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Water balance and mean water residence time of the Vembanad Wetland of Kerala State, India

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Abstract The Vembanad Wetland complex of Kerala State in India comprises the Vembanad backwater lake and the deltaic regions of five rivers, which drain into the lake. The wetland has many functions, including flood and pollution control, biodiversity, agriculture, inland navigation and tourism. Artificial impacts including land reclamation and reductions in tidal flushing have led to significant environmental degradation of this wetland complex. This study examines the hydrology of the Vembanad Wetland in terms of river flow variability, seasonal water level variations, residence time and overall water balance. Estimates of water residence time in the Vembanad backwater lake are nearly identical for the scenario of freshwater flows during monsoons and for the non-monsoon scenario, if the lake is left open for tidal flushing. Therefore, one of the strategies for ecological restoration of the Vembanad Wetland is to allow periodic tidal flushing by rescheduling the operation of the Thanneermukkom (TM) barrage during the non-monsoon period. The study also shows that a major share of the freshwater drained into the wetland from the rivers is discharged to the Arabian Sea. Increasing the storage within the river basins is essential for the optimal utilization of river flows and the wetlands' sustainability.

Key words Vembanad Wetland, India; hydrology; hydroperiod; residence time; water balance

INTRODUCTION

Wetlands are complex ecosystems that perform many important environmental and societal functions. Being transitional zones between uplands and estuaries, tidal wetlands mediate the exchange of sediments, nutrients and pollutants between terrestrial and aquatic ecosystems, thereby playing an important role in determining surface water quality. They also offer protection to coastal settlements by attenuating floods and tidal surges. Wetlands are important feeding, breeding, and resting grounds for resident and migratory fish and waterfowl, as well as hosting unique vegetative and microbial communities. Wetland hydrology is a key driver influencing their structure and functions (Mitsch & Gosselink 1986; Brooks 2005) and one that is significantly impacted by activities such as drainage, infilling, dam construction, water diversions, and dredging. Alterations to wetland hydrology can induce changes to many other wetland processes.

The majority of wetland restoration activities tend to focus on re-establishing hydrological equivalence because of the important role it plays in wetland structure and function. Two important hydrological parameters for wetland hydrological restoration are the duration of the wet phase or hydroperiod, and water residence time. The former is characterized by the seasonal pattern of water levels; while the latter is the time a given amount of water spends in a wetland. Both these parameters govern important chemical processes within wetlands (Mitsch & Gosselink, 1986).

This paper investigates the hydrology of the degraded Vembanad Wetland complex (Fig. 1) in Kerala State, India. This tidal wetland complex comprises the Vembanad backwater lake, which is connected to the Arabian Sea at Cochin and the lower deltaic regions of the Achencoil, Pamba, Manimala, Meenachil, and Muvattupuzha rivers, which drain into the main Vembanad lake. Large-scale reclamation and the construction of the Thanneermukkom (TM) barrage, which regulates tidal ingress to its upstream side, have significantly impacted this wetland complex. The actual wetland complex is delineated and the hydrology of the system characterized.

THE VEMBANAD WETLAND COMPLEX

The Vembanad Wetland complex receives freshwater from five major rivers (Fig. 1) as well as salt water during the semi-diurnal tides. Across the regional delta the Achencoil, Pamba, Manimala,

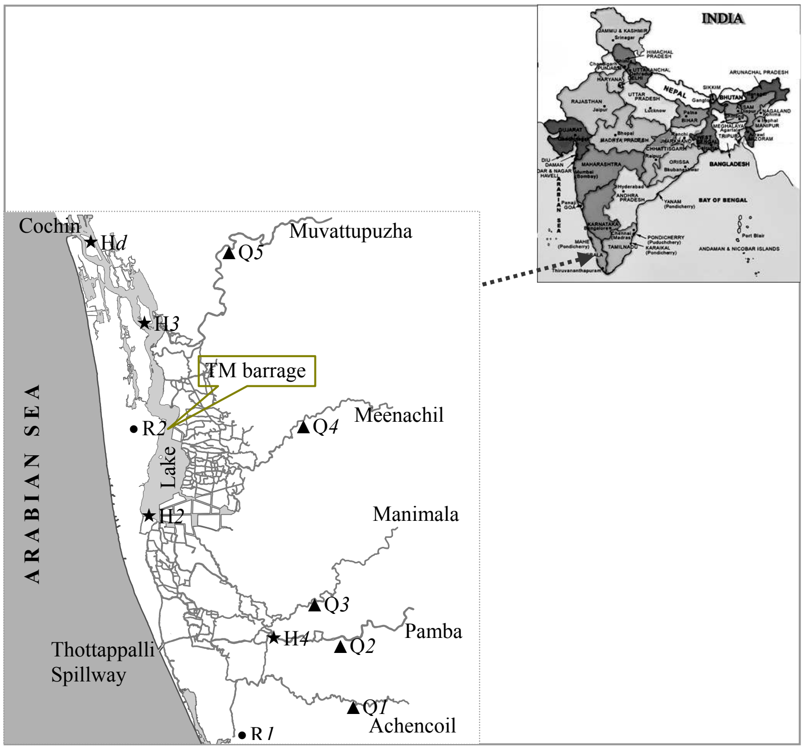

Fig. 1 Location map of Vembanad Wetland with hydrological monitoring stations (R*n*: Raingauge. Q*n*: Discharge monitoring station. H*n*: Water level monitoring station).

Meenachil and Muvattupuzha rivers as well as the Kariar stream join and flow through the Vembanad Wetland. Based on the drainage pattern and contours in the 1:50 000 scale SOI topographic maps, drainage basins of the Achencoil, Pamba, Manimala, Meenachil and Muvattupuzha rivers and a stream named Kariar are delineated. The lower deltaic region of rivers, where individual catchments cannot be distinguished is delineated into one single entity named Vembanad Wetland, with its western boundary defined by the shoreline of the Arabian Sea. The northern and southern boundaries of the wetland complex extend to the Cochin estuary. Details of the different river basins and Vembanad Wetland complex are given in Table 1. The combined catchment area of the complex is 6126.5 km^2, while the Vembanad Wetland covers an area of 2033 km^2. Within the actual wetland the water surface area of the Vembanad lake was mapped at 213.3 km^2 in 1990 (Gopakumar, 2009).

Rainfall pattern

The Vembanad Wetland region has a sub-humid climate with temperatures varying between mean minima of 22°C (in January) to mean maxima of 35°C (in March). Relative humidity varies from 80% to 95%. The region experiences southwest monsoons from June to August and northeast monsoons during the September–November period, with a short break in between in September. The average rainfall intensity is 1 cm/hour, whereas, during the monsoons, rainfall intensity can exceed 5 cm/hour (Pisharoty, 1990). Approximately 60% of the average annual rainfall (2517 mm) occurs during the southwest monsoon period while 30% occurs during the northeast monsoon. Average annual rainfall within the upstream catchment area varies from 2970 mm in the Meenachil Basin to 4360 mm in the Manimala basin. Average monthly rainfall pattern for the wetland complex is shown in Fig. 2.

River flow pattern

Average seasonal and annual flows at the five river gauging stations are given in Table 2. Seasonal flows include the monsoon flows from June to November and baseflow contributed from

Table 1 Areas of the Vembanad Wetland and its associated river basins.

No.	River basin/unit	Area (km^2)
1	Achencoil	1013.16
2	Pamba	1705.34
3	Manimala	793.79
4	Meenachil	1030.94
5	Kariar	94.74
6	Muvattupuzha	1488.52
7	Wetland region	2033.01
	Total	8159.50

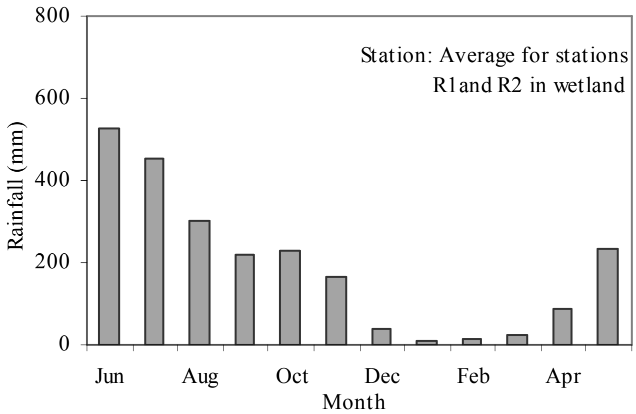

Fig. 2 Average monthly rainfall within the wetland region (Data source: CWRDM).

December to May. Since the catchments of river gauging stations cover only 4957 km^2 area of the total upper basin areas, average seasonal and annual discharges per unit catchment area of gauging stations are computed, and by assuming that these unit discharges are also valid for the remaining area of the respective basin, river flows from the upper basins are estimated (Table 2). Among the five rivers, Muvattupuzha contributes the maximum unit discharge both during the monsoon and non-monsoon seasons. The Achencoil, Manimala and Meenachil basins contribute about 95% of their annual discharge as monsoon flows and remaining 5% as non-monsoon flows. The corresponding seasonal flows from other basins are 91.4% and 8.6%, respectively, in the Pamba basin, and 82.4% and 17.6%, respectively, in the Muvattupuzha basin. The average monthly river flow pattern from Achencoil and Muvattupuzha basins are presented in Fig. 3.

Since no discharge or rainfall data are available for the basin area of Kariar, its contribution to river flows is computed by assuming a unit discharge same as that of the contiguous Meenachil river basin, in which there are no storage reservoirs or inter-basin water transfer. Out of the total annual flow of 16609.47 Mm^3 contributed to the wetlands from a total upper river basin area of

Table 2 Average seasonal and annual discharges from the upper river basins.

River basin	Drainage area (km^2)	Monsoon flow (Mm^3)	Base flow (Mm^3)	Total flow (Mm^3)
Achencoil	1013.16	1410.63	72.00	1482.64
Pamba	1705.34	3781.50	351.94	4133.44
Manimala	793.79	1788.76	90.60	1879.37
Meenachil	1030.94	2713.78	155.24	2869.02
Muvattupuzha	1488.52	4931.77	1049.55	5981.34
Kariar	94.74	249.36	14.31	263.66
Total	6126.49	14875.80	1733.64	16609.47

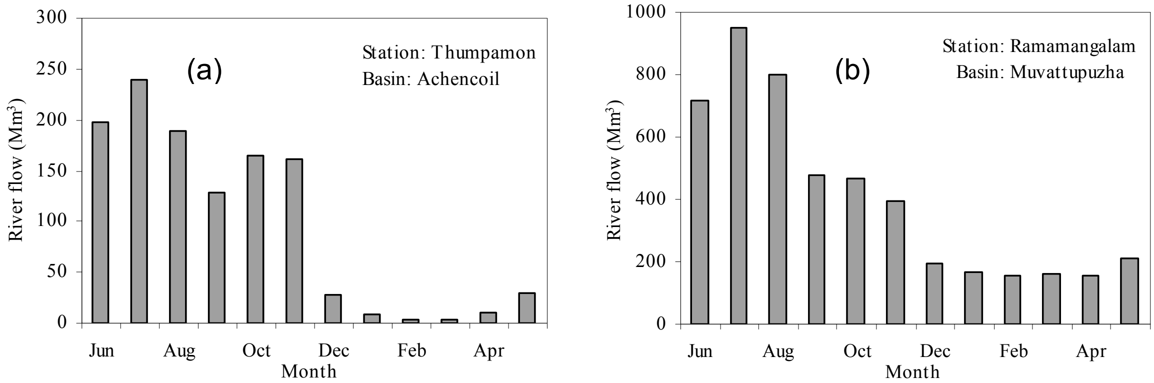

Fig. 3 Mean monthly flow at the gauging stations in: (a) Achencoil (Q1), and (b) Muvattupuzha (Q5) rivers.

6126.49 km^2 (Table 2), 14875.80 Mm^3 (89.6%) occurs during the monsoon season and the remaining 1733.64 Mm^3 (10.4%) is received as baseflow during the non-rainy months.

A summary of the variability of river flows to the wetland complex is provided in Table 3. There is a degree of similarity for all five gauging stations, especially in terms of the high flows. However, they do differ in terms of low flows. The lower region of the flow duration curves characterizes the poor ability of the Achencoil, Manimala and Meenachil rivers to sustain low flows during dry seasons. For about 50% of the time, these three rivers have negligible low flows (Table 3), whereas the Pamba and Muvattupuzha rivers have a slightly elevated low flow regime (Fig. 4), with median flows of 49.1 m^3/s and 83.75 m^3/s, respectively. Two reservoirs located in the upper regions of the Pamba basin have a total storage capacity of 493.5 Mm^3 and these sustain periods of low flow during the dry seasons. Flow duration analysis and seasonal discharge from the river basins (Table 2) indicate that reservoir operations play a significant role in sustaining low flow regimes of the Pamba and Muvattupuzha rivers.

Table 3 Median daily flows at the gauging stations of the five major rivers.

River basin	Station	Median flow (m^3/s)	10% dependable flow (m^3/s)
Achencoil	Thumpamon (Q1)	11.29	103.60
Pamba	Malakkara (Q2)	49.10	331.90
Manimala	Kalluppara (Q3)	13.85	161.50
Meenachil	Kidangur (Q4)	15.90	143.90
Muvattupuzha	Ramamangalam (Q5)	83.75	349.95

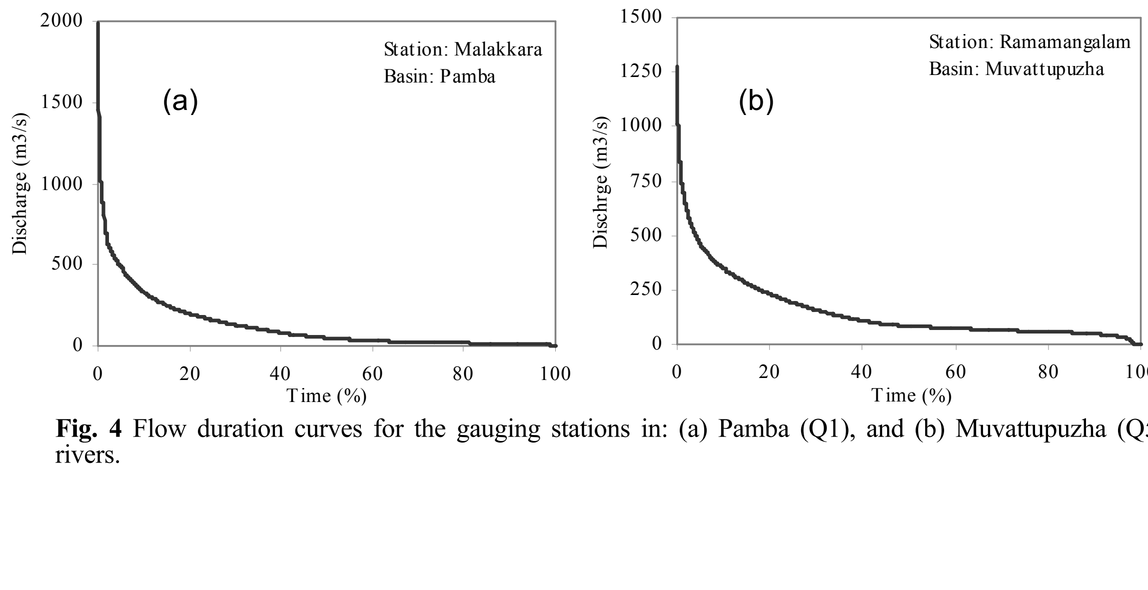

Fig. 4 Flow duration curves for the gauging stations in: (a) Pamba (Q1), and (b) Muvattupuzha (Q5) rivers.

Flood events

Topographically, large areas of the Vembanad Wetland complex are either near or below mean sea level (MSL). In the southern and eastern regions 398.14 km^2 area of the lake is below MSL, while 763.23 km^2 of the complex has an elevation of 1 m above MSL. Approximately two million people live in this area. The low relief makes the wetland susceptible to extensive flooding during the monsoon. Although flood plain and wetland storage help contain flooding, large areas of the region are inundated for a long period of time. Flooding frequencies for the gauging stations are given in Table 4.

Seasonal water level variations

Knowledge of the hydroperiod of wetlands is important for many reasons. Mean daily water levels at three stations, Alleppey (H2), Panavally (H3) and Cochin (Hd) are shown in Fig. 5. The occurrence of a number of flood events at stations H2 and H3 during the monsoon period from June to November are well demonstrated in this figure. During the monsoon months of higher river flows to the Cochin estuary, tidal influence is observed in the lake only to a distance of about 10 km from the Cochin sea mouth.

Table 4 Annual maximum discharges at the river gauging stations for various return periods.

Basin	Station	Discharge (m^3/s) for return periods in years				
		2	10	25	50	100
Achencoil	Thumpamon	374	676	839	965	1094
Pamba	Malakkara	1066	1636	1929	2150	2375
Manimala	Kallupara	562	761	834	880	921
Meenachil	Kidangur	680	847	957	1062	1169
Muvatupuzha	Ramamangalam	988	1350	1481	1563	1634
Achencoil+Pamba+M animala		1973	3018	3518	3882	4237

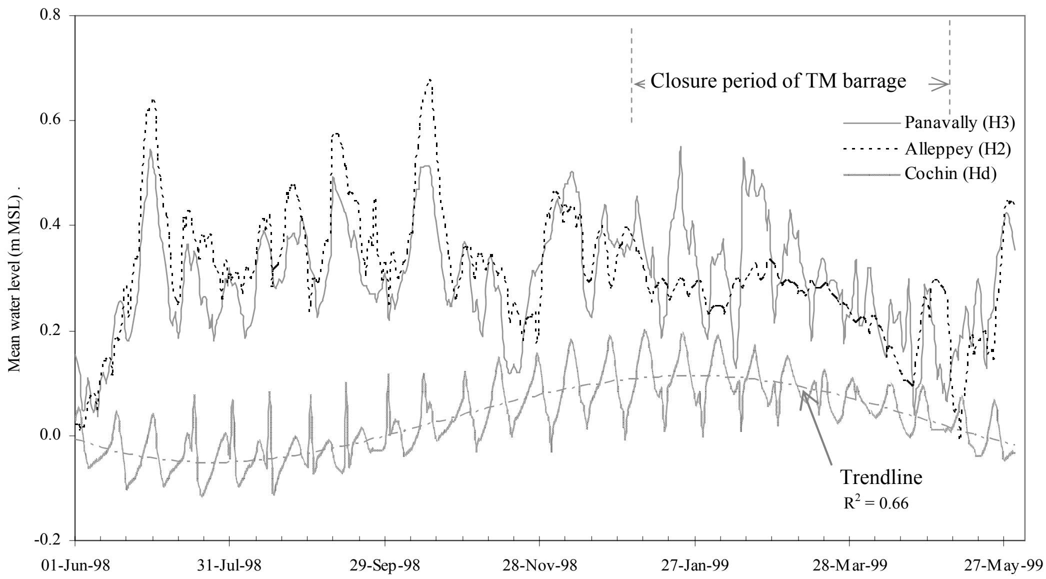

Fig. 5 Daily mean water levels in Vembanad Wetland for the water year 1998–1999.

During the non-rainfall period from December to May, when discharges are very low in all the rivers except Muvattupuzha, tides have a dominant role in the water level variations in Vembanad drainage system. To prevent saline intrusion, tidal action on the lake is closed off from mid-December to mid-March by the operation of the TM barrage (Fig. 1). When the TM barrage is kept open, a continuous ebb is observed up to Alleppey (H2) on the southern end of the lake. In the water year 1998–1999, gates of TM barrage were closed on 7 January 1999 and reopened on 9 May 1999. It can be observed from Fig. 5 that, after the closure of TM barrage, water level at station H2 on its upstream side gradually drops, although the daily range of water levels is very small. Since the river flows to the lake are very low during the non-monsoon period, a significant rise observed in the water level at station H2 from 22 April is due to the water inputs from the unusually higher summer rainfall received in the month of April. Summary of the water level variations at selected stations for a typical year presented in Table 5 indicate a maximum daily range of water level of 1.01 m and 0.30 m, respectively, at Cochin estuary (Hd), and at Alleppey station (H2).

Table 5 Summary of water level variations in wetlands during a typical water year.

	Cochin (Hd)	Panavally (H3)	Alleppey (H2)
Lowest low water level (m, MSL)	–0.54	–0.22	–0.09
Highest high water level (m, MSL)	0.56	0.76	0.69
Max. range of daily water level (m)	1.01	0.66	0.38

Water residence time

The renewal rate (i.e. 1/residence time) of water in a coastal wetlands can be defined as the ratio of throughput to average volume within the system. Here we used a single compartment, tidally averaged box model (Wolanski, 2007) to quantify the renewal rate and residence time with a conceptual understanding of estuarine systems. In this method, the estuary is treated as a single compartment of fixed volume, V, subjected to river freshwater inflow upstream with a discharge Q_f and a salinity S_f (generally $S_f = 0$). There is an oceanic inflow with a discharge Q_{in} and a salinity S_o, and an outflow to the ocean with a discharge Q_{out} and a salinity S_1. Mass is conserved, so that the outflow of water is equal to the inflow of water. Neglecting groundwater inflow/outflows as well as evaporation, the resulting continuity equation is:

$$Q_{in} + Q_f = Q_{out} \tag{1}$$

Salt is a conservative substance, hence the inflow and outflow fluxes of salt are equal:

$$Q_{in}\, S_o + Q_f\, S_f = Q_{out}\, S_1 \tag{2}$$

The residence time, T is defined as the volume of water in the estuary divided by the river flow rate:

$$T = (V_{estuary} / Q_f)\,(1 - S_1/S_o - S_f/S_o) \tag{3}$$

Assuming that the salinity in the estuarine system is negligible when freshwater flows from the rivers are high, equation (3) can be modified as:

$$T = (V_{estuary} / Q_f) \tag{4}$$

where, $V_{estuary}$ is the volume of the estuary.

By definition, renewal rate of freshwater in the estuary:

$$v_f = 1 / T \tag{5}$$

In a situation when the river flows are negligible, tidal flushing is more effective than runoff in the determination of volumetric flows and mass transport throughout the system. When oceanic mixing with the seawater across its down-estuary face is intense, all the old estuarine water that leave the estuary at falling tide is flushed out to coastal waters, and thereby replaced by coastal waters entering the estuary at rising tide. Mean water residence time in the estuary for the case of mixing and exchange with coastal waters under negligible river flows is:

$T = V_{estuary} T_{tide} / V_{TP}$ (6)

where $V_{estuary}$ is the mean estuarine volume, and T_{tide} is the tidal period. V_{TP} is the mean tidal prism volume.

Residence times and renewal rates of the Vembanad lake were estimated for three different scenarios. First, long-term mean residence time is estimated by considering the annual freshwater inputs only from the upper rivers and the volume of the lake at the mean annual water level. Based on daily water level measurements of the Alleppey (H2), Panavally (H3) and Cochin (Hd) stations (Fig. 1), mean water level of the Vembanad lake for a typical water year is calculated as 0.21 m MSL. Using the digital elevation model (DEM) of the lake (Gopakumar, 2009), the volume of Vembanad lake at a mean water level of 0.21 m MSL is determined as 438.71 Mm^3. The long term mean residence time of the lake estimated from equation (5) and dividing the volume of the lake with the mean annual rate of freshwater flows to the Arabian Sea and with an annual freshwater input of 18755.72 Mm^3 (Table 2), the mean water residence time in the lake (T) and turnover rate (T^{-1}) are estimated as 8.54 days and 42.75 $year^{-1}$, respectively. Although the above estimates provide an overall view of the volumetric flows in the Vembanad lake system, some of the key factors, like variability in freshwater flows and effect of tidal flushing of the water system, are not accounted for in the estimates.

The second scenario considers the influence of the monsoon, during which salinity in the estuarine lake system is almost negligible due to the higher freshwater flows from the rivers. In this scenario, and using water level data of stations H2, H3 and Hd as reference levels, the mean water level of the lake during the monsoon period is calculated as 0.244 m MSL. This corresponds to a lake volume of 447.02 Mm^3 and combining this with a mean total monsoon river flow of 14875.80 Mm^3 (Table 2) (equivalent to a freshwater flow rate of 81.29 Mm^3/day), the estimated turnover rate of water in the lake for the six-month period is 33.3.

For the third scenario, the residence time of water in the lake system is estimated on the tidal flushing during the non-monsoon season from December to May. During this season, river flows are very low and, primarily the tides control the exchange of water between the lake and the Arabian Sea, when the TM barrage is left open. In such conditions, tidal influence extends up to the southern end of the Vembanad lake, located at 54.4 km from the Cochin mouth. By selecting a subset of water level data of stations H2, H3 and Hd for the situation when TM barrage is kept open during the non-monsoon period, the mean water level of the lake under the third scenario is estimated as 0.329 m MSL, which corresponds to a lake area and volume of 214.47 km^2 and 464.44 Mm^3, respectively. The tidal period in this region is 12 hours 25 minutes and under this scenario, mean spring tidal range varies from 0.97 m at Cochin mouth to 0.20 m at the end of the lake and the mean tidal prism volume is estimated as 50.232 Mm^3. The mean residence time of the system based on the tidal flushing, computed with equation (6), is 4.8 days and the corresponding turnover rate is 38.

There is considerable seasonal variability in water residence time within the Vembanad lake system, as detected by the three scenarios. Under the second scenario, mean water residence time is 5.5 days and freshwater flows flush out the lake system 33 times during the period from June to November. In the non-monsoon period, if the lake system is open to tidal flushing, mean water residence time is 4.8 days and the lake would be flushed 38 times during the period from December to May. The above non-monsoon period scenario prevailed in the wetland before the construction of TM barrage in 1975. After the construction of TM barrage, every year, flushing of the lake is cut off for a minimum period of 90 days. The water residence times of Vembanad lake, discussed above, are the mean value estimates for three different time periods of the year. But, the water residence time is not a constant since it depends on freshwater flows, range of tides and tidal length. Since the residence time varies with the position along the tidal length, during the period of tidal flushing, the outer reaches of the lake system will have a smaller residence time than its upper reaches.

OVERALL WATER BALANCE

One of the important factors that can be used to summarize the hydrological state of a given wetland is the balance between the inflows and outflows of the water system. The general balance between water storage and inflows and out flows of a wetland (Mitsch & Gosselink, 1986) can be expressed as:

$$\Delta V = P + S_i + G_i - ET - S_o - G_o \pm T \quad (7)$$

where V = volume of water storage in wetlands; ΔV = change in volume of water storage in wetland; P = precipitation; S_i = surface inflows; G_i = groundwater inflows; ET evapotranspiration; S_o = surface outflows; G_o = groundwater outflows; T = tidal inflow (+) or outflow (–).

Although there may be temporary variations such as during floods or droughts, on an annual basis it can be assumed that the amount of water entering the Vembanad Wetland and the amount of water leaving the system are equal. Water inputs consist of precipitation received directly on the lake and wetland area and runoff from the associated catchments. Water outputs consist of the evaporation from the lake surface, evapotranspiration from the wetland and discharges to the Arabian Sea. In the shallow groundwater table conditions of wetland, groundwater inflows and outflows are assumed to be equal. Tidal inflows and outflows are also assumed to be equal. By assuming that there is no change in the water storage of wetland, equation (7) is modified as:

$$S_o = S_i + P - ET \quad (8)$$

The average annual flows from the total drainage area of the Vembanad Wetland has been computed as 16609.47 Mm^3 (Table 2), which is equivalent to an average annual surface inflow rate (S_i) of 526.6 m^3/sec. Since no measurements are available for the outflows from the system through Vembanad lake, outflows are estimated by subtracting the estimates of evaporation from those of annual precipitation.

Based on a land use map available for the region (NEERI, 2003), the area of land and water bodies in the Vembanad Wetland are measured as 341.02 km^2 and 1692 km^2, respectively. Mean annual precipitation in the wetland is estimated as 2517 mm/year. The mean crop reference evapotranspiration for Alleppey region of the wetland has been estimated (Indo-Dutch Mission, 1989) as 1430 mm/year. Therefore, the amount of water (P-ET) entering the drainage system from the total land area is 1087 mm, which is equivalent to an annual average flow of 58.32 m^3/sec. Evaporation from water surface is estimated by multiplying reference evapotranspiration with the evaporation factor for water (FAO, 1984). By taking an average evaporation factor of 1.125, evaporation from the water surface is estimated as 1609 mm/year. Assuming the mean annual precipitation received directly on the lake and other water bodies to be the same as 2517 mm/year, the net input of water directly through the water surface area is 908 mm; equivalent to an average flow rate of 9.82 m^3/sec. The total average annual flow rate equivalent to (P-ET) for the land area and water surface is 68.14 m^3/sec.

By using the estimates of S_i and (P-ET) in equation (8), net average annual outflow (S_o) from the wetland to the Arabian Sea is computed as 594.74 m^3/sec or equivalent annual volume of 18755.72 Mm^3. The overall water budget of the Vembanad Wetland is schematically presented in Fig. 6. Considering the major contribution of river flows (88.54%) in the total average annual outflow from the wetland, and the variability in monthly river flow patterns as discussed earlier, it can be concluded that creating more storage in the river basins is essential to ensure optimal utilization of river flows for the future water resource development in the river basins, and to sustain the different functions of the wetlands.

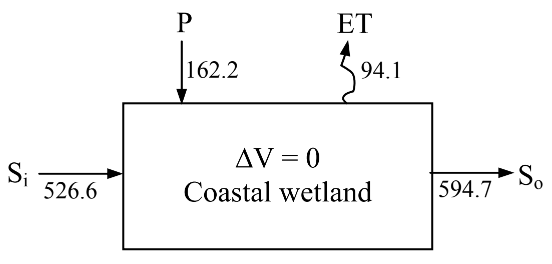

Fig. 6 Annual water budget of Vembanad Wetland. All values expressed in m^3/sec.

CONCLUSIONS

In this study, the hydrological regime of the Vembanad Wetland has been characterized. The following conclusions are given:

– Out of a total average annual river flow of 16 609 Mm^3 contributed to the Vembanad Wetland, 89.6% of the flows are received during the monsoon season and the remaining 10.4% occurs as baseflow during the remaining 6 months. Flow-duration analysis characterizes the poor ability of Achencoil, Manimala and Meenachil river basins to sustain low flows during the non-monsoon season. Operation of reservoirs existing in the upper area of Pamba and tailrace discharge received by the Muvattupuzha from the Idukki hydroelectric project are the primary reasons for the slightly better low flow regime in these rivers.
– Increasing flood proneness is one the major water management issues faced in the wetlands. Flood frequency analysis for the river gauging stations located adjacent to the wetland show that, due to increasing occurrence of high flood events in the last two decades, annual maximum discharges estimated for all the five gauging stations for various return periods are higher than the respective estimates made earlier during the KWB Study (1989).
– Mean water residence time of Vembanad lake system is estimated to be 5.5 days for the monsoon period of high freshwater flows, and 4.8 days during the non-monsoon period if the lake system is open to tidal flushing. Since the estimates for the two different seasons are very close, it can be concluded that prior to the construction of TM barrage, water in the Vembanad lake system was well flushed throughout the year, either by the monsoon flows from the rivers, or by tidal flushing during the non-monsoon months. Therefore, rescheduling the operation of TM barrage to allow periodic tidal flushing of the lake during the non-monsoon period shall be treated as one of the strategies for ecological restoration of the Vembanad water system.
– With the assumption that the amount of water entering the wetlands is equal to the amount of water leaving the system, net average annual outflow to the Arabian Sea is computed as 594.74 m^3/sec. Considering the major contribution (88.54%) of river flows to the net annual outflow from the wetland, and the large seasonal variations in river flows, it is concluded that creating more storage in the river basins is essential to ensure optimal utilization of the river flows for future water resources development and to sustain the different functions of wetlands.

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