

HEAT ENERGY EXCHANGE OVER A LARGE WATER BODY UNDER STABLE ATMOSPHERIC CONDITIONS

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Abstract. The surface heat budget over the Rihand reservoir covering 300 km² is investigated making use of hydrometeorological data collected at a number of stations during May and June 1983. The observations had to be restricted to 0800–1400 hr for operational reasons in this remote part of India. The winds were weaker, and in general the temperature and humidity gradients were stronger at that time of day than during the afternoon.

The mean albedo between 0700–1200 hr is found to be about 34% which could be due to the high turbidity of the water. A simple relation of the form, $R = (1 - \alpha)Q_i - 85$ is proposed to estimate net radiation over the water body from the global radiation. This relation is useful for the computation of net radiation since it avoids the computation of effective back radiation, which requires data on humidity, cloud amount and surface water temperature. The overall means of net radiation, latent and sensible heat fluxes were found to be 420, 96 and -11 W/m², respectively. A net heat gain of about 335 W/m² was observed during the study period. The measured effective back radiation agreed reasonably well with the value computed from the theoretical formula.

Nomenclature

Symbol Description

Q_i	total incoming radiation,
Q_b	effective back radiation,
R	net radiation at the surface,
R_m	measured net radiation above the reservoir,
Q_n	net heat exchange at the surface,
Q_e, Q_h	latent and sensible heat fluxes, respectively (according to Kondo's (1975) method),
Q_{el}, Q_{hl}	latent and sensible heat fluxes, respectively (according to Smith's (1974) method),
α	albedo of the water surface
ρ	density of air,
L	latent heat of evaporation,
U	wind speed at anemometer level,
C_p	specific heat of air at constant pressure,
R.H.	relative humidity of air,
B	Bowen Ratio,
T_w	water temperature at the surface,
T_a	dry bulb temperature,
e_s, e_a	saturated vapor pressure at T_w and vapor pressure at T_a obtained from dew point temperature,
C_e, C_h	bulk transfer coefficients for latent and sensible heat fluxes, respectively.

1. Introduction

Studies dealing with the physics of lakes/reservoirs are very sparse in India. Since limnological studies use, by and large, the same methodologies used in

oceanography and frequently provide insight into marine physical processes under restricted conditions, the National Institute of Oceanography (NIO) agreed to undertake a massive hydrometeorological investigation of the Rihand reservoir at the request of the National Thermal Power Corporation (NTPC).

Rihand reservoir is situated at 24.27° N; 83.08° E near Shakti Nagar, on the Uttar Pradesh-Madhya Pradesh border (Figure 1). The surface area of the reservoir is about 300 km². It is an artificial lake created by constructing a dam across the Rihand river. The mean depth is about 5 m and the maximum depth is 20 m. The water is highly turbid and the transparency is less than one metre. Coolant water to nearby power plants is drawn from this reservoir and the warm water is discharged back into it. The difference between the inflow and outflow water temperatures is about 10 °C. A chain of super thermal power stations is under proposal around the reservoir. The objective of the hydrometeorological studies was to know the reservoir cooling capacity, on which the efficiency of the power plant would depend. The operation of the power stations would also depend on the level of water in the reservoir. It may be recalled that there was an acute shortage of power supply in the state of Uttar Pradesh in July 1973 due to the low level of water in the reservoir. At the request of the state government, an aerial cloud seeding experiment was undertaken at the reservoir during August-September 1973 (Kapoor *et al.*, 1973). Water bodies lose heat and mass mainly through the evaporation process. Study of the heat budget of the reservoir is considered to be very important for assessment of the cooling capacity and water-level variations of the water body.

2. Data

We have collected data on meteorology and hydrography at selected stations in the reservoir (Figure 1) with the help of a motor boat. Continuous measurements of meteorological parameters were also made over land about 2 km away from the shore using an automatic Aanderaa Weather Station. The measurement height was about 8 m above the ground. The weather elements were monitored at 15 min intervals. The accuracies of measurement are as follows: Global radiation – ± 20 W/m²; Air temperature – ± 0.25 °C; Relative humidity – $\pm 2\%$; Wind speed – ± 0.2 m/sec. The data were collected for representative days during May-June 1983.

Net radiation could be recorded directly at half hourly intervals for a few days in June 1983 using the Type S1 net radiometer (Swissteco Instruments, Switzerland). The equipment was installed on a wooden platform about 2 m above the water surface built on a dead submerged tree. Due to some infrastructural problems, the data could not be obtained throughout the day. The accuracy in the net radiation measurements is $\pm 2.5\%$.

The weather elements at different stations were measured about 2 m above the water surface. Water temperature at the surface and at different depths were

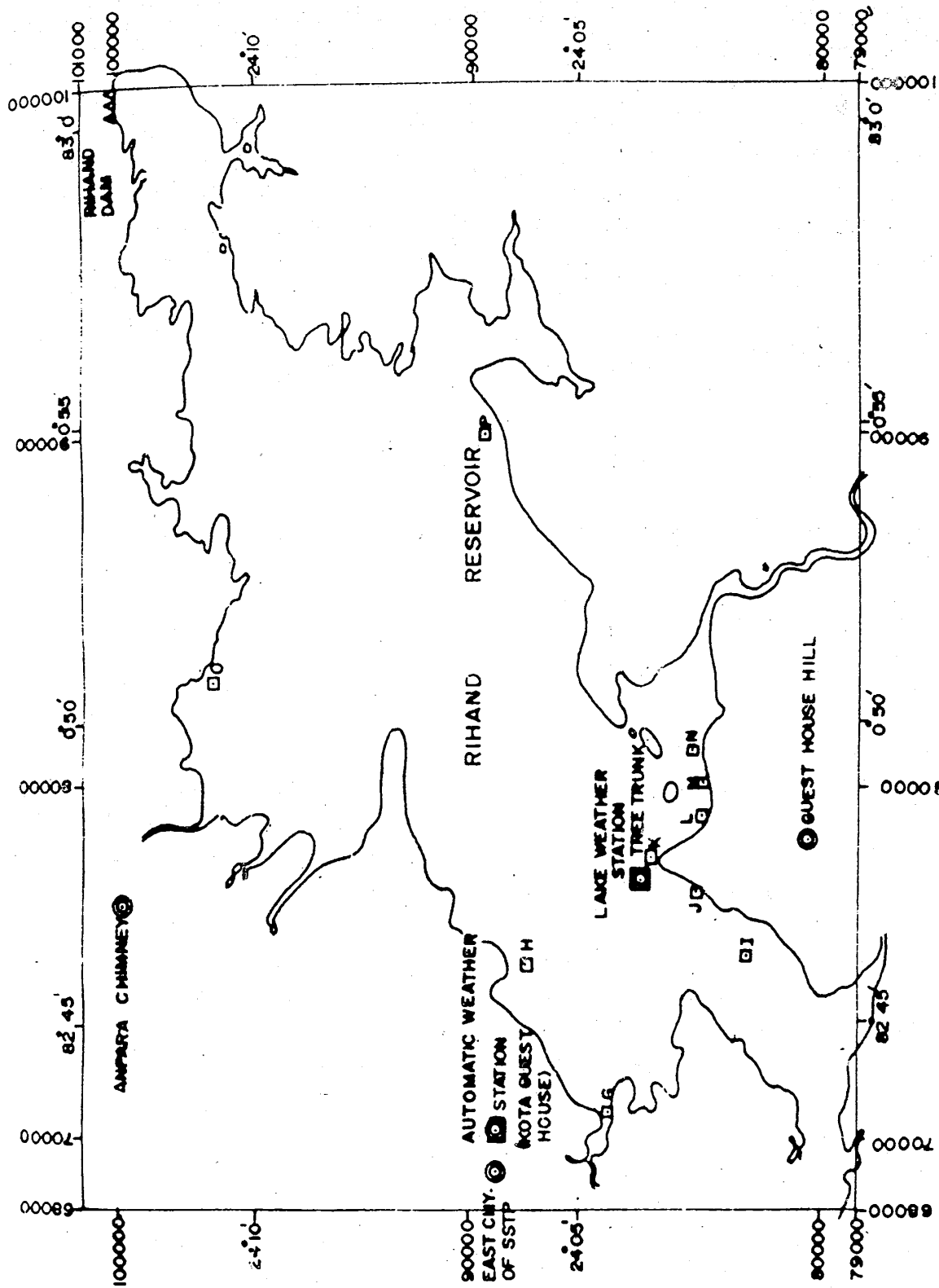


Fig. 1. Location map of the Rihand reservoir.

obtained using a specifically designed Digital Temperature Probe (N.I.O. Make, accuracy: $\pm 0.1^\circ\text{C}$). Most of the meteorological data were confined to the period 0800–1400 hr, as we could not extend our operations due to navigational problems arising out of adverse weather conditions like thunderstorms and afternoon squalls.

3. Methodology

The heat balance at the surface of the reservoir could be expressed as

$$Q_n = Q_i - \alpha Q_i - Q_b - Q_e - Q_h \quad (1)$$

Global radiation (Q_i) was directly measured by the automatic weather station and Q_b is computed according to Laevatsu and Hubert (1970). The reflected radiation is estimated from,

$$\alpha Q_i = Q_i - Q_b - R \quad (2)$$

and the latent (Q_e) and sensible (Q_h) heat fluxes are estimated from the bulk aerodynamic formulae:

$$Q_e = \rho C_e L (e_s - e_a) U, \quad (3)$$

$$Q_h = \rho C_h C_p (T_w - T_a) U. \quad (4)$$

It is well known that the transfer coefficients depend upon wind speed and atmospheric stability. There are several schemes (Laevatsu and Hubert, 1970; Emmannuel, 1975; Kondo, 1975; Bunkar, 1976; Stevenson, 1982; Hsu, 1983; etc.) for determining these coefficients. Here, we have chosen Kondo's (1975) method to compute C_e and C_h . The additional advantage of this method is that the correction for measurement height could also be incorporated. The heat budget parameters at different stations were thus computed over the reservoir.

Another slightly different method was also tried making use of the equations proposed by Smith (1974) from the data collected over Lake Ontario, for the sake of comparison. The equations used are as follows:

$$Q_{el} = \overline{LqU_3}, \quad (5)$$

$$Q_{hi} = \rho C_p \overline{tU_3}, \quad (6)$$

where

$$\overline{qU_3} = 0.005 + 1.0 \times 10^{-3} U_{10} (q_s - q_a) \pm 0.7, \quad (7)$$

$$\overline{tU_3} = -3 \times 10^{-4} + 1.3 \times 10^{-3} U_{10} (T_w - T_a) \pm 1.3 \times 10^{-3}. \quad (8)$$

4. Results and Discussion

4.1. DIURNAL MARCH OF WEATHER ELEMENTS

Figures 2(a-d) show the diurnal march of weather parameters during 15–31 May and 1–9 June 1983 collected at the station 2 km inland. Global radiation slowly increases with time, reaching its peak around 12–13 hr and decreasing thereafter. The slight fluctuations observed during the second set of days (1–9 June) were due to the presence of cloud. The entire curve pertaining to the first period (15–31 May) shifted upward in the second period. This is due to the northward progression of the sun which normally reaches its northernmost position around 21 June. The air temperature was quite high, the maximum exceeding 38 °C

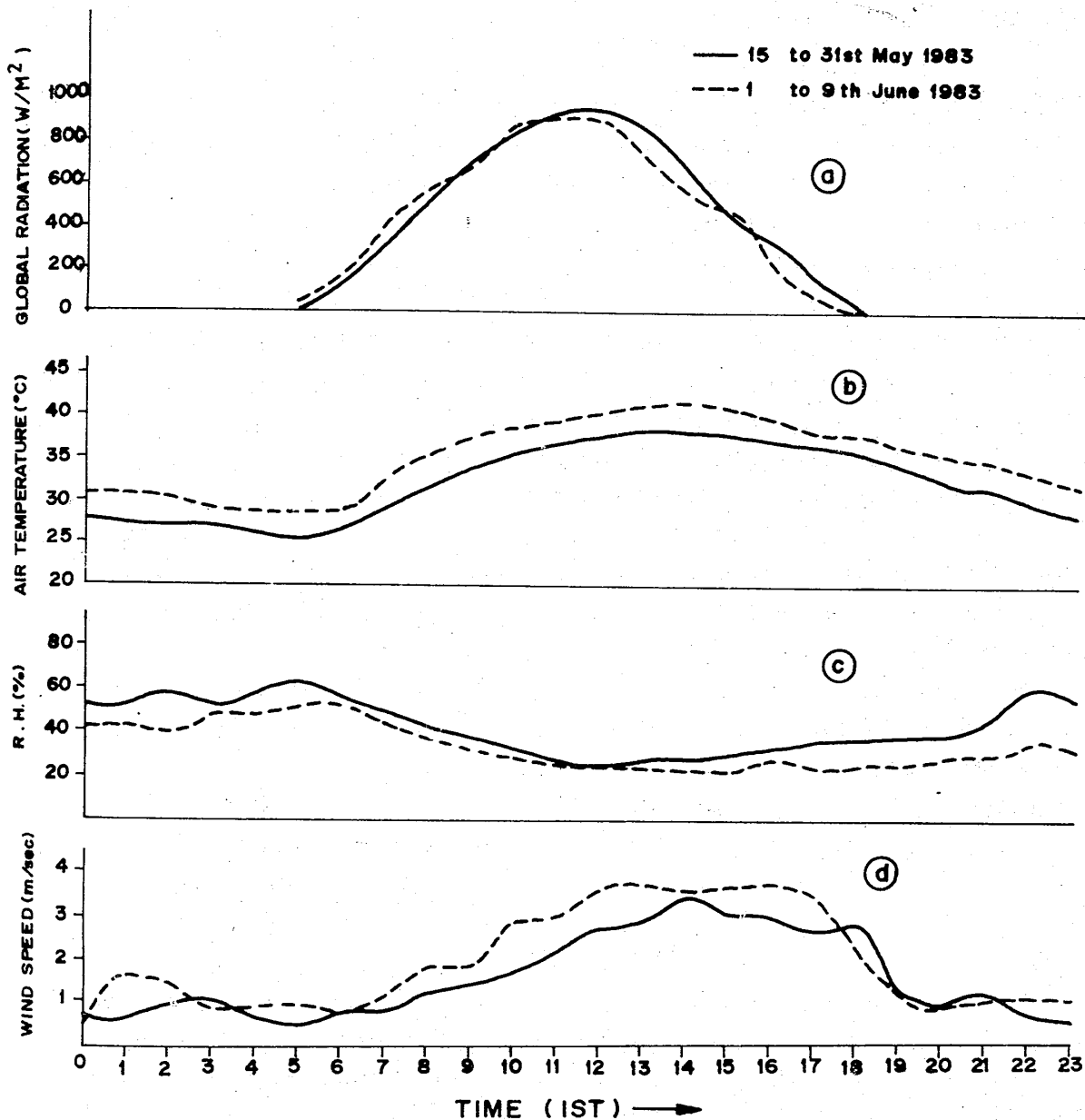


Fig. 2. Diurnal variation of weather elements near the Rihand reservoir.

TABLE I
Weather parameters and heat fluxes at different stations

Parameter	G 1/6	I 9/5	I 16/5	K 13/5	K 26/5	K 31/5	O 17/5	O 6/6	P 18/5
U	3.8	2.5	4.3	3.0	1.3	1.5	3.7	3.8	3.6
R.H.	42.2	53.3	55.7	52.8	47.9	40.1	56.8	34.4	56.6
$T_w - T_a$	-4.1	-3.4	-2.1	-2.8	-2.2	-4.6	-1.6	-7.2	-3.4
$e_s - e_a$	25.2	15.5	15.6	16.9	21.8	24.4	16.5	21.3	13.2
B	-0.11	-0.14	-0.09	-0.12	-0.08	-0.12	-0.07	-0.22	-0.16
Q_e	201	61	140	102	59	32	128	130	81
Q_{el}	155	75	120	94	58	71	110	149	81
Q_h	-21	-09	-11	-12	-04	-04	-07	-30	-11
Q_{hl}	-24	-15	-13	-16	-05	-11	-09	-50	-18

(Q_e , Q_{el} , Q_h , Q_{hl} , are expressed in W/m^2).

during the first period and reaching about 40°C in the second period. The relative humidity was very low, ranging between 20–40% during the daytime hours (Figure 2c). Wind speed was generally lower in the early hours of the day but gradually strengthened, reaching a maximum in the afternoon.

4.2. LATENT AND SENSIBLE HEAT FLUXES

Table I presents the weather conditions and the heat fluxes at different stations over the reservoir computed using the two different methods. The data were collected from the 13 May to the 6 June 1983, and the observations were confined to 08–14 hr. Light winds and the negative temperature gradient ($T_w - T_a$) indicated that the atmosphere was generally stable during the experiment. In fact, to estimate the stability of the atmosphere accurately, one should incorporate the effect of water vapour. The relative humidity was quite low and the vapour pressure gradients were strong. The Bowen ratio (B) is high and negative, which indicates a transfer of heat from the atmosphere to the reservoir.

The latent and sensible heat fluxes (Q_e , Q_h ; Q_{el} , Q_{hl}) are in general small as would be expected in stable conditions. It is interesting to see that there is good agreement between the two methods even though the equations were developed for other environments under different conditions. From this it may be suggested that the equations proposed by Smith (1974) may be applicable for the computation of heat fluxes over lakes/reservoirs in tropical regions.

4.3. ESTIMATION OF ALBEDO

It is known that the albedo depends on several factors like cloud amount, roughness of the water surface and sun's altitude (Kondratyev, 1969). In order to estimate the actual albedo over the reservoir, simultaneous global and net radiation measurements were made above the Rihand reservoir on the 8 June 1983 under clear sky conditions. The results are shown in Table II.

TABLE II
Estimation of albedo from the observed data

Time (IST)	Sun's altitude	Global radiation (W/m ²)	Wind speed	Net radiation (W/m ²)	Albedo %
0700	16.1	316	-	-	-
0730	22.6	399	0.90	136	46
0800	29.1	524	1.27	282	31
0830	35.6	599	1.34	354	28
0900	42.4	683	1.94	364	35
0930	49.1	721	2.69	409	32
1000	55.8	780	1.94	445	33
1030	62.5	815	2.31	455	34
1100	69.3	886	2.39	482	36
1130	76.0	890	3.66	509	34
1200	82.7	904	4.10	509	34
1230	82.7	899	3.88	527	32
Mean	54.0	701	2.44	406	34

The water surface was almost smooth during the period of our experiment. The wind data are also shown in the table. We have assumed a constant value of 81 W/m² for Q_b , based on the data collected on the 6 June 1983. Making use of Q_i , Q_b and R , albedo changes with time were computed from Equation (2). It could be seen that the albedo was more or less constant during the observational period except at a very low altitude of the Sun. The mean value is found to be about 34%, which seems to be higher than normal expectations. This may be attributed to the high turbidity of the water (Smith, 1987) and the smooth surface of the reservoir. To confirm this value, we have used an equation proposed by Viswanadham and Ramanadham (1967) to compute net radiation under clear sky conditions, viz.,

$$R = 0.86(1 - \alpha)Q_i - 4.2, \quad (9)$$

where R and Q_i are expressed in ly/hr. This equation was developed based on a larger data set collected at a coastal station (Visakhapatnam) under clear sky conditions. Converting ly/hr into W/m², the above equation can be modified to

$$R = (1 - \alpha)Q_i - 48.9. \quad (10)$$

From the mean values of Q_i and R in Table II, the mean albedo obtained from Equation (10) is 36% which is consistent with the observed value (34%) here. The slight difference could be due to the fact that the effective back radiation (81) observed here is higher than their value (48.9). This could be attributed to the lower humidity observed throughout the study period. More details are given in the next section.

TABLE III

Surface heat budget under stable atmospheric conditions. Unit: W/m^2

Station	Date	Q_i	$(1 - \alpha)Q_i$	Q_b	R	Q_e	Q_h	Q_n
K	13/5	821	542	81	461	102	-12	371
K	26/5	853	563	85	478	59	-04	423
K	31/5	743	490	88	402	32	-04	374
I	16/5	733	484	82	402	140	-11	273
O	17/5	732	484	81	403	128	-07	282
O	6/6	792	523	93	430	130	-30	330
P	18/5	677	447	83	364	81	-11	294
Mean		764	505	85	420	96	-11	335

4.4. SURFACE HEAT BUDGET

The mean values of the heat budget parameters at the different reservoir stations are presented in Table III. Normally one would expect a more or less constant value of Q_i under clear sky conditions on a short time scale. But the fluctuations observed here might have been caused by the irregular sampling interval. The radiation absorbed at the surface $[(1 - \alpha)Q_i]$ is worked out using the constant value of albedo (34%) as discussed in the previous section. The effective back radiation is almost constant at all stations and the mean is $85 W/m^2$. From the available measured net radiation during night time (1900-0500 hr), the mean is found to be $81 W/m^2$ (Table IV) which is very close to the computed Q_b value during the day-time from the observed meteorological data. This confirms that the data obtained from the net radiometer are reliable. From the above argument, it is thought that the value $85 W/m^2$ is a more representative estimate of net radiation over the water body. So if we replace 48.9 by 85, Equation (10) could be further modified as

$$R = (1 - \alpha)Q_i - 85. \quad (11)$$

We believe that this equation gives reasonably good estimates of net radiation over the reservoir under clear sky conditions during the pre-monsoon period. This relation avoids computation of Q_b which requires data on cloud amount, relative humidity and water temperature. However, further studies are needed to verify its validity.

The values of R shown are computed from Q_i and Q_b ; albedo is assumed to be constant. The values of Q_e and Q_s are computed according to Kondo (1975). Unfortunately, direct measurements of net radiation were not available for all these days to compare with computed values. The mean Q_e of all the stations is about $96 W/m^2$, which is equivalent to $3.3 kg/m^2/day$ of evaporation. This seems to be an underestimation since the observations are taken under stable atmospheric conditions. Q_s is negative and only 10% of latent heat flux. The net heat exchange (Q_n) is found to be positive, indicating that the reservoir gained heat at

TABLE IV

Measured net radiation (W/m^2) during night time (1900–0500 hr)

Time	Rm (Measured)
1900	-90
1930	-72
2000	-76
2030	-70
2100	-78
2130	-87
2200	-90
2230	-80
2300	-80
2330	-82
0000	-80
0030	-80
0100	-82
0130	-83
0200	-84
0230	-84
0300	-85
0330	-88
0400	-88
0430	-79
0500	-78
Mean	-81

the surface during the study period. From this it can be inferred that about 335 W/m^2 is expected as heat storage in the reservoir if there are no other contributing factors. This can be verified by computing the heat storage from the time-depth temperature profiles collected at different stations. It was already mentioned that the difference in inflow and out-flow water temperatures is about 10°C . Secondly, the flow is controlled at the Rihand dam which can induce horizontal motion in the reservoir in addition to the wind-driven currents. Under these conditions, one cannot expect a balance between heat storage and the net heat energy exchange at the surface. A separate study is planned to investigate this aspect.

5. Conclusions

(1) The mean albedo over the reservoir during 0700–1200 hr is found to be about 34% and is almost steady. A simple relation of the form, $R = (1 - \alpha)Q_i - 85$ is proposed to estimate net radiation over the reservoir. There is good agreement between the measured and computed effective back radiation, which suggests that the performance of the instrument is quite good.

(2) The mean values of net radiation, and latent and sensible heat fluxes are found to be about 420, 96 and -11 W/m^2 respectively during the observational period (0800–1400 hr).

(3) A mean net heat gain at the surface (335 W/m^2) is observed during the study period. The influence of this and the in situ processes on heat storage of the reservoir will be reported later.

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