TR/BR-12/1999-2000

WATER BALANCE OF SAGAR LAKE

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667 (UTTARANCHAL)

PREFACE

There are different opinions about the existence of Sagar lake. Historical records witness an artificial origin whereas geological evidences are in favour of natural origin. Like other lakes, the Sagar lake is also facing severe problems. The quality and life of lake are diminishing because of high rate of silt deposition, inflow of waste water and farming of flora and fauna.

In order to understand the important aspects of the lake and for better planning and management, the water sources and availability of water at different times, the hydrological studies like water balance, sedimentation pattern and water pollution aspects are essential.

The water balance provides quantitative individual contribution of sources of water in the system over different time periods and establishes the degree of variation in water regime due to changes in components of the system. The present report contains the methodologies adopted and the quantification of various inputs, output and storage parameters. The monthly water balance for the lake has been prepared and presented in the report.

This report has been prepared by Sri. Surjeet Singh, Scientist-B and Sri. L.N. Thakural, SRA as per work program of GPS Regional Centre, National Institute of Hydrology, Sagar (M.P.). The guidance and assistance for completing the study have been provided by Dr. Bhishma Kumar, Sc-E and Head, Nuclear Hydrology Division, NIH, Roorkee and Sri. S.K. Singh, Sc-E and Head, RC Sagar.

(K.S. Ramashastri)
Director

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Lakes play an important role in shaping the hydrological, ecological and environmental balance of the region by developing flora, fauna and habitation of aquatic biota. Like other lakes of the world, Sagar lake is also facing manifold problems of siltation and deterioration of water quality, thus, threatening the survival of the lake.

Previously most of the scientific studies carried out on the Sagar lake have focused on the physico-chemical properties of the lake water and the possible inter-relationship and interaction between their properties and biological factors like plankton, macrophytes, macrofauna, etc. Therefore, to understand various hydrological processes of the lake, water balance study has been carried out.

The present study has been carried out for the quantification of various water balance components like inputs and outputs and thus to visualise the influence of these parameters on the storage changes.

The outcome of the study will be very much helpful in proper management of the lake water and in conducting other relevant hydrological studies leading to conservation of the valuable lake water for the community.

1.0 INTRODUCTION

There are about three million lakes on the earth and more than 70% of the world's fresh water occurs on three continents - North America, Africa and Asia. Generally, lakes receive water as precipitation on the surface, through runoff to sea and from the groundwater entering as springs. The total area of all the lakes on the earth is 2.7 X 10^6 km^2 and their total volume 1,66,000 km^3. A lake is an inland body of water filled or partially filled by water whose surface dimensions are sufficiently large enough to sustain waves capable of producing a barren, wave- swept shore (Zumberge and Ayers, 1964). Lakes are either manmade or natural reservoirs which store water during its passage to sea. Lakes are formed by some geological processes like subsidence, large scale faulting, damming valleys by rock falls, gorging action of glaciers, etc. As a summary, a water body should fulfil the following requirements to be a lake:

(1) It should fill or partially fill a basin or several connected basins.
(2) It should have essentially the same water level in all parts with the exception of relatively short occasions caused by wind, thick ice cover, large inflows, etc.
(3) It should have so small an inflow to volume ratio that a considerable portion of suspended sediment is captured.
(4) It should have a size exceeding a specified area, e.g. 0.01 km^2, at mean water level.

Being the valuable natural resource, lakes have always been of great importance to mankind. From ancient times they have been providing water for domestic purposes. Since long, lake water is being used for industrial and irrigation purposes. Lake is also one of the means of transport and has always attracted the attention of human beings from the recreational point of view. Lake is also a place for sanctuary for migrating birds, development of flora and fauna and an excellent spot for habitation of aquatic biota which are important for maintaining the ecological and environmental balance and the hydrological cycle. Some of the saline lakes are also useful sources of important minerals. In short, a lake is a sort of catalyst in the development of a city, region or a country as a whole. Where natural lakes are absent, man has constructed artificial reservoirs for water storage, flood control, hydroelectric power generation and other purposes.

In a global prospective, the most important problems concerned with lakes are:

(1) Lowering of lake level due to excessive use of water.

(2) Rapid siltation caused by accelerated soil erosion in the catchment.

(3) Acidification of lake water due to acid precipitation.

(4) Concentration with toxic chemicals.

(5) Eutrophication.

(6) Disintegration of aquatic system is a possible end result of any of the above.

Knowledge of the hydrology of lakes is essential for their proper use and conservation. Water quality is also closely linked to water and energy budgets, mixing, stratification and other physical aspects of lakes. The quantitative estimation of the thermal and biological processes is impossible without a morphometric description of a lake.

Hydrologic characteristics of lakes vary because of variation in depth, width, surface area, basin material, surrounding ground cover, reservoir, prevailing winds, climate, surface inflows and outflows and other factors. Therefore, each lake requires its own hydrological models and these models need to be characterized by different degree of variance from a generalized conceptual model.

1.1 Need And Scope Of The Study

Sagar lake is infested with environmental, ecological, biological and hydrological problems. Lake water quality is deteriorating day by day because of flora and fauna weed control in the lake water and more and more developmental activities in the catchment area. Though Sagar division receives rainfall above national average, the major portion of small lake dries during pre-monsoon season. The life of lake is also decreasing because of sediment entering into the lake through city waste water and catchment runoff during monsoon season. Previously no detailed hydrological study of water balance has been done on the lake. Thus, to identify various inputs, output and storage volume of the lake, water balance study was undertaken.

Keeping in view the above aspects, the water balance study on the Sagar lake is done. Since the study involves a variety of data on various aspects such as geographical, geological, meteorological, hydrological, etc, and their processing, analysis and interpretation in various forms, the complied data and outcome of the study will be very much helpful to cope up with manifold problems of the lake and its proper management. Various components of water balance will also be helpful in conducting other relevant studies in future such as sedimentation study, water quality study, etc. The study will help in:

(i) forecasting of the lake levels for shoreline and property utilization.

(ii) designing, selection and operation of forecasting model.

(iii) predicting environmental impacts i.e. preservation of living resources through the maintenance of water quality standards.

(iv) obtaining valuable information base for effective management.

(v) global studies of climate variability.

2.0 REVIEW OF LITERATURE

Amongst the early investigators who stressed upon the groundwater flow pattern around a lake are Mayboom (1966), Williams (1968) and Janquet (1976). Bergstorm and Hansen (1962), Skinner and Borman (1973) and Cartwright et al. (1979) have computed the groundwater flow from the Michigan lake. Bergstorm et al. (1962) calculated the groundwater component as residual term. Skinner and Borman (1973) also estimated the groundwater component as the residual of the water balance equation but Cartwright et al. (1979) made direct measurements of hydraulic gradients in the southern part of the Michigan lake. The wide variations between their estimates in seepage rates indicate the need of refined methods for determining the groundwater flux from lakes.

Allred et al. (1971), Sloan (1972) and Mc-Bride (1969) measured the groundwater flow from lake with the help of water level observation wells. Some insight into the groundwater regime of discharge estimates was provided by Winter (1976, 1978), who used two and three dimensional steady state models applied to hypothetical groundwater-lake systems.

Winter (1976, 1978, 1983, 1986) has shown in a series of papers that a variety of hydrologic conditions within the groundwater system influence the quantity and distribution of seepage to lakes. Specifically, he has shown that the hydraulic heterogeneity within the transporting media can concentrate or dissipate seepage. However, he simulated lakes as having no lake bed sediments.

Rinaldo-Lee and Anderson (1980) conducted investigation into the cause of high levels for Bass Lake during the early 1970's in a groundwater dominant lake in North Western Wisconsin. A groundwater flow model was used to determine whether increased recharge rates of the magnitude that probably occurred as a result of average precipitation in the early 1970's would be significant to account for the observed rise in the lake level or whether regulation of the water level in the reservoir would be expected to affect the lake level.

Anderson and Munter (1981) studied the development of groundwater mound near Snake Lake by means of two dimensional transient groundwater flow models. The areal flow model was used to demonstrate the effect of stagnation zone on the water budget of lake.

Almendinger (1990) has analysed the variation in lake water level due to various inflows and outflow components to/from the lake. A review of a simple analytic groundwater model of a water table between two infinitely long canals demonstrates that a shift in groundwater recharge changes the water-table elevation most near the middle of the interfluve. Three types of lake-level sensitivities (two local and one regional) are defined as the partial derivative of lake level with respect to : (1) lake size (radius); (2) lake pumping rate; and (3) regional groundwater recharge. Lakes far from rivers are more susceptible to lake-level change than are lakes close to the rivers.

Shaw and Prepas (1990b) have evaluated the near shore seepage patterns to quantify the seepage in lakes using Manto-Carlo simulation model. They observed the seepage velocities to be log-normally distributed within a small area of lake bed and positively correlated with mean seepage flux. The statistical parameters of seepage flux were evaluated. The modelling indicates that the most sensitive parameter affecting the accuracy of seepage meter estimates of seepage patterns and average seepage flux along the transact was the variability in the spatial distribution of seepage flux within a small area of lake bed.

Singh and Seethapathi (1986) analysed the flow pattern beneath a hypothetical lake with assumed setting of boundaries. They used USGS groundwater flow model and based upon the results of transient simulation, they developed type-curves for the assessment of recharge from a lake assuming the aquifer to be homogeneous and isotropic and lake to be of square cross-section having uniform depth.

Prof. W.D. West (1964) (vide Krishnan, 1967) suggests different theories of existence of the Sagar lake. Historical records assign an artificial origin whereas geological evidences are in favour of natural origin of the lake (Mishra, S.K., 1969). The Water Resources Department, Sagar, M.P. has estimated the annual rate of silt deposition as 0.062 ha-m per sq.mile of catchment area. Recently in a project , Forest Department, Sagar, M.P. has estimated the total annual quantity of silt deposition to be 0.45 ha-m in which 55 % is contributed from the built-up free catchment area of 4.08 sq.mile and rest is contributed from the built-up free catchment area of 3.22 sq.mile of the feeder Kanera canal. In another project by PHED, Sagar, M.P. (1997) it is said that the silt deposition in the whole area of small lake is at the rate of 3.25 cm-layer per year and with the present rate of siltation the small lake will be filled up in the next thirty to forty years.

Most of the scientific studies carried out on the Sagar lake have concentrated on the physico-chemical properties of the lake water and the possible inter-relationship and interactions between their properties and biological factors like plankton, macrophytes, macrofuna, etc. The first study of this kind on the micro-biological aspects was published in the year 1975 (Adoni, 1975). Thereafter a number of studies on the lake water were published in the year 1980 (Awatramani, 1980), 1986 (Yadav, 1986) and 1990 (Yatheesh, 1990). Among these studies, most of them are Ph.D. thesis available in the university library and some are state govt. publications.

Among the studies on the Sagar lake, diurnal variations have been studied by Saxena and Adoni (1973), Thakur and Bais (1986) and Joshi (1987). Studies related to Macrophytes have been done by Singhal (1980) and Yadav (1986) and Yatheesh (1990) has studied the trophic status with special reference to macrobenthic-invertebrates. Awatramani (1980) and Ghosh (1986) have done limnological studies of some aquatic ecosystems of Sagar lake. Some ecological studies on and surrounding the lake have been done by Saran (1980), Babu and Tamrakar (1987) and Gupta (1987). Thakur and Bais (1986 & 1987) has conducted chemical analysis of lake water. Awarwal and Bais (1991) has done the hydrobiological study on the lake. The general observations of these studies show a high trophic status and a high organic pollution level in the Sagar lake. Recently one status report has been prepared by Sinha and Thakural (1998). In this report, efforts are made to compile all possible published work on the Sagar lake. This includes brief description of the histrological and the geographical background of the lake, details of water quality analysis carried out in various years, present status of the lake and various schemes proposed and implemented for the improvement of pathetic condition of the lake. The studies done on the Sagar lake have focused on biological, chemical and ecological aspects. No literature is available on the hydrological aspects of the lake.

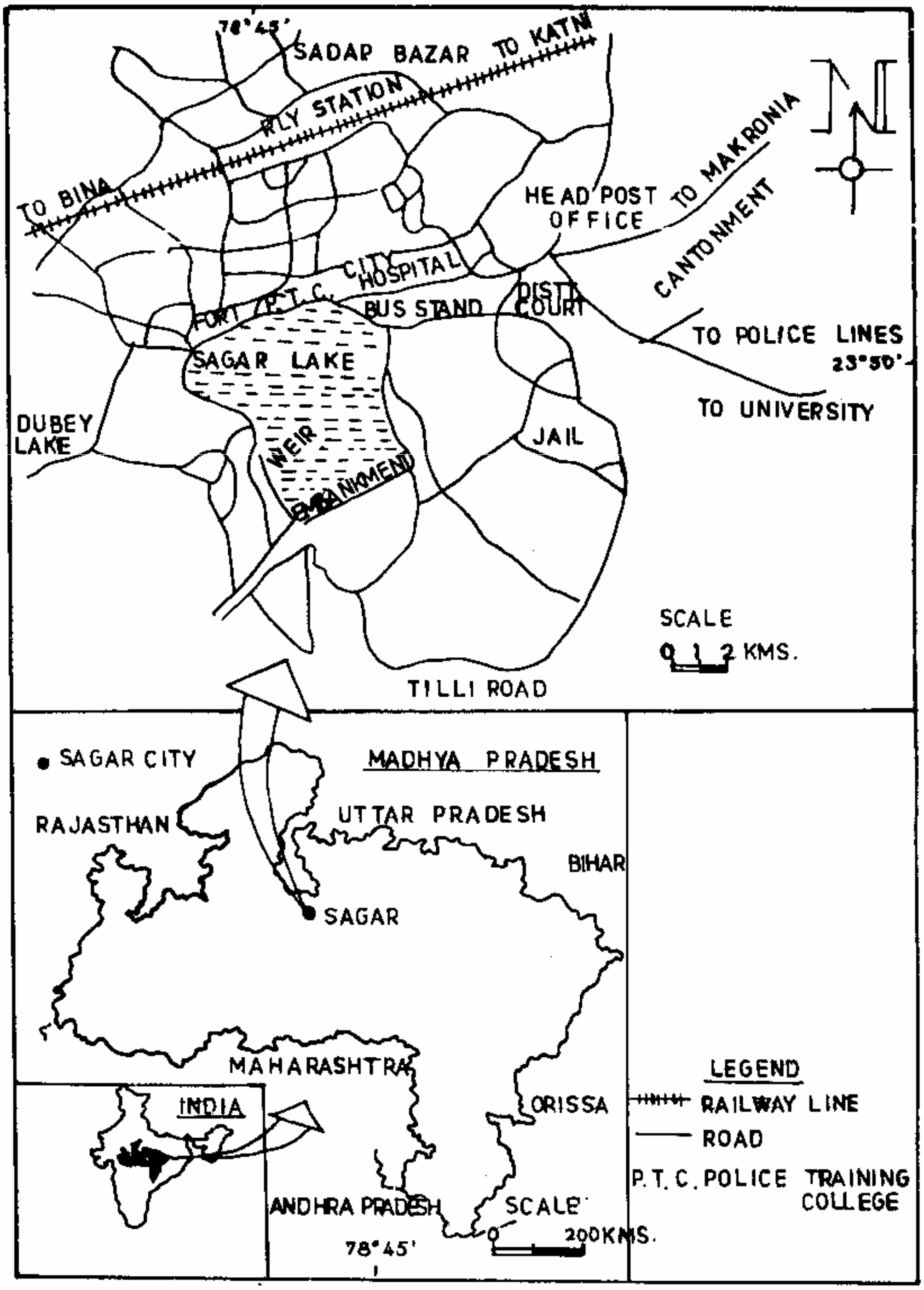
3.0 STUDY AREA AND DATA

The lake under investigation is situated in the middle of the city Sagar district of Madhya Pradesh. Sagar city falls a few kilometres to the North of Tropic of Cancer at an altitude of 517m and at the latitude of 23° 50' N and longitude of 78° 45' E and it can be seen on toposheets No. 55I/13 and 55I/9. The District is named after this waterbody indicating the historical significance of this lake. This waterbody was the source of perennial water supply to the town nearly half a century since 1912, tells the tale. The lake has periphery of 5230 m with maximum length 1247 m, width 1207 m. Mean depth of the lake is 2.48 m with maximum depth of 5.3 m at full tank level. The lake is divided into two parts, the main lake with water spread area of 107.7 ha at full tank level and the small lake with water spread area of 37.03 ha. The volume of the lake is 389 ha-m at full level. The catchment area of the lake basin is 1817 ha, out of which the total water spread area is 145 ha. at full tank level. The landuse pattern of the basin is 40.9 % barren land, 20.9 % agriculture, 18.7 % settlement, 11.5 % open forest and 8.1 % water body. The index map and geomorphological map of the Sagar lake catchment are shown in Fig. 1 and 2.

3.1 Geology And Geomorphology

The geological formation of the lake bed mainly comprises of quartzite sandstone of Vindhyan age and the Deccan traps. The Deccan traps are basaltic in nature having vertical, polygonal and columnar joints. The Vindhyan quartzite sandstone is hard and compact with nearly vertical joints. The bedding planes are thickly bedded and horizontal having low porosity. These joints behave like channels for water infiltration. The ground water recharge is very poor, i.e., only 10 to 15 % of the total rainfall is percolated to the ground water (Krishnan, 1967).

The soils of this area are of two types - the red or reddish brown lateritic soil on hill tops and the black soil at the foothills. The vegetation of Sagar district can be included under Northern tropical dry deciduous forest (Krishnan, 1967).



(SOURCE: AGARAWAL, 1991)

FIG.1: INDEX MAP OF THE SAGAR LAKE

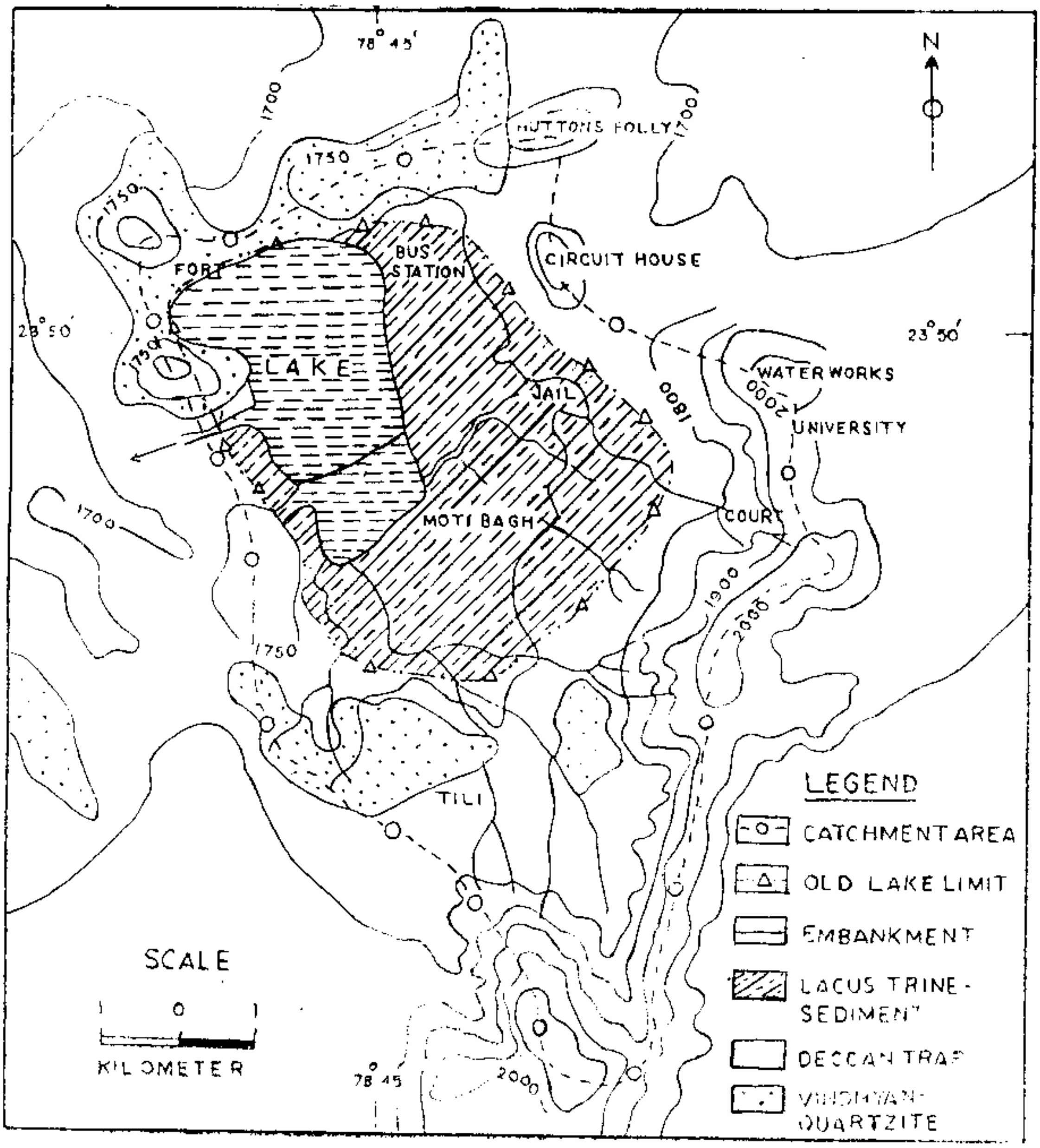


Fig. 2 : Geomorphology of the Sagar lake

3.2 Data Requirements

The following data are generally needed for the estimation of hydrological balance of a reservoir basin:

1. Map of the basin with all the channels marked on it.
2. Map showing type and location of raingauges.
3. Map showing location of observation wells.
4. Rainfall data from a well-distributed network of raingauges over the basin.
5. Groundwater levels in observation wells spread over the basin.
6. Record of canal discharges at different control points.
7. Length, cross-section and other design detail for all canals, distributories and minors and their command areas.
8. Landuse pattern in the basin.
9. Cropping pattern.
10. Location of tanks, reservoirs, etc. and their monthly water levels.
11. Data on geology and aquifer characteristics.
12. Data on evaporation, temperature, relative humidity, sunshine hours, wind velocity, etc.
13. Lake water level.
14. Inflow-Outflow data of the lake.

3.3 Sources Of Data

The primary data collected during this study include daily water level of Sagar lake and surrounding wells and discharge measurements in Kanera canal during the monsoon season. The other required data were collected from various Government departments such as Water Resources Department, Sagar; Land Records Department, Sagar; Nagar Nigam Office, Sagar; Indian Meteorological Department, Nagpur. Landuse pattern and cropping pattern, etc. were collected from the Department of Agriculture, Sagar. Geological information was collected from the Department of Geology, Dr. H.S. Gour University, Sagar.

4.0 WATER BALANCE

The main source of water for the Sagar lake is rainfall during monsoon season and little quantity of city waste water that flows into the lake throughout the year.

4.1 Methodology

The water balance equation is derived from the mass balance, i.e., continuity equation. This balance states that all waters entering into a storage basin during any particular period of time must either go into storage, consumed or go out during that period. The general water balance equation may be written as

$$\Delta S = I - O \quad \ldots \quad (1)$$

where ΔS = change in lake storage
I = inflow to the system
O = outflow from the system

In case of the Sagar Lake, the inflow includes surface inflow (S_i), subsurface inflow (SS_i), inflow of city waste water through drains (D_i) and direct precipitation (P_i) over the lake surface. The outflow term includes overflow from Mogha weir (W_o), leakage through Mogha weir (L_o), siphon out of water over Mogha weir (S_o) during summer season, subsurface outflow (SS_o) and free water evaporation (E_o). Incorporating these components, eq. (1) could be written as

$$\Delta S = S_i + D_i + P_i + SS_i - E_o - W_o - L_o - S_o - SS_o \quad \ldots \quad (2)$$

The computation of different components is presented below.

4.1.1 Precipitation

A raingauge station of the IMD observatory is located in the catchment area of the lake near the Collectorate office. The daily rainfall data of this observatory has been collected from the Indian Meteorological Department, Nagpur, Maharashtra. The average daily rainfall data during the study period have been plotted (cumulative) and shown in Fig. 3. Major part of rainfall occurs during the monsoon season and very less amount of rainfall occurs in non-monsoon period.

4.1.2 Lake Area and Volume

The topographical map of the lake was collected from the Water Resources Department, Sagar (M.P.). The spread area of the lake at full tank level and at different contour levels was computed manually using the Digital Planimeter.

A variety of methods are available for the estimation of lake volume. The volume of Sagar lake has been estimated using depth contours (Rodda,1985). The area enclosed by successive pairs of depth contours is average out and multiplied by the contour interval to yield a series of volume elements which are then summed using the following relation

$$V = \sum_{i=0}^{n} \frac{l_c}{3}\left(A_i + A_{i+1} + \sqrt{A_i \cdot A_{i+1}}\right) \qquad \ldots \qquad (3)$$

where V = volume element

l_c = contour - line interval

A_i = cumulative area within the limits of the contour line I

n = number of contour lines

The relation between area, elevation and volume was not available for the Sagar lake. These relationships have been developed and are given in Table 1 and are shown in Figs. 4 and 5.

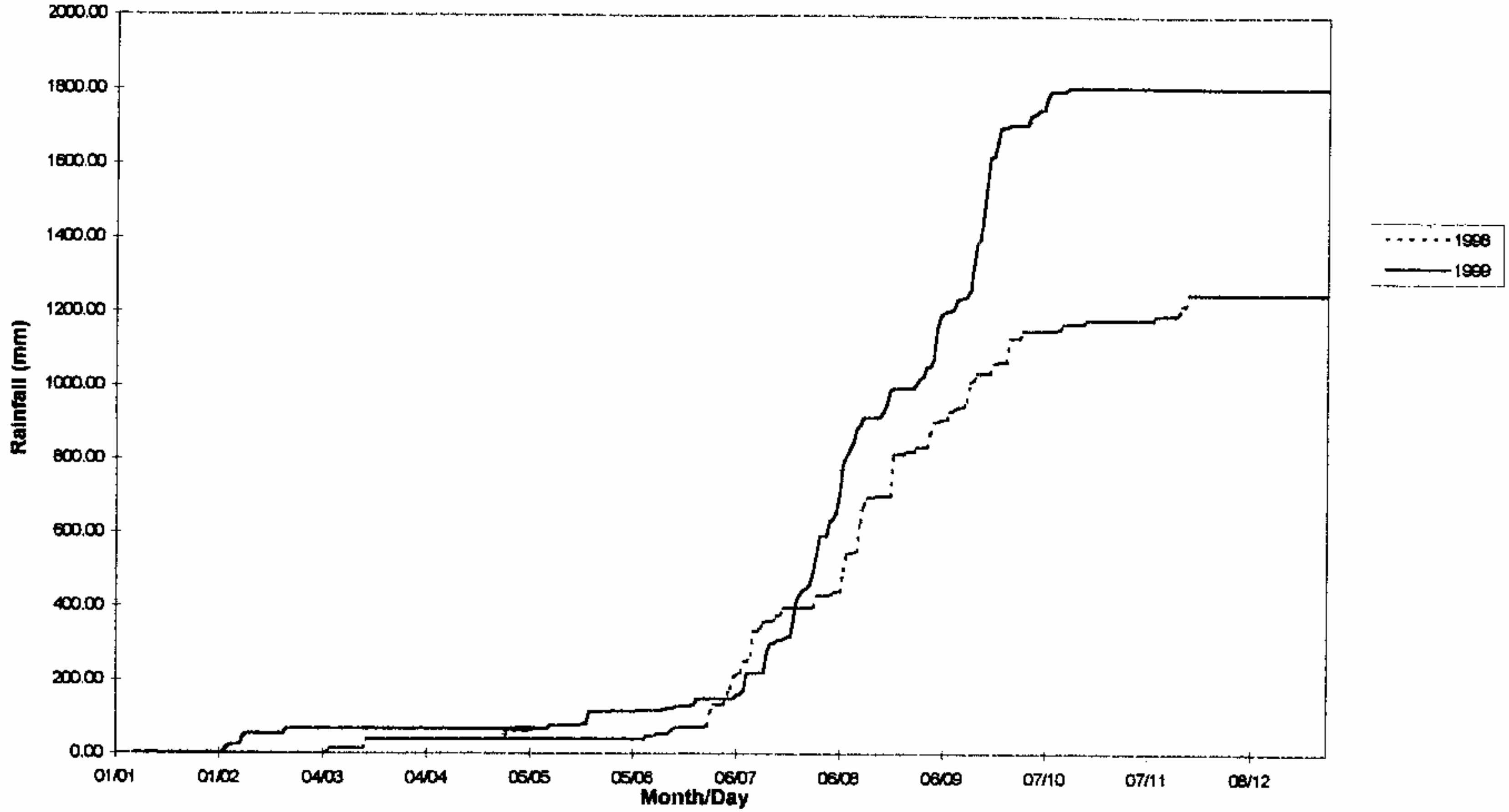


Fig. 3 : Cumulative rainfall (mm) in Sagar Lake catchment during 1998 and 1999

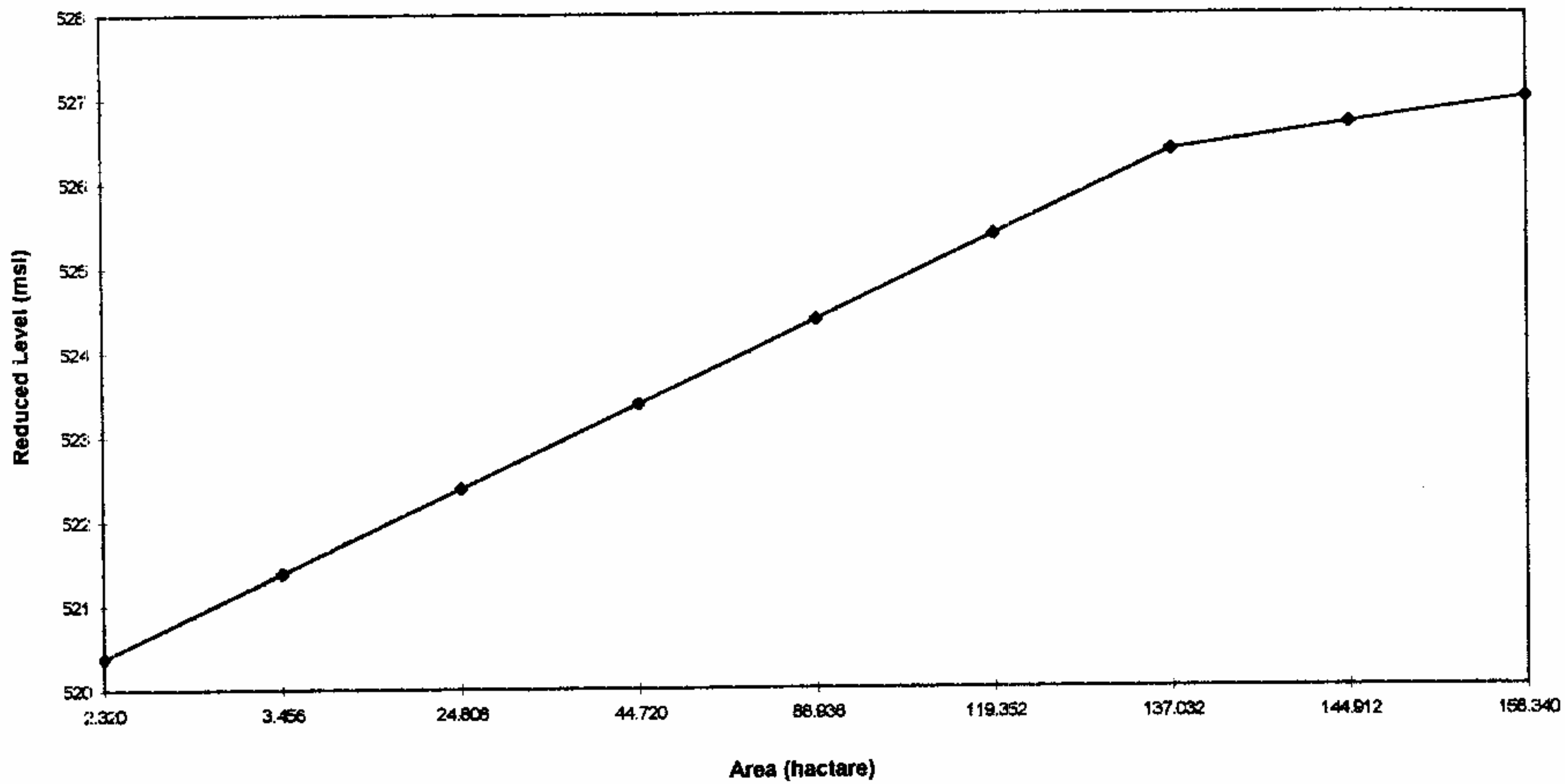


Fig. 4 : Variation of surface area of Sagar Lake with depth

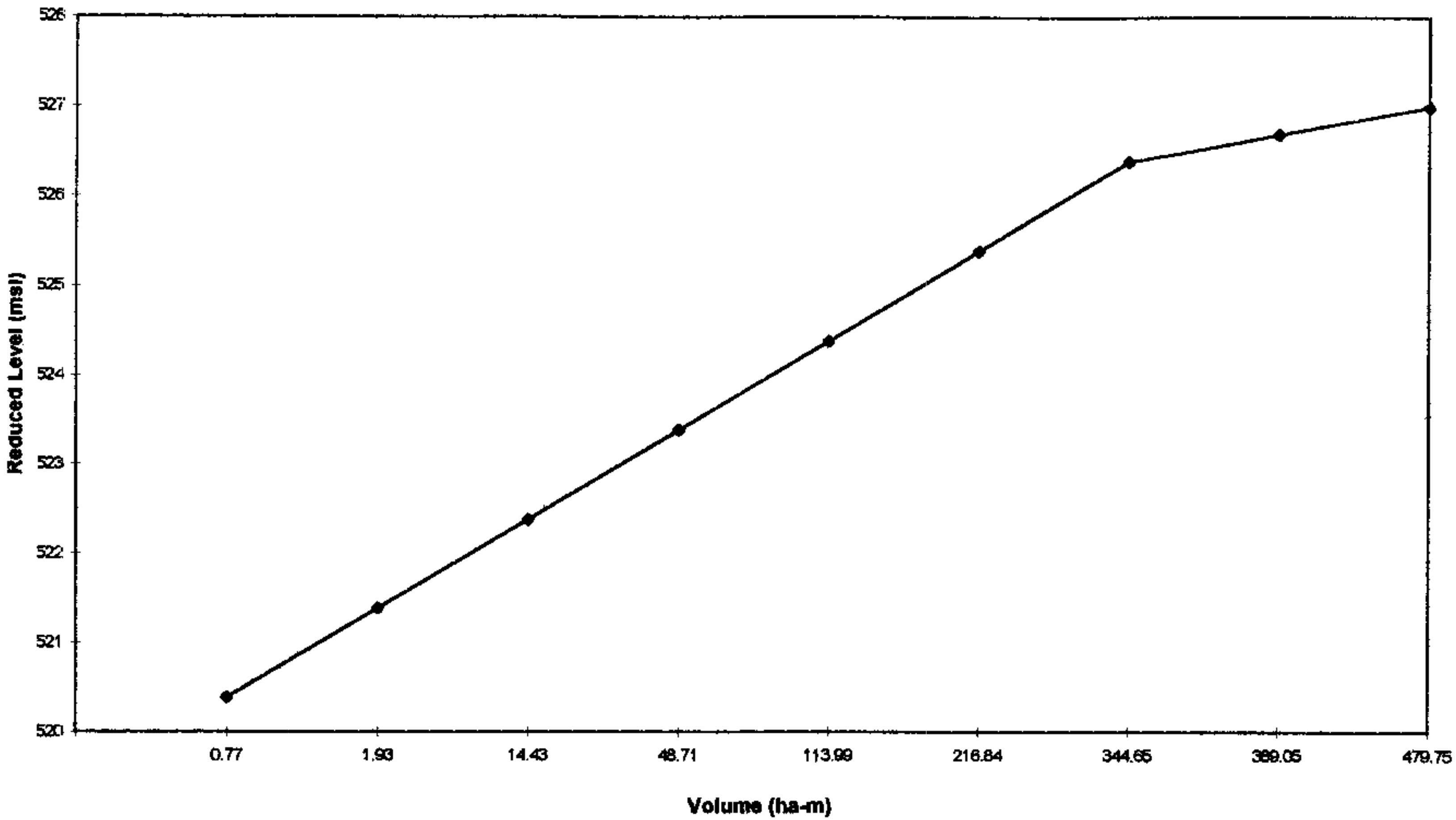


Fig. 5 : Variation of volume of Sagar Lake with depth

Table - 1 : Lake area and volume at different depths

R.L.	Area	Volume
(m)	(1000 m^2)	(1000 m^3)
520.385	23.2	7.7
521.385	34.6	19.3
522.385	248.1	144.3
523.385	447.2	487.1
524.385	889.4	1,139.9
525.385	1,193.5	2,168.4
526.385	1,370.3	3,446.5
526.700	1,449.1	3,890.5
527.000	1,583.4	4,797.5

4.1.3 Change in Storage

The lake level changes with time as a natural phenomenon. However, the change in storage can be seen with the change in water level in 24 hours or in a month or in a year. The increasing or decreasing trend of the storage can be studied with the daily observations of the lake water level. The changing trend of lake storage will help in understanding the various processes going on with the lake and the quantitative assessment of lake water at different times.

The water level of Sagar lake is being monitored manually almost daily at the Mogha weir site. For estimation of storage change, the measured water levels were analysed to visualise the increasing or decreasing trend of water level with time. The daily water level variation for each month during the year 1999 has been plotted and shown in Figs. 6 and 7. The variation of lake stage with rainfall for the year 1999 has been shown in Fig. 8. The decline of water level is almost gradual and uniform as a result of evaporation and siphoning out. However, the abrupt changes in water level are seen in the month of August and September because of heavy inflow and overflow of water.

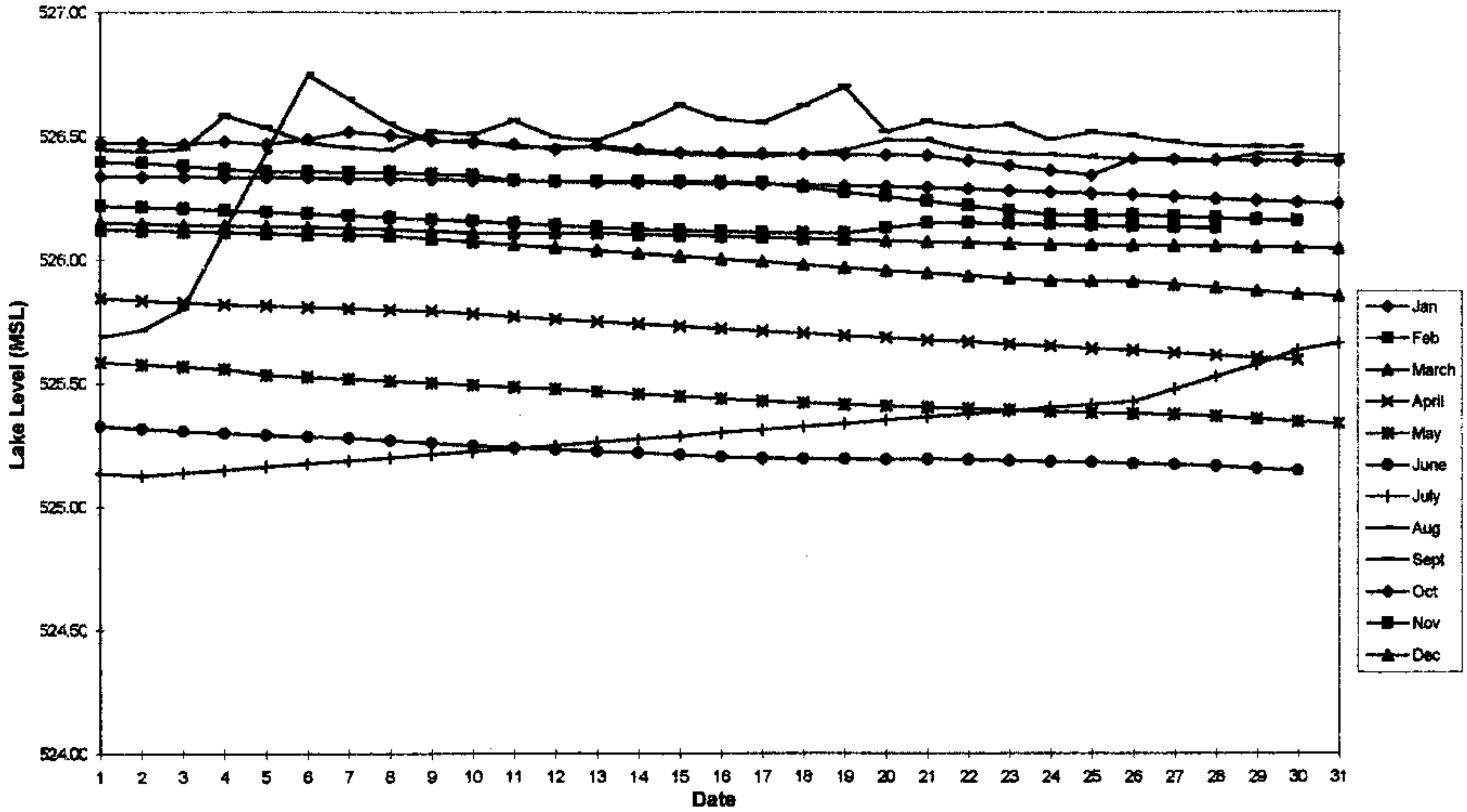


Fig. 6 : Daily variation of lake level during the year 1999

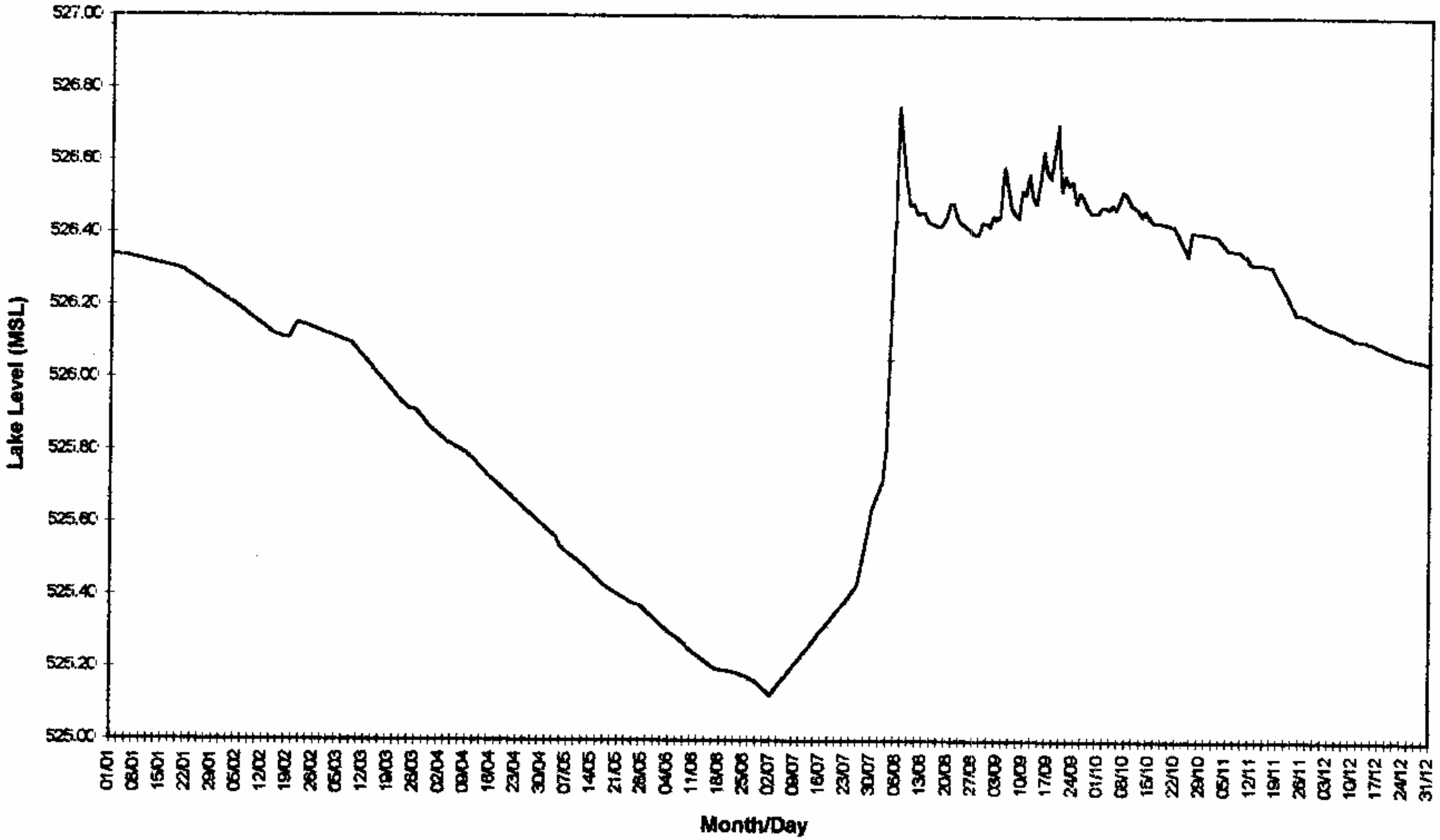


Fig. 7 : Variation of water level of Sagar Lake with time during 1999

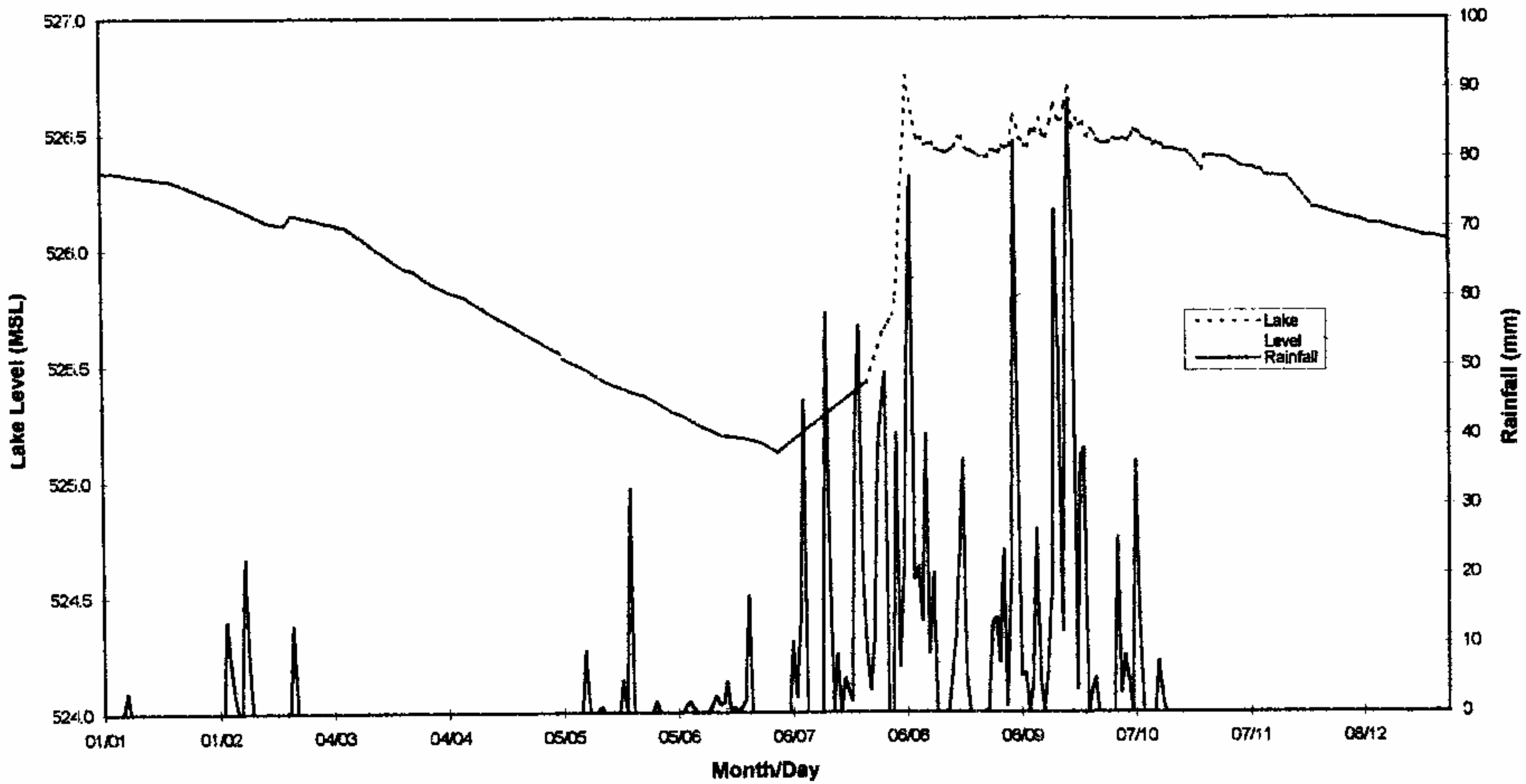


Fig. 8 : Variation of lake stage of Sagar Lake with daily rainfall during 1999

In general, the lake level continuously follows the decreasing trend upto the second or third week of May depending upon the onset of monsoon. After which the level starts rising upto end of August and then declines. The trend of change in the lake level can be defined as the rate of change of water level with respect to input to and output from the lake at any time or time period. The drop or rise in water level indicates only less input and more output or more input and less output from the lake respectively.

The computer program in FORTRAN language has been developed for computation of lake water spread area and lake volume. From which area and volume of lake can be estimated at any lake level at any date. The monthly changes in total storage of lake for the years 1998 & 1999 are presented in Table 2 and Fig. 13.

Table - 2 : Change in storage (m^3) of Sagar Lake during 1998 and 1999

Month	Year	
	1998	1999
January	-	-159721
February	-	-128350
March	-	-358889
April	-	-325902
May	-	-311249
June	-	-219867
July	-	658844
August	-29982	995350
September	91541	34510
October	-46569	-105884
November	-32694	-328700
December	-43396	-148273

4.1.4 Surface Inflow (S_i)

The total surface inflow in response to the rainfall has been divided into two parts, the first being measured flow through Kanera canal and the other unmonitored flow estimated using Soil Conservation Service - Curve Number (SCS - CN) method.

Inflow Through Kanera Canal

The Kanera canal catchment covers almost half of the total catchment area of the lake. The Kanera canal is a seasonal canal and flows during monsoon season only. In order to estimate the flow through this canal during monsoon period, daily monitoring of water depth, flow width and water flow velocity has been done at the canal section at Baghraj bridge. The measured velocities were corrected by correlating them with the hydraulic radius of the Kanera canal using the Manning's formula as

$$V = \frac{1}{n} . R^{\frac{2}{3}} . S^{\frac{1}{2}} \qquad \ldots \qquad (4)$$

$$V = \left(\frac{1}{n} . R^{\frac{2}{3}} \right) S^{\frac{1}{2}}$$

$$V = \beta . S^{\frac{1}{2}} \qquad \ldots \qquad (5)$$

where V is flow velocity, n is Manning's coefficient, R is hydraulic radius, S is canal bed slope and β is conveyance factor.

The hydraulic radius was computed using the canal section parameters. The value of $R^{2/3}$ was then plotted against the measured velocity of flow as shown in Fig. 9. After drawing the best fit line, β was obtained as 0.65. The velocities were then corrected using eq. (5). The inflow discharge through the canal was thus estimated using the measured parameters as

$$Q = V . A \qquad \ldots \qquad (6)$$

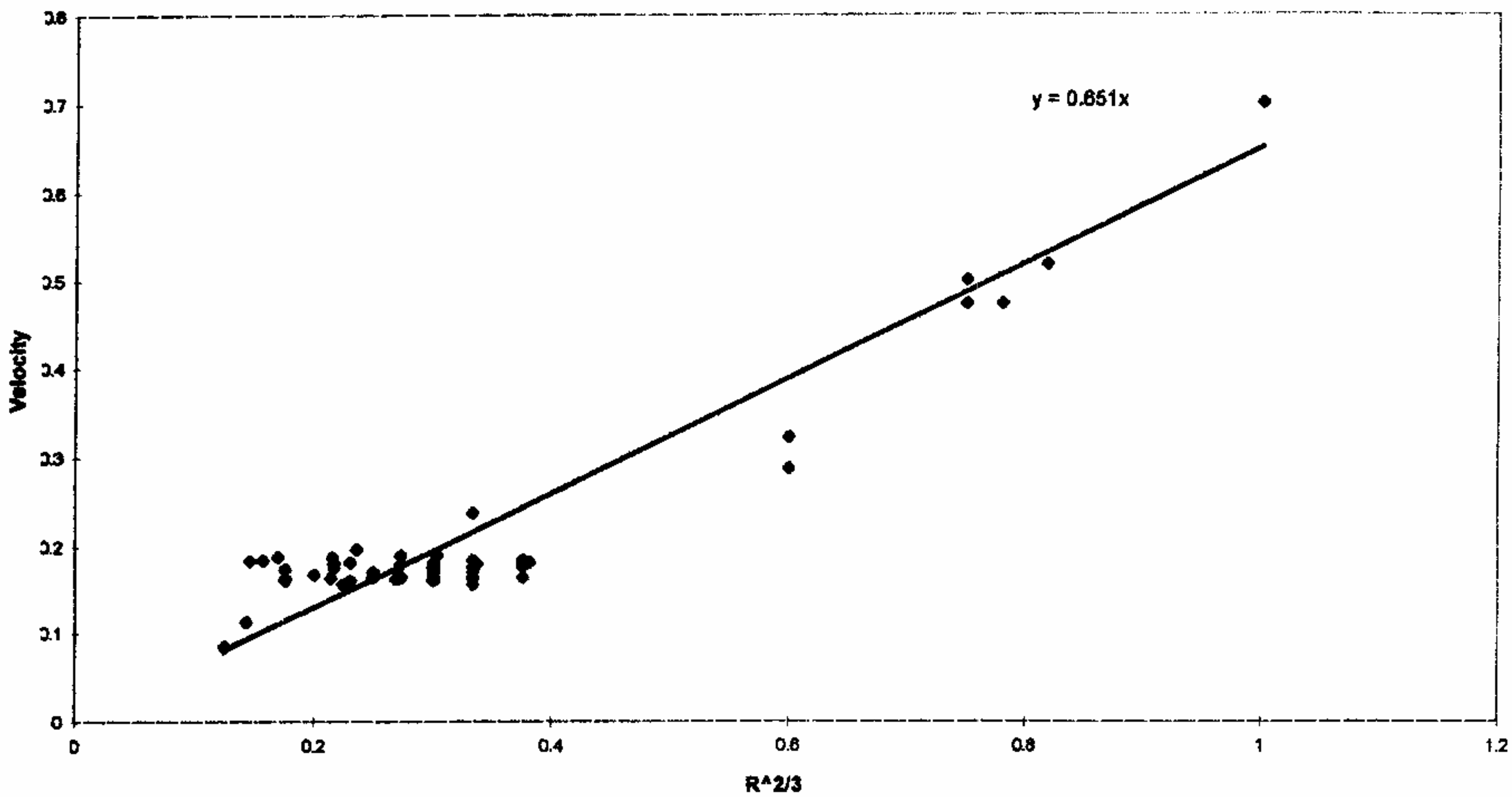


Fig. 9 : Computation of conveyance factor for Kanera Canal

where Q is inflow discharge, (m^3/sec); and A is wetted area, (m^2).

The monthly flow through the canal is estimated using the trapezoidal rule and is given in Table 3.

Table - 3 : Inflow of Kanera canal into the Sagar Lake during 1999

Month	Discharge (m^3)
January	-
February	-
March	-
April	-
May	-
June	-
July	22,105
August	5,985,023
September	3,523,841
October	317,233
November	88,598
December	-
Total	**9,936,800**

Inflow Using SCS - CN Method

Half of the lake catchment area (other than the Kanera canal catchment area) contributes surface runoff to the lake through a number of drainage channels, most of them being submerged during rainy season. Since the monitoring of flow through all these input channels was not possible, the inflow through these channels has been estimated using SCS - CN method.

Soil Conservation Service - Curve Number Method

Soil Conservation Service of US Department of Agriculture has developed a more useful runoff curve number method based on daily rainfall for the estimation of daily runoff from small catchments. In this method, runoff depth is a function of total rainfall depth and an abstraction parameter called Curve Number (CN) which is function of soil group, land cover and antecedent moisture condition (AMC). The CN varies from 1 to 100 based on :

1. Soil type
2. Landuse and treatment
3. Ground surface conditions, and
4. Antecedent moisture condition (AMC)

Based on the assumption of proportionality between retention and runoff, the curve number method states that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff.

$$\frac{P - Q}{S} = \frac{Q}{P} \qquad \ldots \qquad (7)$$

Where P is potential runoff, Q is actual runoff and S is potential maximum retention. The variables P, Q and S are in the same units. The antecedent moisture condition (AMC) is an index of the soil condition with respect to runoff potential before the storm.

Before runoff occurs, some quantity of precipitation is caught as initial abstraction mainly comprising of interception, infiltration and surface storage.

For field applications, eq. (7) is modified by reducing the potential runoff by an amount equal to the initial abstraction.

$$\frac{(P - I_a) - Q}{S} = \frac{Q}{P - I_a} \qquad \ldots \qquad (8)$$

where I_a = initial abstraction. For Indian conditions, I_a is 0.3 S for black soil region and AMC I, and 0.1 S for black soil region and AMC II & III.

Eq. (8) for Q may be rewritten as

$$Q = \frac{(P - I_a)^2}{P - I_a + S}, \; P > I_a \qquad \ldots \qquad (9)$$

The parameter S depends upon the catchment characteristics. The US Soil Conservation Service has expressed S as a function of Curve Number (CN) :

$$S = \frac{25400}{CN} - 254 \qquad \ldots \qquad (10)$$

The hydrologic soil group describes the type of soil and are labelled as A, B, C and D. The hydrologic soil group is classified based on the texture of distributed soil as shown in Table 4 :

Table - 4 : Classification of Hydrologic soil group

Group	Minimum Infiltration Rate (in/hr)	Soil Texture
A	0.30 - 0.45	Sand, Loamy Sand or Sandy Loam
B	0.15 - 0.30	Silt Loam or Loam
C	0.16 - 0.15	Sandy Clay loam
D	0 - 0.05	Clay Loam, Silty Clay Loam, Sandy Clay, Silty Clay or Clay

The SCS - CN method has three AMC levels depending on the season and 5 - day antecedent precipitation, i.e., AMC I, AMC II and AMC III. In AMC I, soils are dry but not at the wilting point. In AMC II, soils reflect average conditions and AMC III has highest runoff potential. The classification of the three AMC levels is given in the Table 5:

Table - 5 : Classification of the three AMC levels

Antecedent Moisture Condition (AMC)	Total 5 - Day Antecedent Rainfall (cm)	Total 5 - Day Antecedent Rainfall (cm)
	Dormant Season	**Growing Season**
I	< 1.3 cm	< 3.6 cm
II	1.3 - 2.8 cm	3.6 - 5.3 cm
III	> 2.8 cm	> 5.3 cm

The runoff curve numbers for various types of landuses, soil treatment practices and hydrological conditions with different soil groups for AMC II are available in Handbook of Hydrology, 1972. The CN thus determined for AMC II may be converted to AMC I and AMC III using Soil Conservation Service National Engineering Handbook, 1985.

For identification of landuse area, the base map of Survey of India (SOI) toposheets with scale 1:50,000 for the lake catchment was digitised using ILWIS 2.2 GIS software. The landuse map was prepared from standard FCC of band 4,3,2 of IRS 1D LISS - 3 data. To prepare the landuse/land cover map, visual interpretation technique was followed using IRS 1D, Path 99 - Row 55, LISS - 3 data. Four landuse/land cover classes (Fig. 10) were identified in the Sagar lake catchment on the basis of the colour, tone, texture, shape, size and association of the objects. The spatial distribution of all the four landuse classes in the catchment area is given in Table 6. The whole of the catchment area of the lake falls under shallow black soil region and hydrologic soil group 'C', i.e., sandy clay loam.

Table 6 shows the landuse, hydrologic condition, percent area under different landuses, the appropriate CN for AMC II for the Sagar lake catchment.

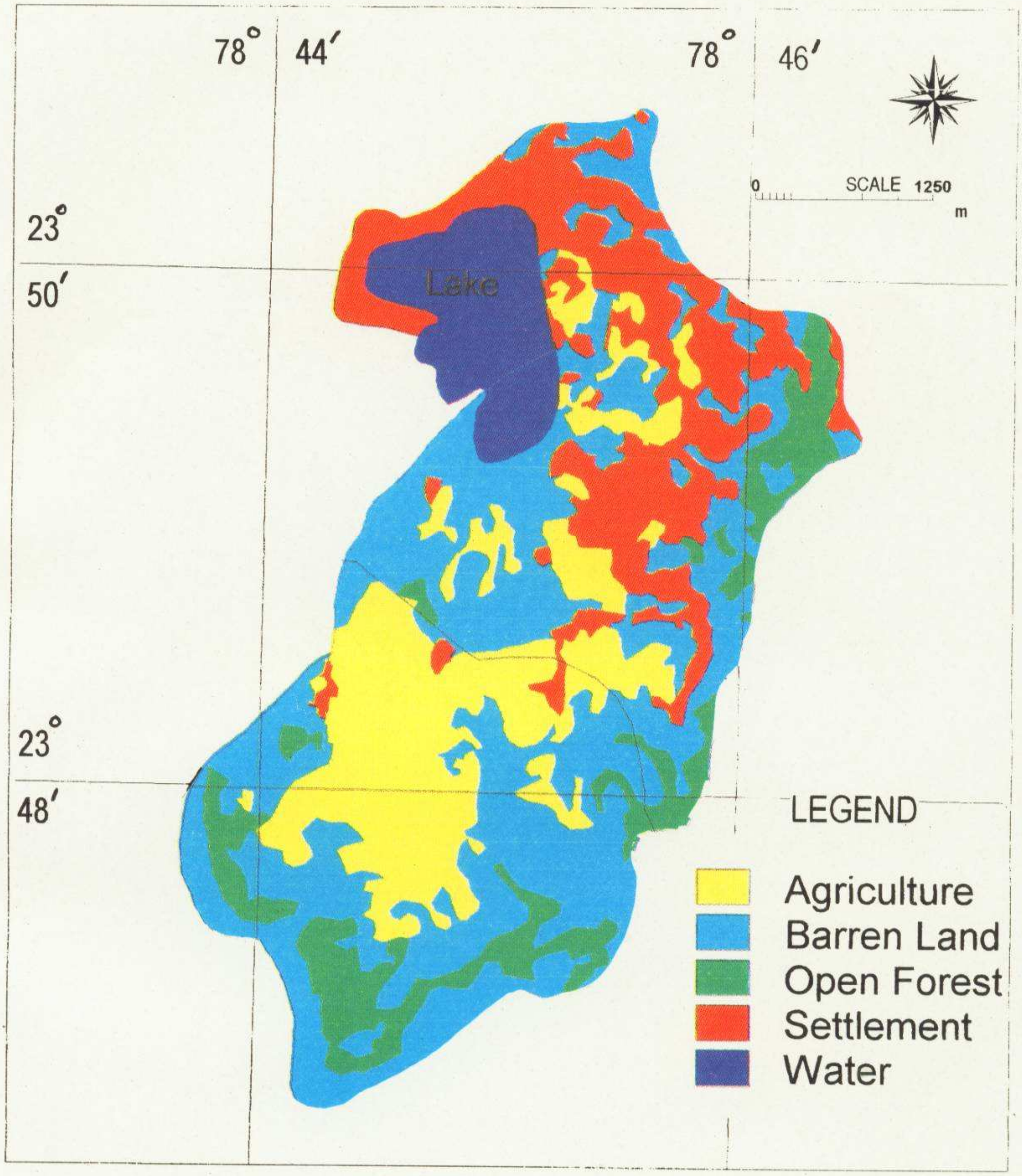


Fig-10 : LANDUSE MAP OF SAGAR LAKE CATCHMENT AREA

Table - 6 : Landuse distribution in Sagar Lake catchment other than canal catchment

Landuse	Hydrologic condition	% of landuse area to catchment area (other than canal catchment)	CN for AMC II
Barren Land	Poor	39.9	79
Settlement	-	38.1	91
Agriculture	Poor	13.5	84
Forest (Fair)	Open	8.5	60

The daily rainfall data for the study purpose was collected from Indian Meteorological Department, Nagpur and Land Records Office, Sagar. The surface inflow was estimated using SCS - CN method with the aid of FORTRAN program on the daily basis. The estimated runoff in units of depth was converted to units of volume. The estimation of runoff flow in different months has been presented in Table 7 for the year 1999.

Table - 7 : Catchment runoff using SCS Method during1999

Month	Discharge (m^3)
January	-
February	-
March	-
April	-
May	-
June	-
July	1,565,349
August	1,946,273
September	3,478,302
October	110,460
November	-
December	-
Total	**7,100,384**

City Waste Water Flow Through Drains (D_i)

The Sagar lake receives the city waste water through a number of drains. On the Western Ghat, many of the houses are discharging domestic waste directly into the lake. The waste water of 12 wards of the city enters into the lake through a number of big and small channels. The estimation of inflow of this waste water has been done on the basis of daily per capita consumption of water. For this purpose, per capita per day consumption of water was taken as 75 litres out of which 50% was considered as waste water seeing the prevailing conditions of the city water consumption and existing drainage system. The daily flow of water is estimated as

$$Q = 0.50 \times 0.075 \times P \times n \qquad \ldots \qquad (11)$$

where P = population, and n = no. of days. The monthly estimates of water (city waste) into the lake from the public activities are given in Table 8. The monthly variations of various inflow components are shown in Fig. 11.

Table - 8 : Discharge of city waste water falling into the Sagar Lake

Month	Discharge (m^3)
January	52,179
February	47,129
March	52,179
April	50,496
May	52,179
June	50,496
July	52,179
August	52,179
September	50,496
October	52,179
November	50,496
December	52,179
Total	**614,363**

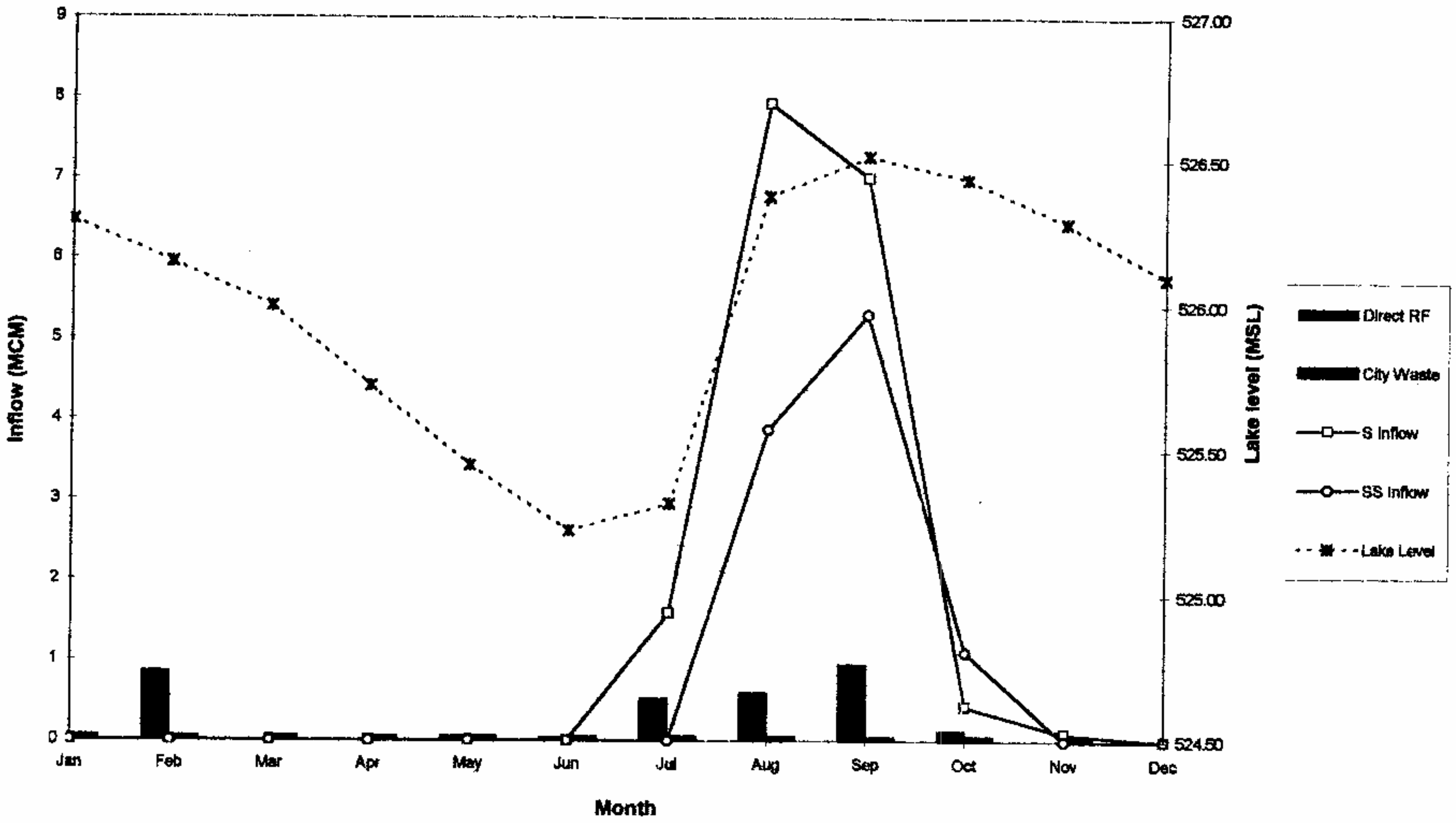


Fig. 11 : Variation of various inflow components of Sagar Lake during 1999

Direct Precipitation Over The Lake Surface (P_l)

During rainfall lake receives water on its open water spread area as direct precipitation. Several studies indicate that lake precipitation is lower than precipitation over surrounding land areas. Average annual precipitation on Lake Balaton (600 km^2) was 17 % lower during the period 1921-58 than over the surrounding land. In July the difference was 20 %, in December 11 % (Szesztay, 1967). For the largest lake in Finland, Lake Suur-Saimaa, the corresponding difference for annual values was 6 % over period of 18 years (Kuusisto, 1978). Since the Sagar lake being small in size, this variability is not considerable. For the estimation of this component daily water spread area of the lake was computed using Lagrange Interpolation technique and multiplied with the rainfall of that day to yield daily precipitation over the lake surface as

$$P = A \times R \qquad \dots \qquad (12)$$

where A is lake area, and R is rainfall. The quantities thus estimated on daily basis were used to get monthly values. The estimation of direct precipitation over the lake surface is presented in Table 9 (also see Fig.11).

4.1.5 Surface Outflow

Discharge Through Overflow Over Mogha Weir (W_o)

Overflow from the Sagar lake occurs during monsoon season only. During monsoon, the lake becomes full and starts overflowing from through Mogha weir every year. The crest length of the weir is 100 m and average R.L. of the crest is 526.41 m above MSL. The discharge overflowing from the weir has been estimated using broad crested weir formula as the daily measurement of flow velocity over the weir crest could not be possible.

Table - 9 : Direct Precipitation over the lake surface during 1999

Month	Discharge (m^3)
January	4,071
February	85,846
March	-
April	-
May	57,856
June	39,834
July	530,165
August	608,525
September	961,676
October	140,355
November	-
December	-
Total	**2,428,327**

The coefficient of discharge (C_d) has been worked out using the measured velocity of flow on the weir. For this purpose, first of all the measured velocities using current meter were corrected. The total discharge (Q) overflowing per second from the weir is then computed using the continuity equation. The C_d is thus computed as

$$Q = \frac{2}{3}\sqrt{2g}\,C_d\,L\,h^{\frac{3}{2}} \quad \ldots \quad (13)$$

where Q = the discharging flowing per second through the gates, m^3

L = the length of the gate over the crest, m

h = the overflow height, m

g = the acceleration due to gravity, m/sec^2

Using equation 13, C_d is obtained by substituting L=1.5 m, Q=1.727 m^3/sec (measured) and $h^{\frac{3}{2}}$=0.592 (measured).

$$1.727 = \frac{2}{3}\sqrt{2g}.C_d.(1.5).(0.592)$$

$$\therefore \quad C_d = 0.65859, \text{ say } 0.66$$

Since the daily overflow heights of water above the weir crest were recorded, the daily overflow discharge were estimated and converted to monthly values using the trapezoidal rule. The monthly discharge through overflow is presented in Table 10.

Table - 10 : Overflow through Mogha Weir during 1999

Month	Discharge (m^3)
January	-
February	-
March	-
April	-
May	-
June	-
July	-
August	11,298,199
September	13,078,952
October	1,631,098
November	-
December	-
Total	**26,008,249**

Leakage Through Mogha Weir (L_o)

As the level of water reaches close to the weir level, some amount of water starts leaking through the body of weir. The leakage starts during monsoon and lasts till February or March. Measurement of this component is done using the velocity-area method

$$Q = V \cdot A \qquad \ldots \qquad (14)$$

where Q = discharge, m^3/sec

V = velocity of flow, m/sec

A = area of flow, m

The computation of such leakage is converted to monthly values and is presented in Table 11.

Table - 11 : Leakage through Mogha weir during 1999

Month	Leakage (m^3)
January	2203
February	842
March	0
April	0
May	0
June	0
July	0
August	13478
September	15552
October	16070
November	10973
December	4666
Total	**63785**

Siphoning Of Lake Water Over The Mogha Weir (S_o)

During the summer season, water level in the downstream side of lake goes down significantly. Most of the wells in the down side become dry. It creates a serious water scarcity problem. To combat this problem, the lake water over the Mogha weir is siphoned out daily for 10 hours. The pipe used for siphoning was 9m long and 3" diameter plastic pipe. This water flows through a nalla which is used for recharging the wells and meets the public requirements in the downside area. The water is siphoned out till onset of monsoon. The siphoned water is estimated using the pipe flow formula as

$$\text{Siphoned Discharge} = \frac{\pi d^2}{4} V \qquad \ldots \qquad (15)$$

where, $V = \sqrt{\dfrac{2gh}{1.5 + \dfrac{fL}{d}}}$

f = 0.04

h = head difference

L = pipe length

d = diameter of pipe

The monthly water siphoned out from the lake has been presented in Table 12.

Table - 12 : Discharge siphoned out from Sagar Lake during 1999

Month	**Discharge (m^3)**
April	13,558
May	13,704
June	9,282
Total	**36,544**

Evaporation (E_o)

The estimation of evaporation is difficult. There are a number of approaches for the estimation of evaporation. Of the three approaches, energy balance, mass transfer and their combination (Penman type), the first one gives more reliable results. The pan evaporation, solar radiation and actual sunshine hours are not recorded at the IMD observatory located near the collectorate office, Sagar. Therefore the pan evaporation data of Raisen district was used for estimation of the lake evaporation. Generally the pan evaporation is multiplied by a factor of 0.70 to 0.75 to get the equivalent lake evaporation. Since the Sagar lake lying in the heart of city, is shallow (average depth 2.48m) and small in surface area, the pan coefficient of 0.8 is taken. The values of Pan evaporation for Sagar district are shown in Table 13. Based on daily lake level, the daily water spread area is computed with the aid of interpolation technique. The monthly evaporation is then estimated as

$$\text{Monthly evaporation} = 0.80 \times A_m \quad \ldots \quad (16)$$

where A_m is monthly average water spread area. Month wise computed evaporation from the Sagar lake is given in Table 14. The monthly variation of the major outflow components is shown in Fig. 12.

Table - 13 : Pan Evaporation for the Sagar District

Month	Pan Evaporation (mm)
January	113
February	135
March	193
April	241
May	293
June	237
July	164
August	143
September	167
October	165
November	123
December	103
Total	**2077**

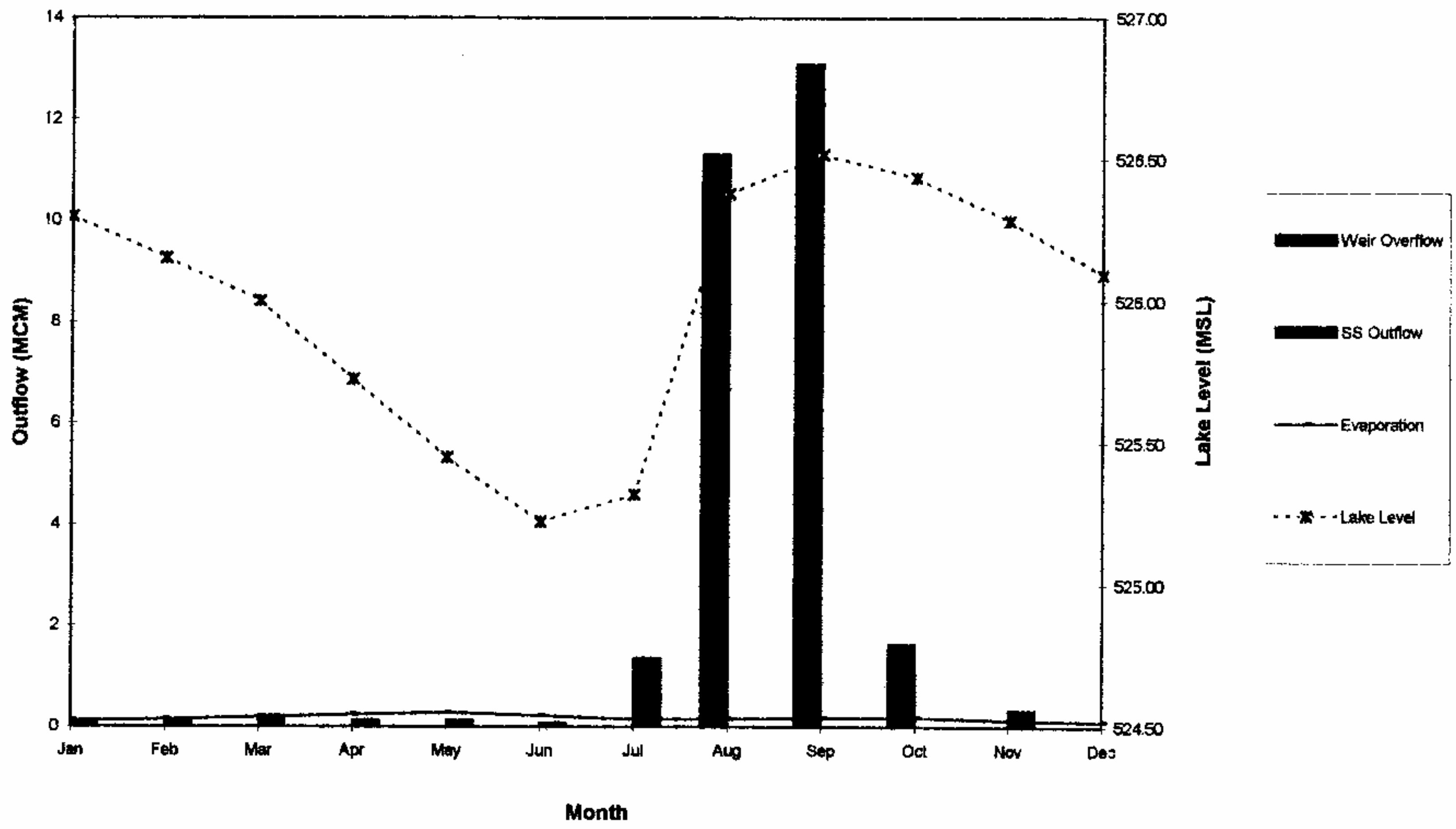


Fig. 12 : Variation of major outflow components of Sagar Lake during 1999

Table - 14 : Monthly evaporation from the Sagar.

Month	Evaporation (m^3)
January	122,030
February	142,303
March	199,141
April	240,203
May	282,243
June	220,561
July	154,832
August	157,115
September	187,600
October	182,661
November	132,557
December	107,637
Total	**2,128,883**

4.1.6 Subsurface Inflow and Subsurface Outflow

The estimation of subsurface inflow and subsurface outflow is most difficult among all the parameters of the water balance eq. (2). Several attempts have been made by researchers world wide but with limited success. Since the bed formation of Sagar lake is Deccan traps basaltic in nature and also the fence diagram for lake catchment was not available, the estimation of subsurface inflow and subsurface outflow components has been done by the conventional method, i.e., first of all the total inflow and total outflow have been estimated. The subsurface inflow/outflow is then worked out by subtracting the total outflow from the total inflow as well as taking account of storage change in the equation 2.

The monthly estimation of subsurface inflow and subsurface outflow components are presented in Table 15 and Figs. 11 and 12.

Table - 15 : Values of the water balance components of Sagar Lake for the year 1999

Month	Lake Level	Pptn	S	Pi	Di	Si	SSi	So	Eo	Wo	Lo	SSo
	(MSL)	(mm)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)
Jan	526.300	3	-0.16	0.004	0.052	0.000	0.000	0.000	0.122	0.000	0.002	0.092
Feb	526.153	65	-0.13	0.086	0.047	0.000	0.000	0.000	0.142	0.000	0.001	0.118
Mar	526.003	0	-0.36	0.000	0.052	0.000	0.000	0.000	0.199	0.000	0.000	0.212
Apr	525.727	0	-0.33	0.000	0.050	0.000	0.000	0.014	0.240	0.000	0.000	0.123
May	525.451	48	-0.31	0.058	0.052	0.000	0.000	0.014	0.282	0.000	0.000	0.125
Jun	525.225	34	-0.22	0.040	0.050	0.000	0.000	0.009	0.221	0.000	0.000	0.080
Jul	525.320	443	0.66	0.530	0.052	1.587	0.000	0.000	0.155	0.000	0.000	1.356
Aug	526.381	436	1.00	0.609	0.052	7.931	3.872	0.000	0.157	11.298	0.013	0.000
Sep	526.519	678	0.04	0.962	0.050	7.002	5.302	0.000	0.188	13.079	0.016	0.000
Oct	526.438	100	-0.11	0.140	0.052	0.427	1.104	0.000	0.183	1.631	0.016	0.000
Nov	526.286	0	-0.33	0.000	0.050	0.089	0.000	0.000	0.133	0.000	0.011	0.324
Dec	526.096	0	-0.15	0.000	0.052	0.000	0.000	0.000	0.108	0.000	0.005	0.088
Total		**1808**	**-0.40**	**2.429**	**0.611**	**17.036**	**10.278**	**0.037**	**2.130**	**26.008**	**0.064**	**2.518**
% of total Inflow/Outflow				**8.000**	**2.000**	**56.000**	**34.000**	**0.120**	**6.900**	**85.000**	**0.200**	**8.000**

Pptn = Rainfall; S = Storage change; Pi = Direct rainfall over lake; Di = City waste water inflow; Si = Surface inflow;
SSi = Subsurface inflow; So = Siphon out; Eo = Evaporation; Wo = Weir overflow; Lo = Weir leakage; SSo = Subsurface outflow

5.0 RESULTS AND DISCUSSION

The estimation of all the water balance components has been presented in Table 15. It is seen from the table that major inflow component to the lake is surface runoff. Water balance of the lake shows that the contributions done to surface runoff, direct rainfall and city waste are 56 %, 8 % and 2 % of the total annual inflow respectively. The remaining 34% is accounted by subsurface inflow.

The variation of subsurface inflow to the lake corresponds with the rainfall and is shown in Fig. 11. The subsurface inflow occurs only during monsoon season and then declines after September.

Seeing the various inputs to the lake and minimum lake level, only a small amount of rainfall is sufficient to fill the lake. Every year a huge amount of water flows out of lake through spill over the Mogha weir. It is observed that even during the years having less than normal rainfall, there is no water shortage in filling the lake.

Table 15 shows that the major outflow from the lake is weir overflow which accounts for about 85 % of the total annual outflow, evaporation accounts for 6.9 % and siphoning out of water accounts for 0.12 % which is operated during pre-monsoon season only. Remaining 8 % of water is attributed to the subsurface outflow. The variation of total inflow, outflow and storage changes is plotted in Fig. 13.

Tables 16 and 17 present the monthly values of various water balance components as percent of total annual rainfall and as percent of average lake volume of the month, respectively.

The water balance of monsoon period is presented in Table 18. The total inflow to the lake during the period is 29.67 MCM, i.e., 97.7 % of the total annual inflow and the total outflow is 28.22 MCM, i.e., 91.7 % of the total annual outflow and the balance of 1.45 MCM is attributed to the storage change of the lake.

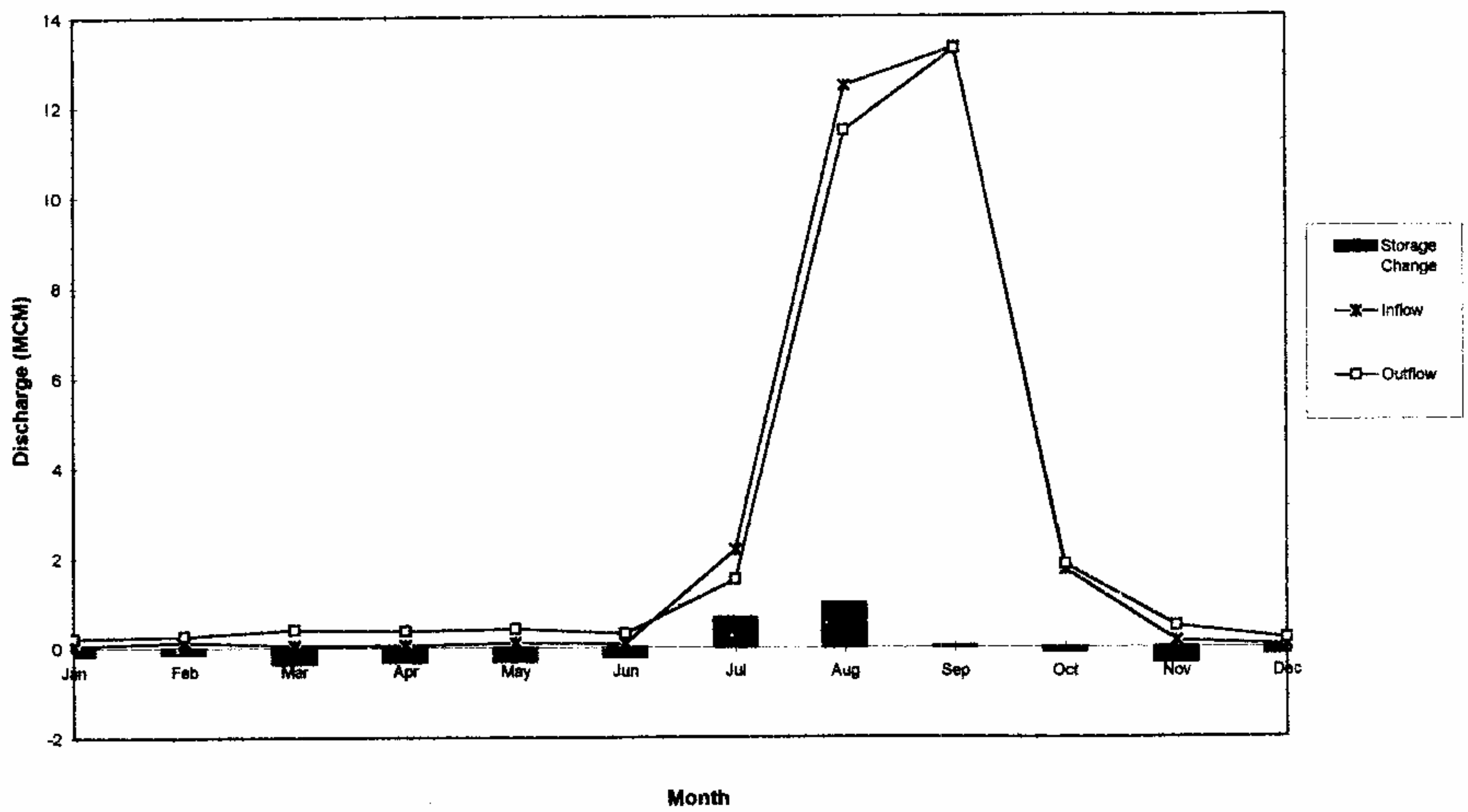


Fig. 13 : Variation of inflow, outflow and storage components of Sagar Lake during 1999

Table - 16 : Values of the water balance components as percent of total annual rainfall

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Di	0.16	0.14	0.16	0.15	0.16	0.15	0.16	0.16	0.15	0.16	0.15	0.16
Pi	0.01	0.26	-	-	0.18	0.12	1.61	1.85	2.93	0.43	-	-
Si	-	-	-	-	-	-	4.83	24.14	21.32	1.29	0.27	-
Ssi	-	-	-	-	-	-	-	11.79	16.14	3.36	-	-
Month Total	0.17	0.40	0.16	0.15	0.33	0.27	6.61	37.94	40.53	5.25	0.42	0.16
Eo	0.37	0.43	0.61	0.73	0.86	0.67	0.47	0.48	0.57	0.56	0.40	0.33
So	-	-	-	0.04	0.04	0.03	-	-	-	-	-	-
Wo	-	-	-	-	-	-	-	34.39	39.81	4.96	-	-
Lo	0.01	0.00	-	-	-	-	-	0.04	0.05	0.05	0.03	0.02
Sso	0.28	0.36	0.65	0.37	0.38	0.24	4.13	-	-	-	0.99	0.27
Month Total	0.66	0.80	1.26	1.14	1.28	0.94	4.60	34.91	40.43	5.57	1.43	0.61
Storage change	- 0.49	- 0.39	- 1.09	- 0.99	- 0.95	- 0.67	2.01	3.03	0.11	- 0.32	- 1.00	- 0.45

Di = City waste water inflow; Pi = Direct rainfall over lake; Si = Surface inflow; SSi = Subsurface inflow;
So = Siphon out; Eo = Evaporation; Wo = Weir overflow; Lo = Weir leakage; SSo = Subsurface outflow

Table - 17 : Values of the water balance components as percent of average lake volume of the month

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Di	1.56	1.50	1.77	1.93	2.31	2.52	2.48	1.51	1.38	1.48	1.51	1.57
Pi	0.12	2.74	-	-	2.58	2.02	25.30	17.67	26.50	3.98	-	-
Si	-	-	-	-	-	-	75.76	230.15	192.89	12.14	2.69	-
SSi	-	-	-	-	-	-	-	112.36	146.06	31.37	-	-
Month Total	1.68	4.24	1.77	1.93	4.89	4.54	103.59	361.69	366.83	48.98	4.20	1.57
Eo	3.66	4.53	6.77	9.28	12.55	11.15	7.40	4.56	5.18	5.20	4.01	3.27
So	-	-	-	0.54	0.62	0.45	-	-	-	-	-	-
Wo	-	-	-	-	-	-	-	327.86	360.30	46.34	-	-
Lo	0.06	0.03	-	-	-	-	-	0.38	0.44	0.45	0.33	0.15
SSo	2.76	3.76	7.21	4.75	5.56	4.03	64.73	-	-	-	9.78	2.66
Month Total	6.48	8.32	13.98	14.57	18.73	15.63	72.13	332.82	365.90	51.99	14.13	6.05
Storage change	4.80	- 4.08	- 12.21	- 12.60	- 13.84	- 11.09	31.46	28.87	0.96	- 3.01	- 9.93	- 4.48

Di = City waste water inflow; Pi = Direct rainfall over lake; Si = Surface inflow; SSi = Subsurface inflow;
So = Siphon out; Eo = Evaporation; Wo = Weir overflow; Lo = Weir leakage; SSo = Subsurface outflow

Table - 18 : Water balance for the monsoon period during 1999

Month	Pi	Di	Si	SSi	Eo	Wo	Lo	SSo
	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)
June	0.398	0.050	-	-	0.213	-	-	0.080
July	0.530	0.052	1.587	-	0.155	-	-	1.356
August	0.609	0.052	7.931	3.872	0.157	11.298	0.013	-
September	0.962	0.050	7.002	5.302	0.188	13.079	0.016	-
October	0.140	0.024	0.370	1.100	0.086	1.567	0.007	-
Total	2.639	0.228	16.890	10.274	0.799	25.944	0.036	1.436
% of monsoon rainfall	7.5	0.7	55.6	33.8	2.6	84.4	0.1	4.7

Di = City waste water inflow; Pi = Direct rainfall over lake; Si = Surface inflow; SSi = Subsurface inflow;
So = Siphon out; Eo = Evaporation; Wo = Weir overflow; Lo = Weir leakage; SSo = Subsurface outflow

6.0 CONCLUSIONS

On the Sagar lake, previously no detailed hydrological study has been done and the water balance study has been performed for the first time. The computation of different water balance parameters has been done either by field measurements or by established methods. The study reveals that the major inflow to the lake is surface runoff which accounts for nearly 56 % of the total annual inflow. Of the total annual inflow, about 98 % inflow to the lake takes place during monsoon period.

The major outflow component from the lake is weir overflow which occurs in monsoon season only and accounts for about 85 % of the total annual outflow. Of the total annual outflow about 92 % outflow from the lake takes place during monsoon period. Since there is heavy inflow to the lake even with normal rainfall in monsoon season, there will be no scarcity of water to fill the lake upto full tank level in any hydrologic year even if the rainfall is below normal, provided the water withdrawal trend from the lake is not disturbed.

The following points will be beneficial in future for the restoration of quality and quantity of lake water:

1. A huge quantity of water overflows every year from the Mogha weir and goes waste. So a storage basin on the downstream side of the nalla can be thought of to make use of this overflowing water.
2. Nallas carrying city waste should be diverted away from the lake. For this awareness of nearby population and some alternative arrangements for drains would be required.
3. The small lake should be made deeper so that water from the storage can be made available even in the summer season.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Bhishma Kumar, Sc-E and Sh. Jiweshwar Sinha for initiating the study, guidance and co-operation. The authors are thankful to Sh. S.K. Singh, Sc-E for providing technical guidance and help.

The authors are thankful to Dr. A.K. Bhar, Sc-F and Co-ordinator of RC Sagar for co-operation and help. The authors also wish to acknowledge various Government departments namely Water Resources Department, Sagar; Land Records Department, Sagar; Nagar Nigam Office, Sagar; Indian Meteorological Department, Nagpur; Public Health Engg. Deptt., Sagar; and Geology Deptt., Sagar University for providing data and other necessary information.

REFERENCES

Adoni, A.D. (1975). Studies on microbiology of Sagar lake. Ph.D. Thesis, University of Sagar (M.P.).

Allred, E.R., Manson, P.W., Schwartz, G.M., Golany, P. and Reinke, J.W. (1971). Continuation of studies on the hydrology of ponds and small lakes. Univ. of Minnesota, Agr. Expt. Sta. Tech. Bull., 274, p: 62.

Almendinger, J.E. (1990). Groundwater control of closed-basin lake levels under steady-state conditions. J. of Hydrol. 112(3-4): 293-318.

Anderson, M.P. and Munter, J.A. (1981). Seasonal reversals of groundwater flow around lakes and the relevance to stagnation points and lake budgets. Water Resour. Res., 17(4): 1139-1150.

Bhar, A.K. (1993-94). Water balance of lakes. Report No. SR-37, National Institute of Hydrology, Roorkee, U.P., India.

Bergstorm, R.E. and Hansen, C.F. (1962). Ground water supplies in Wisconsin and Illinois adjacent to lake Michigan. In: H.J. Pincus (Ed.), Symposium on Great Lakes Basin, Chicago Meeting of the Am. Assoc. Adv. Sci.

Cartwright, K., Hunt, C.S., Hyghes, G.M. and Brower, R.D. (1979). Hydraulic potential in Lake Michigan bottom sediments. J. of Hydrol., 43: 67-78.

David, R. Maidment (1992) Handbook of Hydrology, McGraw-Hill, New York, pp: 5.26-5.27.

Dwivedi, V.K. (1996). Environmental aspects of Lake Hydrology. UNDP Project, NIH, Roorkee, India.

Environmental and Development Profile of Sagar Lake. (1997) Prefeasibility Project Report submitted to NCLP,Govt. of India by PHED, Sagar, M.P., India.

Hydrological Studies of Lake Nainital, Kumaun Himalayas, Uttar Pradesh, (1998-99) Project Report sponsored by Department of Environment, Govt. of U.P., India.

Khobragade, S.D. and Bhar, A.K. (1992-93). Classification of lakes and inventory of natural lakes in India. Report No. TN-98, National Institute of Hydrology, Roorkee, U.P., India.

Krishnan, V.S. (1967). M.P. District Gazetteers : Sagar District. Government Press, Bhopal, M.P., India.

Kuusisto, E. E. (1978). Conceptual modelling of inflow into Lake Suur-Saimaa from the surrounding watersheds. Publ. Of the Finnish Water Res. Inst., 26, pp: 66.

McBride, M.S. (1969). Hydrology of lake Sallie, Minnesota, with special attention to groundwater-surface water interactions. Univ. of Minnesota, M.S. Thesis, p: 61.

Meyboom, P. (1966). Unsteady groundwater flow near a willow ring in Hummocky moraine. J. of Hydrol., 4: 38-62.

Report on the Geohydrological Investigation of Sagar Block of Sagar District. (1979). Water Resources Department. (S. No. 162), Sagar, M.P., India.

Rinaldo-Lee, M.B. and Anderson, M.P. (1980). High water levels in groundwater dominant lakes- a case study from north-western Wisconsin. Ground Water, 18(4): 334-339.

Rodda, J.C. (1985) Facets of Hydrology II, John Willy and Sons Publisher, N.Y., p: 155.

Shaw, R.D. and Prepas, E.E. (1990b). Groundwater-lake interactions. II. Nearshore seepage patterns and the contribution of groundwater to lakes in central Alberta. J. of Hydrol., 119(1-4): 121-136.

Singh, S.K. and Seethapathi, P.V. (1986). Recharge from large depression storage. Technical Report No. TR-86, National Institute of Hydrology, Roorkee, U.P., India.

Skinner, E.L. and Borman, R.C. (1973). Water resources of Wisconsin Lake Michigan basin. USGS Hydrologic Atlas, 432.

Sloan, C.E. (1972). Groundwater hydrology of prairie potholes in North Bakota. U.S. Geol. Survey Prof. Paper, 585-C-28 p.

Subramanyan, V. (1973). Geomorphology and its applied aspects of the area around Sagar. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Szesztay, K. (1967). Some problems of lake hydrology. Res. Inst. For Water Res. Development of Hungary, Publ. in foreign languages no. 3, pp: 130.

USDA, SCS: 1985, National Engineering Handbook, Section 4: Soil Conservation Service, Washington, D.C.

Winter, T.C. (1976). Numerical simulation analysis of the interaction of lakes and groundwater. U.S. Geol. Survey Prof. Paper, 1001, 45, pp: 48.

Winter, T.C. (1978). Numerical simulation of steady state three dimensional ground water flow near lakes. Water Resour. Res., 14(2): 245-254.

Winter, T.C. (1983). The interaction of lake with variably saturated porous media. Water Resour. Res., 19(5): 1203-1218.

Winter, T.C. (1986). Effect of groundwater recharge on configuration of the water table beneath sand dunes and on seepage in lakes in the sandhills of Nebraska, U.S.A. J. of Hydrol., 86: 221-237.

Zumberge, J.H. and Ayers, J.C. (1964) Section 23-Hydrology of lakes and swamps: Handbook of Applied Hydrology. Edited by V.T. Chow, McGraw-Hill, New York.

Bibliography Of The Studies Done On The Sagar Lake

Adoni, A.D. (1975). Studies on microbiology of Sagar lake. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Agarwal, N.C. and Bais, V.S. (1991). Comparative hydrobiological study of Sagar lake. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Agarwal, S.C., Studies on litter fungi of Sagar lake. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Awatramani, M. Govind. (1980). Limnological studies of Sagar lake, Sagar. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Babu, S.K. and Tamrakar, S. (1987). Environmental impact study of Sagar lakc, Sagar, M.P. National Symposia on "Role of earth Sciences in Environment", IIT, Bombay, India.

Ghosh, K. (1986). Limnology of some aquatic ecosystems with special reference to microbes and benthos. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Gupta, R. (1987). Ecological study of periphyon of Sagar lake. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Joshi, G.H. (1987). Diurnal studies of physico-chemical properties of limnological importance. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Saran, H.M. (1980). Ecology of some lentic and lotic freshwater habitat around Sagar with special reference to production studies. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Saxena, S.B., and Adoni, A.D. (1973). Diurnal variation in Sagar lake, Sagar (India). I. Studies in the deepwater area. Hydrobiologia, 43(3-4), pp: 535-543.

Singhal, P.K. (1980). Primary productivity of some inland freshwater with special reference to macrophytes of Sagar lake. Ph.D. Thesis. Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Sinha, J. and Thakural, L.N. (1998). Status report on Sagar lake, National Institute of Hydrology, Roorkee, U.P., India.

Thakur, S.S. and Bais, V.S. (1984). Diurnal variation in physico-chemical conditions of Sagar lake. Bull. Env. S. vol. 1, No. 2.

Thakur, S.S. and Bais, V.S. (1986). Season variation of pH and alkalinity and their inter-relationship in Sagar lake. Geobios. News. Reports, 5, pp: 187-190.

Thakur, S.S. and Bais, V.S. (1987). Season variation of temperature, alkalinity and dissolved oxygen in Sagar lake, Sagar (M.P.). Acta. Hydrochem. Hydrobiol. 152, pp: 143-147.

Yadav, Manoj (1986). Qualitative and quantitative analysis of macrophytes and macrofauna. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

Yatheesh, S. (1990). Study of the trophic status of the Sagar lake with special reference to the macrobenthic - invertebrates. Ph.D. Thesis, Dr. H.S. Gour Vishwavidyalaya, Sagar, M.P., India.

DIRECTOR	**:**	**Dr. K. S. RAMASHASTRI**
COORDINATOR & HEAD	**:**	**Dr. A. K. Bhar**
STUDY GROUP	**:**	**Sh. Surjeet Singh** ***Scientist 'B'*** **Sh. L. N. Thakural** ***SRA***