 5 was to study the determinants of demand for urban water in the Greater Tehran Area. This is a vital matter for efficient management of water supply in the city because first, the current policy which ignores the effect of price on demand and gives the highest priority to the urban beneficiaries, irrespective of the value of water in alternative uses, may result in an inefficient allocation of the resource, and second, most of the demand forecasts which have been either carried out by the TRWB or consultant engineers, have been based primarily on population projections and have proved to be unreliable. In order to improve forecasts and estimate the value of water to the urban users, we have used principle component and regression analysis techniques to estimate a demand function for urban consumption.

The demand was found to be responsive to a number of variables including the water rate. This is in contrast to the common belief among the majority of water engineers who tend to disregard the role of price as a determining factor in the consumption of water and, as a result, base their forecasting on a 'requirement' rather than a 'demand' approach.

Upon the projection of the explanatory variables other than price, forecast of the future demand, for a period of fifteen years, as a function of price of water was made.

Finally (Chapter 6), to obtain the optimum distribution of water for urban and rural uses on the basis of the value of water to the beneficiaries, the estimated demand function along with the revenue contribution of crops was considered in the objective function of a chance constrained programming model, representing the current as well as the future sources of supplies up to 1985. The model considered the stochastic nature of the streamflows and produced the optimum distribution of water resources without any prior commitments to any of the users. It also generated a set of operating rules for each reservoir which, once followed, provides the beneficiaries with a supply of water which is more reliable than the current release commitment which is based on the average inflow of water.

7.2 Recommendations for Future Research

There are a number of areas where further research can be carried out. Here we make some tentative suggestions.

With regard to the problems associated with the implementation of the new Water Law, efforts are needed to look at those clauses which diverge from the established principle of economic efficiency. For instance, a scheme should be devised to protect the already dwindling aquifers in many parts of the country. The scheme could be based on an incentive system which encourages people to conserve water, e.g. tax those who extract more than a specific quota (based on the safe yield of aquifer) and use the revenue as an incentive payment to those who use less than the given quota. The advantage of such a scheme is that it provides an opportunity for the use of water if the opportunity cost of water is greater than the tax rate, and at the same time encourages people to conserve water in the hope of receiving the incentive payment.

To increase the efficiency of farming in the country it is essential that research is carried out to develop a proper farming education programme. This is, in fact, a fundamental problem behind the low level of efficiency in the agricultural sector of the country. Farmers are simply not familiar with modern and efficient farming and, in particular, irrigation know-how. In this respect, it would be interesting to appraise the economics of the existing large scale pilot schemes in lieu of smaller but more widespread ones.

With regard to the problem of regional allocation and use of water, further research is required to investigate the effects of soil and water qualities, and transportation costs on the optimum cropping pattern. For instance, the effect of transportation cost on the optimum cropping mix, could be to grow bulky and perishable crops in areas which are closer to the main routes to the markets.

As far as the urban demand for water is concerned our model only produced an average demand function. For an effective management of urban water supply, additional research is needed to identify the exact nature of demand in different parts of the city. This is particularly important because socio-economic characteristics of the city vary greatly from one part to another. Consequently, the behaviour of the consumers could be different. In addition, there is a need for a detailed analysis of the seasonal behaviour of the demand. A study of this nature could be carried out in line with that of Howe and Linaweaver (1967).

The future water demand functions in our study were based on the assumption that; the behaviour of factors affecting the function will remain reasonably unchanged over the period of analysis, and that the projected values of the components of the demand function would prevail. These two assumptions, though reasonable for the period of projection considered in our study (Hittman Associates Inc. 1969), they should come under scrutiny if a longer period of projection is required. In this connection, resreach could be conducted to investigate the effects of three groups of intrinsic, extrinsic and technological factors on the average per capita consumption. Intrinsic variables are those which are basically under the control of the water planner and are influenced by the policy objectives, e.g. regulation on the design of water user appliances, pricing policies, public education etc. Extrinsic factors are basically beyond the control of the water planner and usually result as a consequence of changes in social structure. For example, the pattern of housing as a result of the city zoning regulations and high cost of land, may be towards high rise apartments. Such a change could substantially influence the sprinkler demand. The effect of technological improvements on the use of water should also be studied. For instance, the new generation of shower type taps are more efficient than the conventional ones in that they perform the job as well as the old ones using less water.

With regard to the model of Chapter 6, it would be interesting to simulate the flow of water over a greater number of years in order to obtain a more accurate picture of the distribution of streamflows. The practical aspects of the model could also be improved by reducing the duration of periods and by introducing additional constraints such as hydroelectricity generation, flood control etc. In addition the model could further be refined by considering the cost of storing water from one period to the next and the effects of evaporation and seepage loss as a function of volume of water in the reservoir.

Finally, the model could be expanded (once necessary data is available) to consider the effect of the Taleghan Dam and the associated irrigation network, which is proposed to come into operation in 1985, upon the allocation and use of water supplies.

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APPENDICES

APPENDIX TO CHAPTER 2

Appendix 2.1

Rationality of farmers in the use and allocation of irrigation water

Here we make a tentative appraisal of the rationality of farmers in some parts of the country with regard to their decision on the allocation of water among competing crops under the prevalence of civil law.

Before proceeding, we should however be aware of limitations on the sort of appraisal undertaken and of the data available as a basis for such an examination. The first limitation has to do with the conventional test of efficiency employed in determining the marginal contribution of a unit of water in different uses. The snag with this technique is that it fails to consider the actual use of the resource.

The proposed test shows the rationality of farmers in allocation of water among different competing crops. What it does not, however, signal is the gross use of water and possible wastage. In other words, this implies that some misallocation might exist which this test does not reveal; that is, the excessive waste of free water rather than misallocation of scarce (Bain, 1966 Ch. 17). These types of misallocation do exist and in fact are quite substantial.

Here, we treat water as a homogeneous resource with regard to its location in space and time.

That is, its use in a particular region where irrigators are farming in a competitive environment. Subject to a set of institutional, physical and financial constraints, they are trying to maximise their revenue by using the available resources, in particular water, to its most profitable use. We would therefore like to see that:

> Water is allocated among different crops in such a manner that the marginal return on a unit of water used in irrigating different crops, in a particular market, tends to be the same.

Admittedly, the test of optimality requires marginal data but, since no empirical evidence with regard to marginal values of factors of production in agriculture exist in Iran, we make use of average figures as an approximation of the other (Baumol, 1965 Ch. 3). Under the prevailing state of agriculture in Iran, average values are reasonably good approximation of marginals, since we could assume that no major economies of scale in the private sector of the industry is possible and therefore proportionality between input-output holds true. The following tables are constructed to show, wherever possible, the ratio of gross revenue of a particular crop to the water requirements.

Returns to Irrigation in the Zayandehrud Water Shed (Esfahan Province)

(Rls/cu.m.)

Crop	Water Requirement cu.m.	Output in Kilos		Gross Revenue Hectare	Average Return on a cu.m. of water
		Main Product	Joint Product		
Wheat	7,500	1,906	1,906	14,638	1.951
Opium Poppy	4,000	18	2,000	10,099	2.524
Cotton	8,900	1,301	-	22,221	2.496
Vegetable	25,000	24,872	-	107,480	2.299
Millet	9,650	2,553	2,553	19,504	2.021
Melon	18,350	14,300	-	64,350	3.506

Returns to Irrigation in the Golpayegan Water Shed

(Rls/cu.m.)

Crop	Water Requirement cu.m.	Output in Kilos		Gross Revenue Hectare	Average Return on a cu.m. of water
		Main Product	Joint Product		
Wheat	7,200	1,403	3,134	11,740	1.630
Barley	7,200	1,579	3,134	9,481	1.316
Opium Poppy	6,000	1,805	-	10,065	1.677
Melon	9,310	4,663	-	20,563	2.208

Return to Irrigation in

Barojerd Water Shed

(Rls/cu.m.)

Crop	Water Requirement cu.m. Hectare	Output in Kilos		Gross Revenue Hectare Rial	Average Return on a cu.m. of water
		Main Product	Joint Product		
Wheat	4,000	1,403	3,143	11,740	2.935
Barley	3,200	1,579	3,134	9,481	2.962
Melon	8,000	4,663	-	20,563	2.570
Vegetable	12,000	9,179	-	40,204	3.350

The above tables show how the average return on a unit of water in a particular region are close to each other. Of course, there are some variations but these variations could be explained once we consider the time of watering, the type of crop etc. For example, melon or vegetable are kinds of crop which are usually used locally. Therefore, any substantial increase in their acreage, which would seem to be more profitable, would result in the collapse of market. This fact stems from low elasticity of demand for this type of crop. With reference to this evidence, and also the fact that price of water at the resale level is about 3-5 times of cost of water (about 0.4 rial per cu.m.), similar to the average returns, we could argue that individual farmers are reasonably rational decision makers with regard to the allocation of water among different crops.

APPENDICES TO CHAPTER 3

APPENDIX 3.2

PUMPING CAPACITY AND ANNUAL SAFE YIELD OF AQUIFER

(m.cu.m.)

Sub-region	Number of wells	Pumping* Capacity	Safe Yield
I	16	2.566	6.60
II	40	5.702	28.80
III	59	8.411	29.90
IV	30	4.275	22.90
V	58	8.268	43.20
	203		131.40

* Pumping capacity of an average well is calculated on the basis of a 22 hour working day and 0.06 Litre/Second.

APPENDIX 3.4

CASH CROP BUDGET

WHEAT UNDER DIFFERENT IRRIGATION REGIME

(Rls/ha)

Treatment	Yield* (kg/ha)	Price (kg/Rls)	Value	Cost of Production**	Revenue
x_{11}	xx 2360 x 3609	8 1	22489	6800	15689
x_{12}	xx 2750 x 3969	8 1	25969	6800	19169
x_{13}	xx 2281 x 3764	8 1	22012	6800	15212
x_{14}	xx 2421 x	8 1	23191	6800	16391
x_{15}	xx 2643 x 3889	8 1	25033	6800	18233
x_{16}	xx 2341 x 3597	8 1	22617	6800	15817
x_{17}	xx 2516 x 3769	8 1	23897	6800	17097
x_{18}	xx 2708 x 4368	8 1	26032	6800	19232
x_{19}	xx 2039 x 2686	8 1	18998	6800	12198
x_{110}	xx 3000 x 3000	8 1	27000	6800	20200

xx Main Product

x By Product

Source: * **National Committee for Irrigation and Drainage, Report No. 8.**
** **Varamin and Garmsar Development Plan.**

APPENDIX 3.4

CASH CROP BUDGET

COTTON UNDER DIFFERENT IRRIGATION REGIME

(Rls/ha)

Treatment	Yield* (kg/ha)	Price (kg/Rls)	Value	Production Cost**	Revenue
x_{11}	1906.25	30	57187.5	5600	51587.5
x_{12}	2630.20	"	78906.0	"	73306.0
x_{13}	1843.75	"	55296	"	54696.0
x_{14}	2400.9	"	72027	"	66427.0
x_{15}	2812.5	"	84375	"	79375.0
x_{16}	2687.5	"	80625	"	74025.0
x_{17}	2229.1	"	66873	"	66273.0
x_{18}	2046.9	"	61407	"	60807.0
x_{19}	2520.8	"	75624	"	75024.0
x_{110}	2500.0	"	75000	"	69400.0

Source: * National Committee for Irrigation and Drainage Report No. 8.

** Varamin and Garmsar Development Plan.

APPENDIX 3.4

CASH CROP BUDGET

SUNFLOWER UNDER DIFFERENT IRRIGATION REGIME

(Rls/ha)

Treatment	Yield* (kg/ha)	Price (kg/Rls)	Gross Revenue	Costs**	Net Revenue
x_{11}	2046	13	26598	9020	17578
x_{12}	2317	"	30121	"	21101
x_{13}	2125	"	27625	"	18605
x_{14}	2250	"	29250	"	20230
x_{15}	2273	"	29549	"	20529
x_{16}	2177	"	28301	"	19281
x_{17}	1885	"	24505	"	15485
x_{18}	2005	"	26065	"	17045
x_{19}	1973	"	25649	"	16629
x_{110}	850	"	11050	"	2030

Source: * National Committee for Irrigation and Drainage Report No. 8.

** Varamin and Garmsar Development Plan.

APPENDIX 3.4

CASH CROP BUDGET

ALFALFA UNDER DIFFERENT IRRIGATION REGIME

(Rls/ha)

Treatment	Yield* (wet) kg/ha	Yield (dry) kg/ha	Price kg/Rls	Value	Product.** Cost	Revenue
x_{11}	102,000	22,440	4.5	100,980	14,900	86,080
x_{12}	98,970	21,770	4.5	97,965	14,900	83,465
x_{13}	95,220	20,950	4.5	24,275	14,900	79,375
x_{14}	-	12,000	4.5	54,000	14,900	39,380

- data not available.

Source: * National Committee for Irrigation and Drainage

** Varamin and Garmsar Development Plan.

APPENDIX 3.4

CASH CROP BUDGET

CROPS WITH ONE IRRIGATION REGIME

Rls/ha

Crop	Notation	Yield (kg/ha)	Price (kg/Rls)	Gross Revenue	Costs	Net Revenue
Melon	x_{51}	23,000	3	69,000	14,900	54,100
Tomato	x_{61}	30,000	3	90,000	23,157	66,843
Spring Cucumber	x_{71}	17,000	3	51,000	18,550	32,450
Autumn Cucumber	x_{81}	13,000	5	65,000	15,550	49,450
Sorghum	x_{91}	4,000	5.5	22,000	5,900	16,100
Maize Grain	x_{101}	4,000	10	40,000	6,900	33,100

Source: Varamin and Garmsar Development Plan.

APPENDIX 3.5

APPLICATION OF WATER TO WHEAT UNDER DIFFERENT IRRIGATION REGIME

(cu.m.)

Treatment	Month				Total
	9	2	3	4	
x_{11}	1,500	1,500	1,500	750	5,250
x_{12}	1,500	1,500	2,400	-	5,400
x_{13}	1,500	1,500	1,800	-	4,800
x_{14}	1,500	1,200	1,500	750	4,950
x_{15}	1,500	1,200	2,400	-	5,100
x_{16}	1,500	1,200	1,800	-	4,500
x_{17}	1,500	1,800	1,500	750	5,550
x_{18}	1,500	1,800	2,400	-	5,700
x_{19}	1,500	1,800	1,800	-	5,100
x_{110} *	2,500	1,400	1,900	1,200	7,000

Source: National Committee for Irrigation and Drainage Report No. 8.

* Mahab. (Control Crop)

APPENDIX 3.5

APPLICATION OF WATER TO COTTON UNDER DIFFERENT IRRIGATION REGIME

(cu.m.)

Treatment	Preplant	Month					Total
	3	4	5	6	7	8	
x_{11}	2925	1800	3600	2700	1800	900	13725
x_{12}	2925	1800	3600	1755	1755	-	11835
x_{13}	2925	1800	3600	1800	3600	-	13725
x_{14}	2925	1350	2700	2700	1800	900	12275
x_{15}	2925	1350	2700	1755	1755	-	10485
x_{16}	2925	1350	3600	1800	3600	-	13275
x_{17}	2925	-	3600	2700	1800	900	11925
x_{18}	2925	-	3600	1755	1755	-	10035
x_{19}	2925	-	3600	1800	3600	-	11925
x_{110} *	3200	2350	2800	2600	2050	-	13000

Source: National Committee for Irrigation and Drainage Report No. 8.

* Mahab. (Control Crop)

APPENDIX 3.5

APPLICATION OF WATER TO SUNFLOWER UNDER DIFFERENT IRRIGATION REGIME

(cu.m.)

Treatment	Month					Total
	1	2	3	4	5	
x_{11}	1200	562	1124	2812	1687	7385
x_{12}	1200	600	1800	2400	1800	7800
x_{13}	1200	600	1800	1800	1200	6600
x_{14}	1200	630	1320	3150	1890	8190
x_{15}	1200	607	1214	1821	2428	7270
x_{16}	1200	692	1284	1976	1284	6436
x_{17}	1200	605	1210	3025	1815	7855
x_{18}	1200	603	1206	2412	1809	7230
x_{19}	1200	722	1444	2166	1444	6976
x_{110}*	1200	1750	1750	2100	2400	10000

Source: National Committee for Irrigation and Drainage Report No. 8.

* Mahab (Control Crop)

APPENDIX 3.5

APPLICATION OF WATER TO ALFALFA UNDER DIFFERENT IRRIGATION REGIME

(cu.m.)

Treatment	Month								Total Water Applied
	1	2	3	4	5	6	7	8	
x_1	1050	2100	3150	3150	3150	3150	1050	1050	17850
x_{12}	1265	2265	2265	2265	2265	2265	1265	1265	16444
x_{13}	-	1438	2876	2876	2876	2876	1438	-	14388
x_{14} *	200	200	1850	2350	2600	2550	2100	1100	15000

Source: National Committee for Irrigation and Drainage
Report No. 8.

* Mahab (Control Crop) Also 250 cu.m. during the 9th month

APPENDIX 3.5

WATER REQUIREMENTS OF CROPS WITH ONE IRRIGATION REGIME

(cu.m.)

Crop	Notation	Month								Total
		1	2	3	4	5	6	7	8	
Melon	x_{51}	1300	1000	1600	2200	2500	800	0	0	9400
Tomato	x_{61}	1200	1500	2000	2200	2400	2300	0	0	1160
Spring Cucumber	x_{71}	1200	1300	1700	2500	2700	600	0	0	10000
Autumn Cucumber	x_{81}	0	0	0	0	0	1600	2000	1900	5500
Sorghum	x_{91}	0	0	1800	2100	2700	2700	1500	0	10800
Maize Grain	x_{101}	0	0	1800	2100	2700	2700	700	0	10000

Source: Mahab

APPENDIX 3.6

LIMITATION ON THE ACREAGE OF CROPS

(hectare)

Crop	Notation	Phase I	Phase II
Wheat	x_1		
Cotton	x_2	7,000	16,000
Sunflower	x_3		
Alfalfa	x_4	5,000	6,000
Melon	x_5	3,000	5,200
Tomato	x_6	2,000	4,000
Spring Cucumber	x_7	1,320	3,000
Autumn Cucumber	x_8	1,850	2,000
Sorghum	x_9		
Maize Grain	x_{10}		

APPENDICES TO CHAPTER 4

APPENDIX 4.1

AVERAGE SEASONAL FLOW OF KARAJ AND JAJERUD RIVERS AND THE AVERAGE CURRENT RELEASE FROM THE RESERVOIRS

(m.cu.m.)

Month	Season (Quarter)	River Flow		Regulated Water*		Damavand River **
		Karaj	Jajerud	Karaj	Latiyan	
Sept. Oct. Nov.	1st	48.00	29.00	79.00	53.00	4.53
Dec. Jan. Feb.	2nd	38.00	33.00	42.00	17.00	8.78
Mar. Apr. May	3rd	178.00	159.00	89.00	72.00	23.72
June July Aug.	4th	162.00	79.00	135.00	101.00	1.22

* Regulated water represents the current quarterly release from the reservoirs, after allowing for contingency (e.g. flood) requirements.

** This column represents the average quarterly flow of Damavand River which reaches the Varamin Plain.

APPENDIX 4.2

SEASONAL PUMPING CAPACITIES AND THE ANNUAL SAFE YIELD OF AQUIFERS

(m.cu.m.)

Month	Season (Quarter)	Urban	Karaj	Varamin
Sept. Oct. Nov.	1st	56.55	42.48	85.53
Dec. Jan. Feb.	2nd	56.55	42.48	85.53
March Apr. May	3rd	57.88	43.42	87.43
June July Aug.	4th	58.43	43.89	88.38
Annual Safe Yield of Aquifer		99.00	70.16	131.10

APPENDIX 4.3

WATER REQUIREMENTS OF CROP - KARAJ

(Cu.m./ha)

Crop	Notation	Quarter			
		I	II	III	IV
Wheat	x_{11}	2000	500	4000	-
Barley	x_{12}	2000	500	4000	-
Cotton	x_{13}	1500	-	4500	6000
Melon	x_{14}	-	-	5000	6000
Alfalfa	x_{15}	4000	-	5000	7000
Sunflower	x_{16}	-	-	4500	2500
Orchard	x_{17}	1500	-	3500	7000
Tomato	x_{18}	-	-	4000	7500
S.Cucumber	x_{19}	-	-	3500	6000
Sugarbeet	x_{110}	2000	-	5500	8000
Water Melon	x_{111}	-	-	2000	5000
Beans	x_{112}	-	-	6500	3000
Potatoes	x_{113}	2000	-	3500	5500

Source: Department of Agricultural Engineering, Ministry of Agriculture.

APPENDIX 4.3

WATER REQUIREMENT OF CROP - VARAMIN

(Cu.m./ha)

Crop	Notation	Quarter			
		I	II	III	IV
Wheat	x_{21}	1950	350	3500	1200
Barley	x_{22}	1950	350	3500	1200
Cotton	x_{23}	2050	-	3200	7750
Melon	x_{24}		-	3900	4500
Alfalfa	x_{25}	3450	-	4050	7500
Sunflower	x_{26}	2400	-	3900	700
Orchard	x_{27}	2800	-	3300	6400
Tomato	x_{28}	-	-	4700	6900
S.Cucumber	x_{29}	-	-	3900	4500
A.Cucumber	x_{210}	3900	-	-	1600
Sorghum	x_{211}	1500	-	1800	7500
Maize Grain	x_{212}	700	-	1800	7500

Source: Mahab 3-3/2

APPENDIX 4.4 CASH CROP BUDGET - KARAJ

Crops	Wheat	Barley	Cotton	Melon	Alfalfa	Sunflower	Orchard	Tomato	S.Cucumber	Sugar Beet	Water Melon	Beans	Potato
Notation	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{110}	x_{111}	x_{112}	x_{113}
1. OUTPUT													
Main Product kg/ha	3000	3500	3000	25000	7000	850	7430	29197	45000 units	50000	18000	1000	10620
Price kg/Rls	8	5.5	20	3	6	13	10	2.5	1 per unit	1.2	3	40	7.6
Joint/By Product	3000	3500	-	-	-	-	-	-	5000	700	3000	6270	-
Price kg/Rls	1	1	-	-	-	-	-	-	1	3	1	1	-
Value of output	27000	22750	6000	75000	42000	11050	74300	72995	50000	62100	57000	46200	80712
2. INPUT													
Seed	1800	824	400	1200	500	130	-	1446	500	xx	1200	4361	18251
Fertilizer	1800	1249	1800	1400	1200	1500	-	3561	1800	1200	1800	1892	2790
Labour	1600	964	1800	1100	1600	500	400	1406	1000	1300	1000	1852	1678
Plant Portection	50	20	1085	1100	-	-	1020	2800	340	360	180	-	249
Manure	-	-	6000	2050	6000	-	5000	12000	6000	4000	6000	-	-
Cost of Production	5250	3057	11085	6850	9300	2030	6420	21213	9640	-	10180	8105	23268
G. Revenue	21750	19675	48915	68150	32700	9020	67880	51782	40360	55240	46820	38095	57444

XX supplied free of charge by the refineries.

Source: Ministry of Agriculture.
Note: Due to discrepancies between different sources of data, some figures have been adjusted.

APPENDIX 4.4 CASH CROP BUDGET - VARAMIN

Crops	Wheat	Barley	Cotton	Melon	Alfalfa	Sunflower	Orchard	Tomato	S.Cucumber	A.Cucumber	Sorghum	Maize Grain
Notation	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}	x_{210}	x_{211}	x_{212}
1. OUTPUT												
Main Product kg/ha	3000	3600	2500	23000	12000	850	7430	30000	17000	13000	4000	4000
Price kg/Rls	8	5.5	20	3	4.5	13	11	3	3	5	5.5	10
Joint/By-Product	3000	3300	-	-	-	-	-	-	-	-	-	-
Price kg/Rls	1	1	-	-	-	-	-	-	-	-	-	-
Value of Output	27000	23100	50000	69000	54000	11050	81730	90000	51000	65000	22000	40000
2. INPUT												
Cost Rls/ha												
Seed	1425	1017	400	300	450	130	-	1800	1500	1500	1300	1300
Fertilizer	2975	2975	1800	1050	3150	1500	-	4757	4700	1100	2000	3000
Labour	2000	2000	1800	1600	240	500	400	1000	1000	1600	2200	2200
Plant Protection	400	400	1600	2600	2000	-	1020	3600	2600	2600	400	400
Manure	-	-	-	8750	8750	-	5000	12000	8750	8750	-	-
Cost of Production	6800	6398	5600	14900	14620	2030	6420	23157	18550	15550	5900	6900
Revenue	20200	16808	44400	54100	39380	9020	75310	66843	32450	49450	16100	33100

Source: Varamin and Garmsar Development Plan

APPENDIX 4.5

ACREAGE LIMITATION OF CROPS

(hectare)

Crop	Karaj	Varamin	Total
Wheat	-	-	-
Barley	-	-	-
Cotton	-	-	-
Melon	-	-	6,479
Alfalfa	-	-	-
Sunflower	-	-	-
Orchard	2,000	1,500	-
Tomato	-	-	2,650
Spring Cucumber	-	-	1,320
Sugarbeet	-	-	-
Water Melon	850	-	-
Potato	470	-	-
Autumn Cucumber	-	1,800	-
Sorghum	-	-	-
Maize Grain	-	-	-

APPENDICES TO CHAPTER 5

Appendix 5.3

a - Domestic Demand

21 Areas : Metered and Public Sewer

$$q_{a,d} = 206 + \underset{(0.585)}{3.47v} - \underset{(0.339)}{1.30pw}$$

13 Areas : Flat Rate and Apartment with Public Sewer

$$q_{a,d} = 29.9 + \underset{(0.558)}{4.39v} - \underset{(8.46)}{33rdp}$$

5 Areas : Metered with Septic Tank

$$q_{a,d} = 30.2 + \underset{(4.66)}{39.5dp}$$

b - Summer Sprinkling Demand

21 Areas : Metered and Public Sewer

$$\begin{aligned} q_{ss} = {} & 1.09 + \underset{(0.451)}{2.07}\,(w_s - 0.65_s) - \underset{(0.224)}{1.12p_s} + \\ & \underset{(0.216)}{0.662\ v} \end{aligned}$$

10 Areas : Metered and Public Sewer, West

$$q_{ss} = 3.053 - \underset{(0.321)}{0.703p} + \underset{(0.228)}{0.429v}$$

11 Areas : Metered and Public Sewer, East

$$\begin{aligned} q_{ss} = {} & 0.784 - \underset{(0.21)}{0.7936} + \underset{(0.429)}{2.93}\,(w_s - 0.6r_s) - \underset{(0.190)}{1.578p} \\ & + \underset{(0.306)}{1.45v} \end{aligned}$$

8 Areas : Flat Rate with Public Sewer

$$q_{ss} = 2.00 + \underset{(0.242)}{0.713v}$$

Appendix 5.4

APPENDICES TO CHAPTER 6

APPENDIX 6.1

SESSONAL DISCHAGE OF KARAJ RIVER

(m.cu.m.)

Year	Quarter			
	I	II	III	IV
1956	55.50	37.50	265	268.00
1957	66.00	51.50	176.50	223.00
1958	30.00	33.00	194.00	147.00
1959	47.00	37.00	181.50	164.50
1960	24.00	32.50	94.09	72.50
1961	31.50	30.00	138.50	104.00
1962	42.50	35.00	153.00	143.50
1963	56.50	44.00	184.00	217.00
1964	36.50	34.00	201.00	114.00
1965	62.00	43.00	196.50	163.50
1966	44.00	38.00	183.00	158.50

Source: Department of Surface Water, Ministry of Water and Power.

APPENDIX 6.1

SEASONAL DISCHARGE OF JAJERUD RIVER

(m.cu.m.)

Year	Quarter			
	I	II	III	IV
1958	30.70	38.40	110.70	50.00
1959	25.70	22.00	115.90	79.90
1960	36.40	41.60	309.00	170.90
1961	21.30	25.20	85.00	25.10
1962	34.60	40.60	259.70	98.60
1963	33.30	35.40	184.30	117.30
1964	47.20	56.30	295.10	149.90
1965	36.90	44.30	140.00	66.80
1966	27.00	30.90	230.00	100.10
1967	30.00	25.70	163.50	119.60
1968	39.20	42.80	140.60	51.60
1969	23.50	37.90	335.40	73.10
1970	19.80	25.80	64.00	24.70

Source: Department of Surface Water, Ministry of Water and Power.

APPENDIX 6.1

SEASONAL DISCHARGE OF LAR RIVER

(m.cu.m.)

Year	Quarter			
	I	II	III	IV
1962	37,532,160	29,600,460	109,304,640	146,059,200
1963	69,647,040	25,997,760	135,198,720	215,032,320
1964	38,854,080	105,831,360	162,881,280	93,882,240
1965	32,322,240	23,587,200	154,275,840	134,447,040
1966	35,432,640	28,252,800	131,440,320	139,579,200
1967	36,158,400	26,930,880	99,688,320	113,866,560
1968	36,391,680	30,024,640	154,249,920	272,574,720
1969	59,635,200	45,152,640	316,016,640	339,474,240
1970	54,639,360	42,949,440	101,321,280	41,679,360
1971	32,607,360	22,109,760	172,031,040	175,167,360

Source: Department of Surface Water, Ministry of Water and Power.

APPENDIX 6.2

Technical Characteristics of the Reservoir Systems

	Karaj	Latiyan	Lar
Main Dam:			
Gross Storage Capacity (m.cu.m.)	205	95	960
Live (useful) Storage Capacity (m.cu.m.)	190	85	860
Height above the original River bed (m)	165	80	105
Main spillway discharge Capacity (cu.m./s)	145	50	120
Regulating Reservoir:			
Gross Storage Capacity (m.cu.m.)	0.7	0.84	
Live Storage Capacity (m.cu.m.)	0.6	0.40	
Lar Diversion Works			
Upper Tunnel (Lar-Kalan) (km)			20
Lower Tunnel (Kalan-Lavarak) (km)			10
Capacity of Kalan Reservoir (m.cu.m.)			0.7
Discharge Capacity (cu.m./s)			18.5

APPENDIX 6.3

CURRENT DEMAND AND THE MONTHLY DISCHARGES OF BABOL AND TALAR RIVERS

(m.cu.m.)

		March	April	May	June	July	August
Babol	Current Demand	20.5	25	16.5	19	11.5	2.25
	Mean Monthly Flow	81.5	51	44	30	33.5	59
Talar	Current Demand	16.5	21	12.50	13	10	5
	Mean Monthly Flow	58.36	43.38	32.63	21.25	18	24.38

AVERAGE FLOW OF DIFFERENT SOURCES OF GROUNDWATER IN THE MAZANDRAN PLAIN

(m.cu.m.)

Source	Available during				
	Six Months	One Month	1st quarter	3rd quarter	4th quarter
Springs and Ghanats	197	32.83	32.83	65.66	98.49
Artesian Wells	46	7.66	7.66	15.32	22.98
Deep Wells	145	24.16	24.16	48.32	72.48

Source: Sir Alexander Gibb & Partners
Lar Dam and Mazandran Irrigation Project.

APPENDIX 6.4

WATER REQUIREMENTS OF RICE - MAZANDRAN

(Cu.m./ha)

Quarterly	Variety				
	Champa	Tichung	Gharib	Mehre	Tarem
I	-	-	1210	640	-
II	-	-	-	-	-
III	1350	1350	1350	3130	1350
IV	4630	4500	4150	6710	4510

Source: National Committee for Irrigation and Drainage
Report No. 8.

APPENDIX 6.5

CASH CROP BUDGET - MAZANDRAN

(Rls/ha)

Rice Variety	Yield	Price	Value	Cost of Product	Revenue
Champa	6750	8	54000	18150	35850
Tichung	8033	8	64264	18150	46114
Gharib	5933	9	53397	18150	35247
Mehre	2667	20	53340	18150	35190
Tarem	3970	15	59550	18150	41400

Source: National Committee for Irrigation and Drainage
Report No. 8.

APPENDIX 6.6

SHORT-RUN VARIABLE COST OF DIFFERENT SOURCES OF WATER

Since this model is about the allocation of water in a system of river basins where capital investment has already been incurred. Our concern is only with the current operating and maintenance costs pertinent to different sources of water. Historical or sunk costs, such as interest on capital borrowed, are not relevant for current decisions because no decision with regard to the use of water could alter this part of the water cash. (Millward, 1971, pp. 205-208). Consequently, only variable costs are considered here.

The available published statistics do not contain the breakdown of costs. However, it is a common practice in the field of water resources management to calculate annual operating and maintenance costs (O & M) in percentages of capital costs (Kuiper 1971, Chap. 5). In this connection Mahab allows 5% of total capital cost for operating cost and calculates maintenance costs of the Varamin Irrigation Project according to the following Table.

Maintenance Cost of Different Components of a Water System (Proportion of Total Capital Invested)

	Average age in Year	Current Age in Year					
		0-5	5-10	10-20	20-30	30-40	40-75
Major Work Dam, Main Canals	75	0.002	0.005	0.0075	0.01	0.015	0.015
Minor Work Secondary Canal	40	0.005	0.0075	0.01	0.015	0.015	Renew
Electro-Mechanic Equipment	10	0.03	0.3		Renew		

Source Mahab B. 3-5

Assuming that the above Table in addition to the proposed 5% operating cost is applicable to other parts of the water resources systems the unit variable cost of surface water is tabulated in the following Table.

CALCULATION OF OPERATING AND MAINTENANCE COST OF WATER

Source		1 Current Age Category	2 Total Capital Invested 10^6 Rls	3 Annual Maintenance Costs in % of 2	4 Annual Maintenance Cost 10^6 Rls	5 Annual Operating Costs in % of 2	6 Annual Operating Cost 10^6 Rls	7 Total Operating and Maintenance Cost 10^6 Rls	8 Average inflow of Water m.cu.m.	Unit variable Cost Rls	At 1973 price level	Date costs reported
Dam:	Karaj	10-20	4360	0.0075	32.70	0.0050	21.8	54.5	469	0.12	0.164	1961
	Latiyan	10-20	3000	0.0075	22.50	0.0050	15.00	37.5	264	0.14	0.179	1967
	Lar	0-5	11850	0.002	23.70	0.0050	59.25	82.95	390	0.21	0.239	1971
Major Irrigation Canal	Karaj	10-20	322	0.0075	2.41	0.0050	1.61	4.02	160	0.0251	0.0323	1966
	Varamin	5-10	1774	0.0050	8.87	0.0050	8.87	17.74	580	0.03	0.030	1973
	Mazandran	0-5	2790	0.002	5.58	0.0050	13.95	19.53	300	0.046	0.052	1971
Lar-Latiyan Transfer Canal		0-5	5330	0.002	10.66	0.0050	26.65	47.31	180	0.26	0.296	1971
Tehran-Varamin Canal		0-5	320	0.002	0.64	0.0050	1.60	2.24	202	0.011	0.011	1973

Groundwater Costs

According to Mahab total cost of one unit of well is as follows:

	Rls
Pump + Electromotor	1,045,000
Others	580,000
	1,625,000

The annual maintenance cost for the pump and electromotor according to Table of page 307 is

1,045,000 x 0.03 = 31,350 Rls

and for the 'other'category is

580,000 x 0.005 = 2,900 Rls

The total/annual operating cost

1,625,000 x 0.005 = 8,125 Rls

Thus the total annual maintenance and operating cost is equal to 42,375 Rls. Considering an average annual pumping left of 860,000 cu.m. the unit operating and maintenance cost is

42,375 ÷ 860,000 = 0.05 Rls/cu.m.

To this, the power cost should be added. This cost for different pumping depth for Varamin Plain is given in Chapter 3, Page

Accepting a similar energy cost calculation for Karaj, Mazandran and Urban area, we obtain:

	Average depth of wells (metre)	Energy Rls/cu.m.	Operating and Maintenance Rls/cu.m.		Unit Variable Cost
Karaj		0.1816	0.05	=	0.231
Varamin		0.145	0.05	=	0.195
Mazandran		0.6726	0.05	=	0.1226
Urban		0.200	0.05	=	0.250

Urban Water Cost

According to TRWB Annual Report 1965 the unit variable cost of water is as follows:

Operating and Maintenance Cost	1.75	Rls/cu.m.
Administration	2.25	
Sales, etc.	0.20	
	4.20	

At 1973 price level this cost is equivalent to 5.38 Rls/cu.m.

To summarise, the unit variable cost of different sources of water at the final point, i.e. where it is used, is as follows:

Variable Cost of Water Rls/cu.m.

Urban from:	Reservoir		Conveyance		Treatment etc.		
Karaj	0.164	+	0.065	+	5.38	=	5.609
Latiyan	0.179	+	0.018	+	5.38	=	5.577
Irrigation from							
Karaj	0.164	+	0.0323			=	0.196
Varamin	0.179	+	0.030			=	0.209
Mazandran	0.239	+	0.052			=	0.291
	Treatment		Pumping		Conveyance		
Tehran-Varamin Canal	0.10	+	0.04	+	0.011	=	0.155
	Reservoir		Conveyance				
Lar-Latiyan Transfer Canal	0.239		0.296			=	0.535
Tributary:			Conveyance				
Varamin			0.03			=	0.03
Mazandran			0.052			=	0.052

APPENDIX 6.7

ESTIMATED DISCHARGE OF TEHRAN CANAL

(m.cu.m.)

Year	Annual Discharge	Quarterly Discharge			
		I	II	III	IV
1980	22	7.04	-	6.38	8.58
1981	30	9.60	-	8.70	11.70
1982	42	13.44	-	12.18	16.38
1983	55	17.60	-	15.95	21.45
1984	70	22.40	-	20.30	27.30
1985	84	26.88	-	24.36	32.76
1986	100	32.00	-	29.00	39.00
1987	120	38.40	-	34.80	46.80
1988	138	40.10	-	40.02	53.82
1989	158	50.56	-	45.82	61.62
1990	180	57.60	-	16.70	70.20
1991	202	64.64	-	58.58	78.78

Source: Mahab 3-51.

APPENDIX 6.8

VALUE OF STREAMFLOWS WHICH IS EXCEEDED α PERCENT OF THE TIME

Region	Probability		75	80	85	90	92	95	97	99
Karaj	Season	1	43.19	42.44	41.64	40.69	40.21	39.26	38.31	37.91
		2	36.55	36.19	35.81	35.36	35.14	34.69	34.24	33.41
		3	170.49	168.05	165.49	162.41	161.87	157.80	154.72	149.08
		4	150.26	147.00	143.57	139.46	137.40	133.28	129.17	121.62
Latiyan	Season	1	29.79	29.38	28.94	28.42	28.16	27.64	27.12	26.17
		2	34.08	33.57	33.03	32.38	32.06	31.41	30.76	29.58
		3	171.55	167.01	162.23	156.50	153.63	147.89	142.16	131.64
		4	78.35	75.90	73.32	70.23	68.68	65.58	62.49	56.81
Lar	Season	1	41.14	40.50	39.83	39.02	38.68	38.81	37.00	35.52
		2	32.62	31.03	29.37	27.36	26.36	24.36	22.36	18.69
		3	138.25	133.76	129.02	129.31	120.50	114.82	109.14	98.73
		4	126.02	120.28	114.23	106.98	103.35	96.09	88.84	75.23