THE 1999 DROUGHT AND ITS HYDROLOGIC IMPACT

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ABSTRACT
The study region is bounded by the Mediterranean coastline in the west, the Jordan River in the east, the southern tip of the Dead Sea in the south and the foothills of Mount Carmel in the north. A mountain range splits the hydrologic system of the region into two subsystems: A western Drainage Area towards the Mediterranean Sea and an Eastern Drainage Area towards the Jordan Valley and the Dead Sea.The main source of water supply in the region is groundwater replenishment from precipitation which makes the population of the area vulnerable to years of drought. The region experienced in the winter of 1998/99 a record minimum in the 100 year long history of rainfall records. The objectives of the study were to analyze the spatial and temporal variability of the annual and monthly rainfall depth in the region, to reveal the particular features of the 1998/99 rainfall and to assess its impact on the state and exploitation of the water resources in the region. It was found that the cumulative rainfall depth was less than 50% of the long-term mean value and in the months of October and November, which are most critical for agriculture, the rainfall deficit was over 87% of the average. The resulting effects were a record minimum of groundwater replenishment and a drastic increase in the pumped volume, which, in turn, led to the drop of groundwater levels, reduction of springflow, reduction of outflow to the sea and rise in salinity of the pumped water in the basins of the Western Drainage Area. In the Eastern Drainage Area, the drop in groundwater levels was accompanied by a drop in salinity, an effect opposite to the one in the Western Drainage area.

The results of the study point to the need for controlling groundwater levels and quality in the region by means of a dynamic operating rule which takes into account seasonal and inter-seasonal variations of rainfall.

KEYWORDS: Drought, Eastern Mediterranean, Hydrologic impact

INTRODUCTION

The Concept of Drought

Drought is defined in this paper as a phenomenon characterized by a small amount of annual rainfall with respect to the longterm average combined with an unfavorable distribution of the rainfall within the year. Drought is typical for climatic regions where rainfall is only seasonal and highly variable both within each season and between the seasons.

Drought poses severe problems if it occurs under one or more of the following conditions: Insufficient reserves of stored water; absence of external sources from which water can be imported; insufficient capacity to meet and/or regulate the demands of humans, fauna and flora for water quantity and quality at required locations and times.

Study Area

The study area of this report is bounded by the Jordan River in the east, the Mediterranean coastline in the west, the southern tip of the Dead Sea in the south and the foothills of Mount Carmel in the north (Fig.1). An east-west cross-section of the topography of the area is characterized by three physiographic regions (U.S. Geological Survey, 1998): A Mountain Belt in the central part of the area , a Coastal plain towards the Mediterranean in the west, and an escarpment towards the Jordan rift valley in the east.

The climate of the area is characterized by a high spatial and temporal variability of temperature, humidity, evaporation and precipitation. Two seasons are distinguished: the wet winter season and the dry summer season. The term hydrologic year is assigned to the period from October 1 of a given calendar year to September 30 of the next calendar year.

Water is the most valuable natural resource in the area. The main source of water supply is natural replenishment from precipitation which makes the population vulnerable to years of drought.

Study Objectives and Scope

The objectives of this study were:

-To present an overview of the hydrologic system in the area
-To describe the variability of rainfall in the study area
-To present a quantitative characterization of the 1998/99 drought in the study area
-To assess the hydrologic impact of the 1998/99 drought

METHODOLOGY

The methodology of the study is based on a modular approach which allows the project to be updated and/or extended in the future by including additional aspects such as: impact of drought on the water supply system, ecological impact, impact on sectors of the economy, drought management options, and so on.

The present study dealt with the construction of the hydrologic module of the project. It comprises a sequence of three stages. The first stage includes the building of a computerized project-oriented primary data base holding fixed data on observation posts and records of observations which are pertinent to the required output of the project . The second stage deals with the statistical characterization of rainfall and drought in the various parts of the study area and shows the rainfall of 1998/99 as an extreme event. The third stage deals with the impact of the 1998/99 drought on the water yield and on the state of the natural water sources. It includes the processing of observations made in the hydrologic year of 1998/99 and the estimation of components of the water balance.

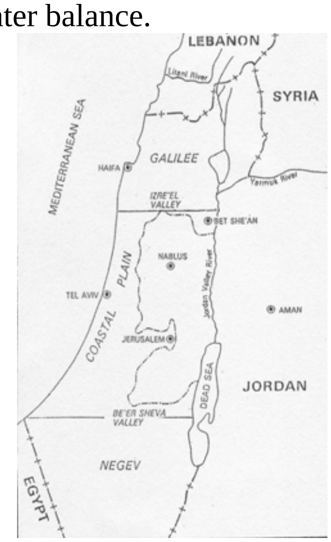

Figure 1: Location Map

THE HYDROLOGIC SYSTEM

The mountain belt splits the hydrologic system of the study area into two subsystems: A Western Drainage area towards the Mediterranean Sea and an Eastern Drainage area towards the Jordan Valley and the Dead Sea. Each of the subsystems includes groundwater basins and surface watersheds. The main source of water is groundwater supplied by pumping wells and springs.

Groundwater Basins

The study area includes four groundwater basins: The Coastal Basin and the Western Mountain Basin in the Western Drainage Area, and the Northeastern Basin and the Eastern Basin in the Eastern Drainage Area (Fig.2). The coastal basin and the Western Mountain Basin are linked to a central water conduit which pumps water from Lake Kinneret (also named Sea of Galilee) and carries it southward to meet water demands in water short areas. It is also used to regulate the supply of water by recharging the groundwater basins in the winter and in years of water surplus in the lake, and by pumping water from the basins in the summer and in years of water shortage.

The Coastal Basin is replenished by rainfall, by artificial recharge and by percolation from anthropogenic sources on the surface of the ground. It is drained by pumping wells and by outflow to the sea. The level of exploitation of the coastal basin is approximately balanced with the level of recharge, but the quality of the water is deteriorating due to the influx of salt and contaminants from the anthropogenic sources (primarily agriculture and recharge with low quality water), as well as due to intrusion of sea water in the west and inflow of brackish groundwater from a neighboring aquifer in the east.

The present estimate of the mean annual groundwater replenishment from rainfall in the study area of the basin is 240 mcm with a 28% coefficient of variation. replenishment from rainfall is gradually decreasing because of urbanization and other alterations of land use.

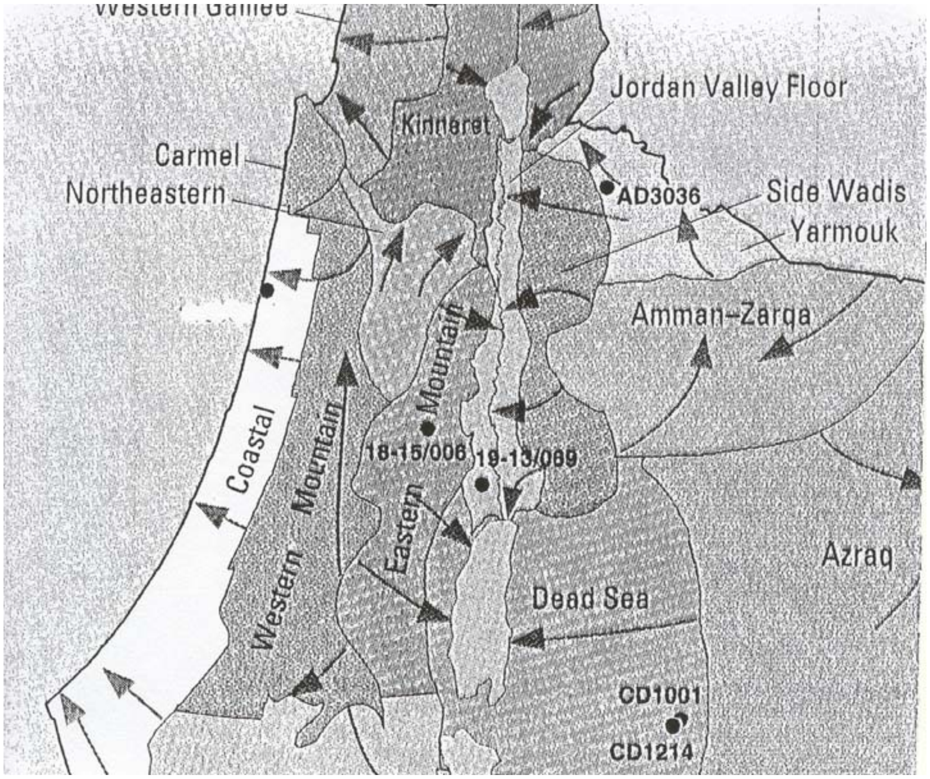

Figure 2: Groundwater Basins

The average concentration of chloride in the basin is close to 200 mg/l and continues to rise at a rate of 2.5 mg/l per year. The concentration of nitrate has reached an average value of 58 mg/l with an annual increment of 0.5 mg/l.

The Western Mountain Basin occupies an area of 6,000 sq. km. It extends from Beer-Sheva northward to the foothills of the Carmel mountain and from the crest of the Mountain Belt in the east to the Mediterranean Sea in the west . The basin has a total thickness of about 800 meters and includes two principal aquifers: an Upper aquifer, of the Turonian-upper Cenomanian age, composed of well bedded and occasionally dolomitized highly permeable limestone, including karstic zones, and a Lower aquifer, of the Lower Cenomanian-Albian age, composed of massive dolomites and limestones with a thick belt of caverns in large parts of the coastal plain. Both aquifers have outcrops in the area of the Mountain Belt and are confined in the area of the coastal plain.

The Basin is recharged by rainfall over the outcrops of the two aquifers at a presently estimated average rate of 360 MCM/yr and a 30% coefficient of variation. The natural outlets of the basin are two groups of springs : Rosh-Haayin (Ras El Ein) or Yarkon River springs which are located at the foothills in the central part of the basin and discharge fresh water, and the Taninim River springs which are located at the northwestern end of the basin and discharge brackish water . Originally, about 2/3 of the water yield were discharged through the Yarkon River springs and the rest through the Taninim. Increased pumping from the upper aquifer was accompanied by a gradual decline in springflow. The discharge of the Rosh Haayin springs ceased completely, and that of the Taninim dropped to 20 MCM/year. The extremely high rainfall in the winter of 1991/92 caused a resumption of flow from the Yarkon springs and an increase in the discharge of the Taninim. However, overdraft since 1993 has resulted again in a continuous decline of the piezometric head accompanied by an almost complete cessation of springflow from the Yarkon and a continued reduction of the discharge from the Taninim springs. Overexploitation may enhance intrusion of saline water bodies. The pumped water is of good quality, but salinity of the water is slowly increasing.

The Eastern Mountain Basin covers an area of about 3080 sq. km. The basin includes two separate aquifers: An upper of the Turonian-Upper Cenomanian age and a lower of the Lower Cenomanian age. The total thickness of the two aquifers ranges from 650 to 800 meters. Groundwater of the basin is recharged by rainfall over the outcrops of the aquifers at an average volume of 172 MCM/year and flows generally southeastward into the Jordan Rift Valley and the Dead Sea. Water levels decline from about +440 meters at the ground water divide in the west to about –320 meters at the Dead Sea. The measured discharge from the basin in 1997/98 totaled 167 MCM including springflow (124 MCM) and pumping (43 MCM). The water is pumped from the lower aquifer by two groups of wells: A western group close to the water divide and an eastern group along the fringe of the Mountain Belt. Most of the pumped groundwater is of good quality with low concentrations of chloride (less than 100 mg/l) and nitrate (less than 30 mg/l). As to the springs, they are classified into two water quality groups: Fresh water springs along the Jordan valley discharging 40 MCM/year, and saline water springs (chloride concentration 500-2000 mg/l) along the northern shore of the Dead Sea discharging about 80 MCM/year.

The Northeastern Basin occupies the northernmost part of the Mountain Belt. The basin covers an area of about 1,044 sq.km and includes two aquifers: An aquifer of Eocene age composed of limestone and chalk, and an aquifer of Turonian- Cenomanian age composed of limestone and dolomite. Both aquifers are replenished by rainfall over their outcrops at a total average volume of about 145 MCM/year. Groundwater is drained by wells, springs and by subsurface flow into the alluvial aquifers of Bet-Shean and the Jordan Rift Valley.

Surface Water Drainage Basins

Surface water in the study area drains either westward to the Mediterranean Sea or eastward to the lower Jordan River and the Dead Sea. Most of the streams carry wastewater all year round. Stream flow typically is higher in the western drainage area due to temperature and orographically induced precipitation and decreases on the eastern side of the Mountain Belt. Peak flows typically occur during February and March, lagging the peak precipitation period by about one month. Many of the streams are affected by water supply diversions and wastewater discharges.

RAINFALL IN THE STUDY AREA

The characterization of rainfall in the study area is based on the processing and analysis of historic records of seasonal and monthly rainfall depths at individual raingauge stations. The following table summarizes the contents of the rainfall data base used in this study.

Table 1: Classification of Rainfall Records Used in this Study

Region	**Number of raingauge stations with various record lengths**					
	≤ 20 years	**21 – 30 years**	**31 – 40 years**	**41 –50 years**	**> 50 years**	**Total**
Western Drainage: Coastal plain	7	15	12	20	1	55
Western Mountain	2	3	5	15	3	28
Eastern Drainage	1	4	11	8		24

Total	10	22	28	43	4	107

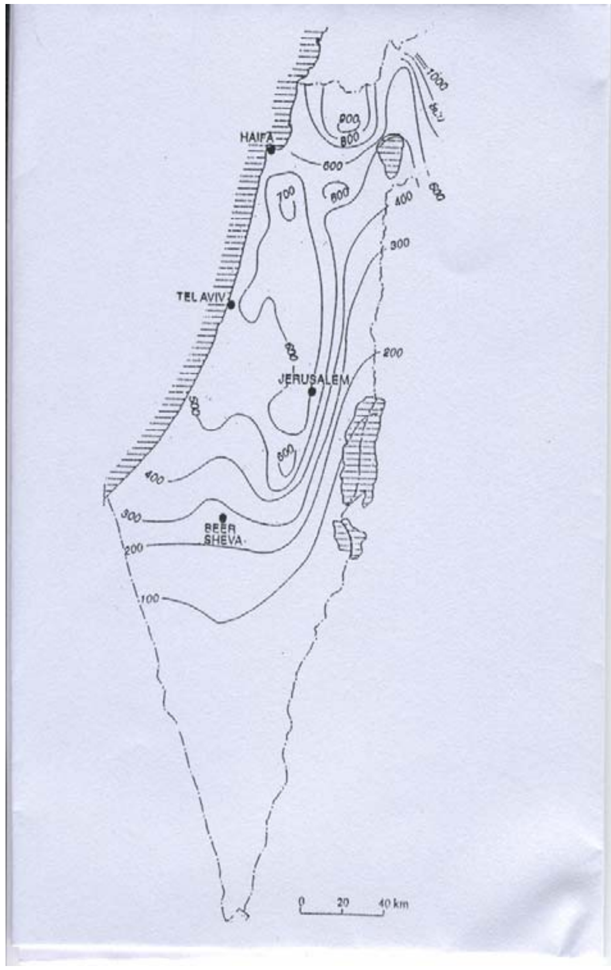

Figure 3: Distribution of mean annual rainfall

Basic rainfall characteristics

The distribution of the mean annual rainfall shown in Figure 3 depicts two distinct rainfall regions : The region west of the Mountain range where the primary variation of rainfall depth is from north southward , and the region east of the mountain range where the rainfall depth undergoes a sharp decline eastward.

Another characteristic feature of the rainfall in the study area is its random variation in time. An example of the high degree of inter-annual rainfall fluctuations is presented by the rainfall stations in

Jerusalem with the joint longest record keeping period in the study area. 24 percent of the 145 years of record deviated from the long-term average of 556 mm by more than one third. Although the deviations are random, series of wet and dry years do occur. Thus, in the period of records six series of wet years and six series of dry years are discernible.

The frequency of annual rainfall depths is asymmetric exhibiting a positive skewness with a long tail of high rainfall depths exceeding twice the average as shown below.

Table 2: Frequency of Annual Rainfall Depths in Jerusalem (1846/47 - 1991/92)

Frequency (%)	**6.9**	**10**	**22.8**	**30.9**	**17.8**	**5**	**5.9**			**0.8**
Annual rainfall depth (mm)	200 - 300	301 - 400	401 - 500	501 - 600	601 - 700	701 - 800	801 - 900	901 - 1000	1001 - 1100	1101 - 1200

The distribution of monthly rainfall within the season also varies from year to year with high fluctuations in the beginning and end of the season as shown in Table 3.

Table 3: Coefficient of Variation (C.V.) of Monthly Rainfall Depths in the Central Part of the Study Area

Month	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**
C.V.	4.4	1.4	1.0	0.8	0.6	0.6	0.7	1.2	1.8	0.6

Thus, the variation of the monthly rainfall about the average is lowest in the months of December –January and highest at the beginning and end of the season (March-April) which are the most critical months for agriculture.

Pair-wise correlation of rainfall depth at raingauge stations and similarity of statistics of the rainfall record allow a subdivision of the study area into rainfall zones and a characterization of the rainfall in each zone by a representative station with a relatively long period of record. Accordingly, the spatial distribution of the mean seasonal rainfall depth at raingauge stations in the study area depicted 5 rainfall zones ranging from over 600 mm/year on the Mountain Belt down to 200 mm/year at the southern end of the area.

Driven by the interest in drought, the statistical analysis focused its attention on the occurrence and recurrence of rain deficient years, i.e. years with rainfall below the average. To this end , the following definitions were introduced:

Rain deficient year: A meteorologic year with cumulative rainfall depth below its average over the period of record
Rainfall deficit: Difference between the average rainfall depth and the cumulative rainfall depth in a rain deficient year
Relative rainfall deficit: The ratio between the rainfall deficit and the average

The analysis was based on time series of rainfall at the selected stations and addressed the following questions:
What information do the data provide about the frequency of:
a) occurrence of a rain deficient year
b) occurrence of a rain deficient year within a given range of deficit
c) recurrence of a rain deficient year
d) occurrence of a series of rain deficient years

It was found that the frequency of occurrence of rain deficient years is more than a half of the total and tends to increase southward. The period of return of two consecutive rain deficient years rises from 6-8 years at the north and south ends of the region to 3 years at the center.

Of particular interest to the study was the relative magnitude of the rainfall deficit i.e. the ratio of the deficit to the average. It was found that the frequency of rain deficient years declines exponentially as the magnitude of the relative deficit increases. Accordingly, the return periods of relative deficits less than 20%, 20 to 30 % , 30 to 40% and over 50% , were found to be 7 years, 15 years, 24 years and 56 years, respectively.

Another phenomenon of importance to the planning of drought management is the occurrence of series of rain deficient years. Here too, the frequency of occurrence of a series declines exponentially with its length. Thus, a single rain deficient year between two rainfall years above the average occurs at a frequency of 62% of the total number of rain deficient years, whereas 2, 3 and 4 year long series occur at frequencies of 21%, 12% and less than 2%, respectively.

The most seldom case was a series of 6 successive rain deficient years with 0.9 % frequency of the total number of rain deficient years.

1998/99 AS A YEAR OF DROUGHT

The area experienced in the last decade two extremes in the 100 year long history of rainfall records : A record maximum in the winter of 1991/92 and a record minimum in the winter of 1998/99 (Israel Hydrological Service, 1999).

The distinct features of the 1998/99 rainfall are an extremely high rainfall deficit over most of the study area and extreme deviations of the monthly rainfall depths from their long term mean values. At ¾ of the stations the rainfall depth in 1998/99 was the lowest over the entire period of record .

In the coastal plain, the cumulative rainfall depth in 1998/99 was less than 50% of the long term mean annual value. The corresponding relative rainfall deficit rises from 53% in the north to 63% in the south.

At 21 raingauge stations (out of 29 stations with more than 30 years of records) the cumulative rainfall depth in 1998/99 was the lowest over the entire period of record. One of these stations is at the oldest agricultural school in the country with 90 years of rainfall records. The Lognormal probability of non-exceedance of the 1998/99 rainfall depth at this station corresponds to an extreme event with a return period of 100 years.

A comparison of the monthly rainfall depths in 1998/99 at the above station with their long term mean values shows that in all months of the season, except for January and April, the rainfall depths do not exceed 40% of their respective mean values. Moreover, in the months of October and November, which are most critical for agriculture, the rainfall depths were only 11-13 percent of the mean, i.e. a relative rainfall deficit of over 87 %. At the end of the season, the cumulative rainfall depth at that station was only 49 percent of the mean .

The deviation of the monthly rainfall depths in 1998/99 from their mean values is expressed in terms of the average ratio of frequencies at the selected raingauge stations and the spatial variability of the

ratio. In the central part of the coastal plain, frequency ratios below the average in the first months of the season and in the peak months of January and February are compensated by extreme frequency ratios above the average in December and March. The spatial distribution of the deviations is highly non-uniform.
The relative monthly rainfall deficit is highest in October (93%), drops to a minimum in January (16%) and goes up again toward a maximum in March (88%).

In the Western Mountain area, the 1998/99 rainfall depth was less than 50% of the long term mean at 70 percent of the raingauge stations. At all of the selected stations , except for one at the northern end, the relative rainfall deficit was about 60% . The 1998/99 rainfall depths at these stations have less than 1 percent Lognormal probability of non-exceedance.

A comparison of the monthly rainfall depths in 1998/99 with their long term mean values at the selected stations shows that in all months of the season, except for January and April, the average rainfall depth at the selected stations does not exceed 44% of the respective mean value, which corresponds to a relative monthly rainfall deficit of 56%. The highest relative rainfall deficit occurs in November (93%). The maximal deviation of the rainfall distribution within the 1998/99 season from the average occurs in the period October – December. The rainfall at the northern end has in most of the months a smaller relative deficit than in the rest of the area, and even exceeds the mean value in December.

In the Eastern Drainage area, the start of rainfall was delayed for about three months, i.e. rainfall started in January instead of the middle of October. Monthly values of rainfall depth were much less than the average values, and the total annual depth of rainfall at the selected stations was the minimum recorded value over the whole period of data.

In the months of October and November which are most critical for agriculture, the rainfall deficit was over 95% of the average, in December - 70%, in January and February about 40%. From March on there was no rain at all.

HYDROLOGIC IMPACT OF THE 1998/99 DROUGHT

Effects on Groundwater

An analysis of the groundwater balances in the basins of the Western Drainage area has shown that the state of the groundwater in those basins in the hydrologic year 1998/99 was affected by two factors:

a. *The magnitude of the rainfall deficit* which reduced the replenishment of the basins to a record minimum of 47% of the long term average in the Coastal Basin and 39% of the long term average in the Western Mountain Basin. The total replenishment deficit in the two basins was 360 million cubic meters which is nearly equal to the mean annual volume of water pumped from the Lake, or nearly a half of the annual volume of water pumped from the two basins.

b. *The drastic increase in the pumped volume* due to both the low rainfall in the beginning of the season and the need to cover the deficit of water supply from the Lake Kinneret.

Corellation between the depth of annual rainfall and the annual volume of pumpage has shown that years of low rainfall are accompanied by high rates of annual pumpage and vice versa. Indeed, the highest record level of rainfall in 1991/92 was accompanied by the highest historic drop of 26% in the pumped volume, whereas the lowest level of rainfall in 1998/99 carried a record increase of the pumped volume by 30% in one year.

The overdraft in the year 1998/99 was covered by three sources:

a. *Mining of water from storage*, which exhibited itself in the drop of groundwater levels in both basins

b. *Reduction of outflow to the sea* in the Coastal Basin, and

c. *Inflow from unidentified sources* into the Western Mountain Basin.

All of the three sources are responsible for the rise in the salinity of the pumped water.

Another effect of the 1998/99 drought on water quality in the Coastal Basin was the lack of fresh water for artificial recharge of the basin, while recharge with reclaimed wastewater which is more saline than the native groundwater went on at a constant rate.

The changes in pumping rates, spring discharges, groundwater levels and salinity which were observed in the Eastern Drainage area in the year 1998/99 showed a drop in groundwater levels accompanied by a reduction in springflow and salinity.

This phenomenon of positive relationship between water levels and salinity is opposite to what was the case in the Western Drainage area and requires explanation. However, the type of impact analysis which was carried out in the Western Drainage area could not be applied in the Eastern Drainage area because of the lack of a calibrated mathematical model of the groundwater basins in the area. First steps towards developing such a model were made in course of the study by multiple linear regression aimed at establishing quantitative relationships between rainfall and springflow, as well as between rainfall and change in groundwater levels.

Effects on Surface Water

The volume of runoff in the Western Drainage Area in the year 1998/99 was only 34% of its long term average. Most of the streams in the area carry poorly treated wastewater throughout the year. Mixing with fresh water from runoff in the winter season reduces the level of pollution. One adverse effect of the 1998/99 drought was degradation of stream water quality due to the low runoff. Another adverse effect was the drying up of some of the streams because of enhanced pumping for irrigation during and after the winter of 1998/99 and the subsequent harmful effect on aquaculture.

CONCLUSIONS

- Seasonal and inter-seasonal variations of rainfall are characteristic features of the region. As such they must be taken into account in planning the short - and long - range exploitation of the region's water sources.
- The rainfall data base and the statistics of monthly and annual rainfall depths which were derived in course of the study can be used to derive probability distributions as an input to the forecast of drought conditions in the area.
- Adaptation of pumping rates to fluctuations of natural replenishment can be achieved by adopting a dynamic operating rule which contains two components:

a) A fixed component representing the permissible minimum pumping rate regardless of the actual state of the groundwater (storage and quality), and b) A variable component which represents an added pumping rate as a function of the actual state of the groundwater , the statistical characteristics of the rainfall and the required reliability level of supply.

- The level of monitoring rainfall and the hydrologic system in the Eastern Drainage area, as well the level of modeling the hydrologic system there, fall short of those required for planning the management of drought conditions in this area. The regression analyses carried out in course of the study are initial steps in modeling the groundwater system in the Eastern Drainage area which need to be continued.

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