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A model for estimation of evaporation losses from reservoirs in arid areas

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ABSTRACT : A study was conducted by using 30 years meteorological data for the estimation of evaporation losses from free water surfaces at Kailana and Takhatsagar reservoirs located in Jodhpur (Rajasthan). The results showed that the daily evaporation losses at full supply level for Kailana varied from 2115.2 to 10832.1 $m^3 day^{-1}$ with an average loss of 5690.5 $m^3 day^{-1}$. Evaporation losses from Takhatsagar, which is comparatively deeper than Kailana varied from 1488.1 to 7620.5 $m^3 day^{-1}$ with an average loss of 4003.4 m^3 day^{-1}. Total average water loss due to evaporation from both the reservoirs was 9693.9 m^3 day^{-1}. The combined evaporation losses from these two reservoirs varied between 2.15 to 11% of total outflow at full supply level. If the maximum level of both the reservoirs is kept within 15 m, the total daily evaporation losses reduced by 1.49 to 7.63% of total daily out flow. A daily average saving of 2956.6 m^3 at maximum level of 15 m for the whole year could save water sufficient enough to meet the total water demand of city for 6.44 days. The evaporation model developed will be of immense use for inclusion of evaporation losses in daily hydrologic budget of these reservoirs and for future planning and management of water resources in arid regions.

Key words: Evaporation; Jodhpur; Kailana; Reservoir; Takhatsagar

Evaporation losses in tropical countries like India are high because of intense solar radiation, greater number of sunshine hours, high wind speed and long rainless periods. Various studies on evaporation in India indicates that the annual evaporation losses from the reservoirs in arid and semi-arid areas vary from 1.5 to 3.0 m (NIH 1994). Evaporation has increasingly importance in water resources planning especially in arid areas. Evaporation over a reservoir can be a major water management problem, more so if the reservoir is shallow or is meant for storing water for a specific use over a period of several years. For the efficient management of available water in the reservoirs, an accurate estimates of weekly or daily evaporation are needed. The estimation of such evaporation requires either detailed instrumentation of the reservoir or an intitutive application of local physical and climate data. Evaporation from reservoir is generally estimated from pan evaporation data. Usually, pan data is reduced to a factor to estimate reservoir evaporation (Kohler *et al*. 1955; Mustonen and McGuinness 1968; Abtew 2001). The factor depends on season, location and pan specific in use. Estimation of evaporation losses from any surface by meteorological parameters uses energy-based and/or energy and aerodynamic based evaporation estimation models. In a mass transfer evaporation simulation method, evaporation is estimated from wind speed, vapour pressure deficit, and calibration coefficient (Hostetler and Bartlein 1990; Shuttleworth 1993). All these models require elaborate instrumentation, large number of data and trained manpower, which are generally not available. Therefore, this study was undertaken to develop a simple and reliable model for daily estimation of evaporation for two important water bodies of Jodhpur in arid areas and to incorporate the results in daily hydrologic report.

MATERIALS AND METHODS

Description of study area

The study was conducted for two reservoirs namely Kailana and Takhatsagar in Jodhpur city (26°18' N latitude and 73°1' E longitude at 224 m above mean sea level) in Rajasthan (India) under arid agro-climatic zone. Normal maximum temperature of the study area varies between 41.6 to 21.2°C, minimum temperature 10.1 to 28.3°C, normal mean humidity 12% to 83%, mean wind speed 0.92 to 3.61 $m\ s^{-1}$ and pan evaporation 3.98 to 15 mm day^{-1}. The average annual rainfall of Jodhpur is 325.3 mm with average of 17.6 rainy days. More than 80% of the total rainfall occurs during July to September. The average annual potential evapotranspiration is estimated as 1800 mm (DST 1994).

Kailana and Takhatsagar are two important reservoirs of Jodhpur city for storage of raw water for city water supply. Kailana reservoir surrounded by low hills was constructed in the year 1890. It has a water spread of about 84.77 ha at full supply level (FSL) with a capacity of 4.81 Mm^3. Reservoir bottom and FSL at Reduced Level (RL) are 256.03 m and 273.71 m, respectively with a depth of 17.68 m and the dead storage of 0.24 Mm^3. The main source of water to this reservoir is Rajeev Gandhi Lift Canal (RGLC) and it also receives water from its surrounding catchment during rains. Takhatsagar adjacent to Kailana reservoir has a water spread of 60.11 ha at FSL with a capacity of 6.52 Mm^3. Reservoir bottom and FSL at RL are 248.41 m and 269.75 m, respectively with a depth of 21.34 m and the dead storage of 0.80 Mm^3. Takhatsagar was constructed in the year 1936 is directly connected to Kailana reservoir to collect water from it.

Data collection

In the study, 30 years (1967-1999, except 1970,75 and 76) meteorological data of the Central Arid Zone Research Institute, Jodhpur located 8 km away from the water bodies were used for estimation of evaporation and development of model. To smooth out sharp variation in climatic parameters, weekly averages has been used for the analysis The data include air temperature (maximum and minimum), relative humidity, wind velocity at 2 m height, sunshine hours and pan evaporation. Besides Meteorological data, information on water bodies i.e. depth, surface area at different depth etc. for Kailana and Takhatsagar were collected from Public Health Engineering Department, Jodhpur. The capacity at different depth was calculated by trapezoidal formula using depth and corresponding average surface area between two successive contours.

Estimation of evaporation

Actual evaporation losses from natural water surface can still not be determined by direct measurement. The most common approach for estimation of reservoir evaporation is the reduction of standard pan evaporation data using

$$E_o = K_p E_{pan} \qquad \text{......... (1)}$$

Where, E_o = reservoir evaporation; K_p = coefficient; and E_{pan} is Class A pan evaporation.

The practical difficulty with the use of equation 1 is the determination of pan coefficient (K_p) which is dependent on the local environment of the pan, its sitting conditions and operation. Ramasastri (1987) considered 22° latitude as demarcating line for south and north part of India and suggested a combination of coefficients with months of the year. For north of 22° latitude he suggested the values of 0.6 for Nov.-Feb., 0.7 for Mar.-Apr. and Sep.-Oct. and 0.8 for May-Aug. As the pan evaporation is measured from mesh covered class A pan, the observed pan data are adjusted by a factor as 1.144 to obtain evaporation from open pan. Using the above criteria for coefficients, the mess factor as 1.144 and combination of pan to reservoir coefficient for north of 22° latitudes, the long-term normal pan data of Jodhpur were adjusted for reservoir evaporation for Kailana and Takhatsagar reservoirs. As it is difficult to always follow the prescribed pan siting conditions, its operation and management especially in rainy season, an alternative regression model was developed using adjusted pan evaporation data (i.e. reservoir evaporation) and governing meteorological parameters (i.e. temperature, wind velocity, humidity and sunshine hours) for estimation of reservoir evaporation. The total water loss due to evaporation depends on surface area of water body, which in turn depends on current depth of water and shape of water bodies. Hence, surface area and depth relationships were developed for both the water bodies. The surface area and depth relationships have further been combined with regression model of reservoir evaporation developed in present study for direct estimation of total evaporation losses for both the water bodies.

RESULTS AND DISCUSSION

The regression analysis between evaporation governing meteorological parameters (Table 1) yielded following model for estimation of reservoir evaporation :

$$E_{est} = 0.33T_{mean} - 0.12\,RH_{mean} + 2.48WS - 0.20\,SS \; (r^2 = 0.964) \quad ...(2)$$

Where, E_{est} = estimated reservoir evaporation mm day^{-1}; T_{mean}, RH_{mean}, WS and SS are mean temperature (°C), mean relative humidity (%), mean wind velocity (ms^{-1}) and duration of sunshine hours, respectively. Comparison of reservoir evaporation as estimated by equation 2 and adjusted pan evaporation values is presented in Fig.1. A high value of r^2 = 0.964 indicate a significant correlation between reservoir evaporation and meteorological parameters and hence can be used for estimation of reservoir evaporation. Rao *et al.* (1972) has developed similar linear regression equations for 25

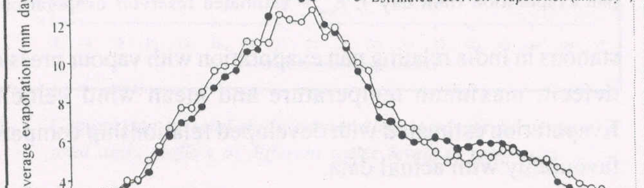

Fig.1. *Comparison of adjusted pan evaporation with estimated reservoir evaporation*

Table 1. *Weekly normal meteorological parameters, adjusted pan evaporation and estimated reservoir evaporation for Jodhpur*

Standard meteorological week	T_{mean} (°C)	RH_{mean} (%)	WS (m s^{-1})	SS (hrs.)	PE (mm day^{-1})	E_{adj} (mm day^{-1})	E_{est} (mm day^{-1})	Absolute relative error
1	17.77	41.14	1.38	8.92	4.06	2.79	2.58	0.081
2	17.38	42.89	1.52	8.76	4.14	2.84	2.61	0.087
3	17.12	40.21	1.41	9.18	4.25	2.92	2.49	0.170
4	18.18	37.62	1.51	9.29	4.81	3.30	3.39	0.027
5	18.25	36.16	1.42	9.28	4.93	3.38	3.37	0.003
6	18.88	33.04	1.46	9.56	5.52	3.79	4.01	0.055
7	20.30	38.32	1.51	9.24	5.83	4.00	4.03	0.008
8	21.05	34.33	1.61	9.21	6.42	4.41	5.03	0.123
9	22.59	31.86	1.57	9.17	6.81	5.45	5.76	0.052
10	24.34	27.70	1.52	9.42	7.84	6.28	6.68	0.060
11	25.84	28.58	1.74	8.91	8.68	6.95	7.73	0.100
12	26.32	28.64	1.70	9.21	8.92	7.14	7.72	0.075
13	27.62	26.14	1.75	9.41	9.66	7.74	8.55	0.095
14	28.78	24.90	1.98	9.70	10.92	8.74	9.60	0.089
15	30.04	23.25	1.84	9.92	11.57	9.27	9.83	0.058
16	30.90	25.45	1.93	10.13	12.03	9.63	10.04	0.040
17	32.57	26.51	2.20	10.24	13.23	10.59	11.12	0.047
18	32.68	28.19	2.24	9.99	13.39	10.72	11.10	0.034
19	33.66	29.55	2.21	10.40	13.62	12.47	11.11	0.122
20	34.25	30.71	2.77	10.45	15.04	13.76	12.55	0.097
21	34.22	38.23	3.05	10.46	14.83	13.57	12.31	0.102
22	34.21	41.47	3.15	10.35	14.59	13.35	12.18	0.096
23	34.79	44.32	3.43	10.14	14.68	13.44	12.77	0.052
24	34.17	48.66	3.12	9.73	13.15	12.03	11.35	0.061
25	33.49	53.77	3.61	9.10	12.64	11.57	11.84	0.023
26	33.04	55.69	3.33	8.08	11.73	10.74	10.97	0.021
27	32.32	59.18	3.19	7.80	10.40	9.52	10.01	0.049
28	31.94	61.80	3.15	7.26	9.56	8.75	9.57	0.086
29	30.99	66.65	2.73	6.24	7.79	7.13	7.82	0.089
30	30.38	68.65	2.92	6.07	7.66	7.01	7.88	0.110
31	30.01	70.19	2.61	5.74	6.88	6.30	6.86	0.083
32	29.64	70.79	2.57	5.65	6.44	5.89	6.59	0.105
33	29.52	70.26	2.37	6.69	6.47	5.92	5.90	0.004
34	29.78	68.37	2.11	7.81	6.68	6.11	5.34	0.144
35	29.61	66.93	1.87	8.15	6.51	5.96	4.80	0.242
36	29.46	65.70	2.02	8.51	6.91	5.53	5.20	0.065
37	29.79	61.94	1.66	9.09	6.99	5.60	4.75	0.178
38	29.88	55.83	1.60	9.43	7.28	5.83	5.31	0.098
39	29.87	50.60	1.28	9.73	7.20	5.77	5.09	0.133
40	29.67	45.52	1.20	9.61	7.20	5.77	5.46	0.055
41	28.96	41.09	1.06	9.60	6.95	5.57	5.42	0.027
42	27.47	39.67	1.03	9.64	6.53	5.23	5.01	0.044
43	26.43	36.10	0.92	9.68	6.09	4.88	4.81	0.014
44	25.80	33.84	0.98	9.88	5.99	4.80	4.98	0.037
45	24.64	33.40	0.97	9.94	5.60	3.84	4.61	0.166
46	23.72	35.24	1.00	9.51	5.10	3.50	4.24	0.174
47	22.30	37.00	1.05	9.26	4.68	3.21	3.72	0.136
48	20.88	37.39	1.16	9.36	4.55	3.12	3.45	0.094
49	20.17	35.90	1.15	9.22	4.33	2.97	3.39	0.124
50	19.52	40.93	1.17	8.86	4.10	2.81	2.68	0.049
51	19.00	41.88	1.26	8.65	3.98	2.73	2.66	0.027
52	17.90	41.69	1.41	8.95	4.05	2.78	2.62	0.060

N.B. : T_{mean} = mean temperature (°C); RH_{mean} = mean relative humidity (%); WS = wind speed (ms^{-1}); SS = duration of sunshine (hrs.); E_{adj} = adjusted pan evaporation (mm day^{-1}); E_{est} = estimated reservoir evaporation (mm day^{-1})

stations in India relating pan evaporation with vapour pressure defecit, maximum temperature and mean wind velocity. Evaporation estimated with developed relationship compared favourably with actual data.

Table 2 presents the details of depth, capacity and surface area of both the water bodies at 1.52 m (5 feet) interval obtained from P.H.E.D. Jodhpur. Since exposed water surface area of a water body depends on its geometry, hence relationships were developed for area and depth for both water bodies (Fig. 2) and yielded equation 3 and 4 for Kailana and Takhatsagar, respectively.

$$A = 108.28 D^3 + 28.266 D^2 + 13628 D \; (r^2 = 0.999) \quad \text{...........(3)}$$

$$A = -89.971 D^2 + 29882 D \; (r^2 = 0.997) \quad \text{...........(4)}$$

Where, A is surface area in m^2 and D is depth of water in m from bottom.

Table 2. *Area-depth-capacity chart for Kailana and Takhatsagar reservoirs*

Sl.No.	Kailana				Takhatsagar			
	R.L. (m)	Depth (m)	Area (ha)	Capacity upto each contour (ha-m)	R.L. (m)	Depth (m)	Area (ha)	Capacity upto each contour (ha-m)
1.	256.03	0.00	0.00	0.000	248.41	0.00	0.21	0.000
2.	257.56	1.53	2.52	2.866	249.94	1.53	3.25	3.398
3.	259.08	3.05	4.17	7.966	251.46	3.05	7.42	12.035
4.	260.60	4.57	7.44	16.815	252.98	4.57	13.24	29.025
5.	262.12	6.10	10.41	30.183	254.51	6.10	18.55	53.520
6.	263.65	7.62	14.86	50.122	256.03	7.62	23.92	86.368
7.	265.18	9.14	21.91	78.349	257.56	9.14	27.75	126.012
8.	266.70	10.67	28.85	118.446	259.08	10.67	31.47	174.152
9.	268.22	12.19	35.91	166.382	260.60	12.19	34.17	219.460
10.	269.75	13.72	46.74	229.365	262.13	13.72	38.09	276.094
11.	271.27	15.24	59.75	310.358	263.65	15.24	43.13	337.260
12.	272.80	16.76	74.90	412.867	265.18	16.76	46.97	395.735
13.	273.71	17.68	84.77	481.395	266.70	18.29	51.70	467.945
14.	-	-	-	-	268.22	19.81	55.97	542.278
15.	-	-	-	-	269.75	21.34	60.1	652.291

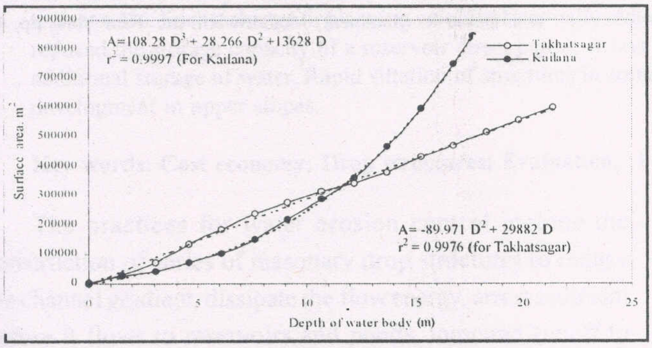

Fig. 2 *Surface area and depth relationships for Kailana and Takhatsagar*

By combining equation 3 and 4 with equation 2, total water losses due to evaporation ($m^3 day^{-1}$) for Kailana and Takhatsagar can directly be estimated at any depth using equations 5 and 6, respectively.

$$E=\{0.33\,T_{mean} - 0.12\,RH_{mean} + 2.48\,WV - 0.20\,SS\} * \{108.28\,D^3 + 28.26\,D^2 + 13628\,D\}/1000 \quad ....(5)$$

$$E=\{0.33\,T_{mean} - 0.12\,RH_{mean} + 2.48\,WV - 0.20\,SS\} * \{-89.97\,D^2 + 29882\,D\}/1000 \quad ....(6)$$

Where, E is total water loss due to evaporation in m^3 day^{-1} and other symbols are same as explained earlier.

The daily evaporation losses at full supply level for Kailana as estimated by equation 5 varies from 2115.2 to 10832.7 m^3 day^{-1} with an average loss of 5690.5 $m^3 day^{-1}$. Evaporation losses for Takhatsagar, which is comparatively deeper than Kailana varies from 1488.1 to 7620.5 $m^3 day^{-1}$ with an average loss of 4003.4 m^3 day^{-1} (computed by equation 6). Total average water loss due to evaporation from both the reservoirs is to the tune of 9693.9 $m^3 day^{-1}$. The total daily water supply from these two reservoirs to the Jodhpur city is 167919 m^3 (5.93 M cft) and the combined daily evaporation losses from these two reservoirs varies between 2.15 to 11% of total daily outflow at FSL. If the maximum level of both the reservoirs is kept within 15 m, the total daily evaporation losses is reduced to the level of 1.49 to 7.63% of total daily out flow (Fig.3). An average daily saving of 2956.6 m^3 at maximum level of 15 m (due to reduced surface area in comparison to FSL) for the whole year would mean a saving of water sufficient enough to meet the total water demand of city for 6.44 days.

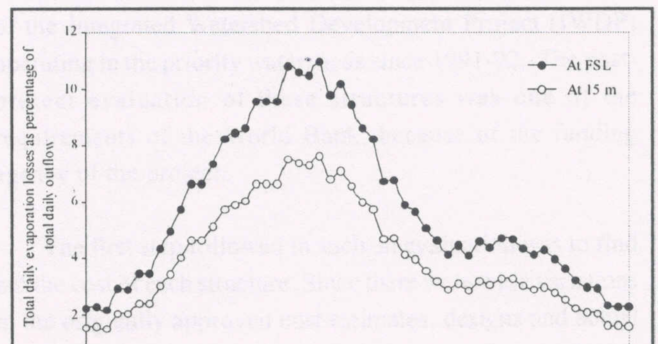

Fig. 3. *Comparison of total daily evaporation losses as percentage of total daily outflow at different water levels in reservoirs*

Kailana and Takhatsagar reservoirs are the only two main water storage reservoirs to provide water supply to Jodhpur city. As per population projection, existing capacity will not be sufficient to meet the water demand beyond the year 2011. Therefore, third additional water storage reservoir will be needed in future. The estimate of total water loss due to evaporation determined from the study of the existing reservoirs can be quite useful for planning and design of the future additional storage reservoir, since the main source of water to existing reservoirs is not the natural rainwater but the costly water transported by Rajeev Gandhi Lift Canal. So the models developed in the present study will be of immense use for direct determination of total evaporation losses at any stage of water in Kailana and Takhatsagar and in decision making for the lift canal operation.

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