HYDRODYNAMIC VARIABILITY ALONG THE OUTLET CHANNEL OF KOLLERU LAKE, INDIA

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ABSTRACT

Hydrodynamic parameters like Salinity intrusion, circulation and mixing properties, flushing characteristics, Total salt etc., along outlet channel of Kolleru Lake have been studied during May 2010 – April 2011. The observations reveal that the channel had lost 94.2% of Total Salt during May - November 2010 and regained upto 94.0% by April 2011. Flushing time has been varied from 1.81 to 5.61 tidal cycles. The Diffusion Coefficient (K_X) varied randomly between 0.0032×10^5 and 5.6×10^5 m^2/s during July - August 2010. The yearly mean K_X ranges between 0.0095×10^5 and 2.1×10^5 m^2/s. The seasonal variation of depth mean salinity along the axis of the channel shows a wide range. During periods of very high discharge, salt wedge has been formed near the confluence and extended few kilometers upstream. For moderate discharge, the channel has become partially mixed with a high degree of stratification. For very less or negligible discharge, the channel exhibits well mixed nature. Topography of the channel and the discharge from Kolleru Lake are identified as key parameters causing significant changes in the channel. The wider extent of the channel and the identical behavior like an estuary confirms the channel as a natural estuarine system.

Key words: Circulation, Mixing, Salt wedge, Flushing time, Diffusion Coefficients, Upputeru channel, Kolleru Lake.

I. INTRODUCTION

Kolleru Lake (Latitude $16^\circ 32' - 16^\circ 47N$ and Longitude $81^\circ 05' - 81^\circ 21' E$) is the largest freshwater lake of India located in Andhra Pradesh along East coast of India. It spans into two districts - Krishna and West Godavari. The lake serves as a natural flood-balancing reservoir for the two rivers Krishna and Godavari connecting by over 68 inflowing drains and channels. The peak discharge contributed by the channels and drains flowing into Kolleru Lake during monsoon season is about $3130\,m^3/s$. It receives drainage from deltaic catchment area of 1348sq. km. and upland catchment area of 3406sq. km. The only outlet to Kolleru Lake discharging its excess waters into Bay of Bengal is 'Upputeru channel'.

The channel is narrow, shallow and meandering with a stretch of about 60 km between Kolleru lake and Bay of Bengal. The water circulation at high river discharge was dominated by a meandering system, with the high seaward flow in the deepest areas(17). The channel has two mouths; one being natural and other was artificially dredged. The channel has become very much shallow towards the natural mouth. Discharge of fresh water and impact of tides are mainly getting through the artificial mouth.

In estuarine environments the flushing and mixing of seawater and fresh water along with pollutants (agricultural, industrial, etc.) are mainly activated by tidal currents and fresh water discharge. The pollutants will be subjected to number of physical, chemical and biological processes in the estuary ultimately resulting in their dilution and dispersion. An overall view of mixing properties of an estuary is produced by methods which provide estimates of the flushing time of the estuary as a whole or a portion of it. The simplest of the more detailed treatment to know the relevant time scale of mixing and flushing is the steady state one dimensional approach, in which the distribution of properties along the length and breadth of the estuary(7). For a narrow and shallow channel, averages may be taken over each cross-section.

The process of dispersion and dilution of pollutants by various phenomena and the knowledge of flow characteristics can be mathematically modeled to fulfill the pre-operational evaluation of discharge pollutants or conducting continuous field experiments. The implementation of modeling to describe these processes due to external and internal forces mostly depends on the dimensions of the channel and environmental conditions. In a well-mixed estuary, the turbulent energy generated by bottom friction is sufficient to mix the mass and momentum efficiently throughout the water column and there exists a reasonable uniformity of horizontal current. So by neglecting vertical component of velocity, a 3-D problem can reduce to a 2-D by depth averaging the governing equations (5). The dynamics of weakly stratified and well-mixed estuaries may be described by integrating the fluid equations over the cross sectional area (9)(13). This leads to reduction of 2D to 1D (5).

The interaction between river flow and tidal currents, in combination with topography of the estuary gives rise to different types of estuarine circulation. Bowden (1980), classified estuarine circulation into three types as Highly stratified or salt-wedge type, Partially mixed with a two layered net flow and Well mixed estuary with the mean velocity is always seaward at all levels. A continuous spectrum of classification with regard to circulation is provided by the Stratification – Circulation diagram (19). In the diagram distinctive areas represent the broad categories mentioned by Bowden (1980).

II. DESCRIPTION OF STUDY AREA

The study area is confined to 27 km upstream from stn 1B (Padathadiki) which has encountered maximum width of about 315m. The location of stations along the channel has been shown in Fig. 1. The station 7 (Kondangi) has minimum width of about

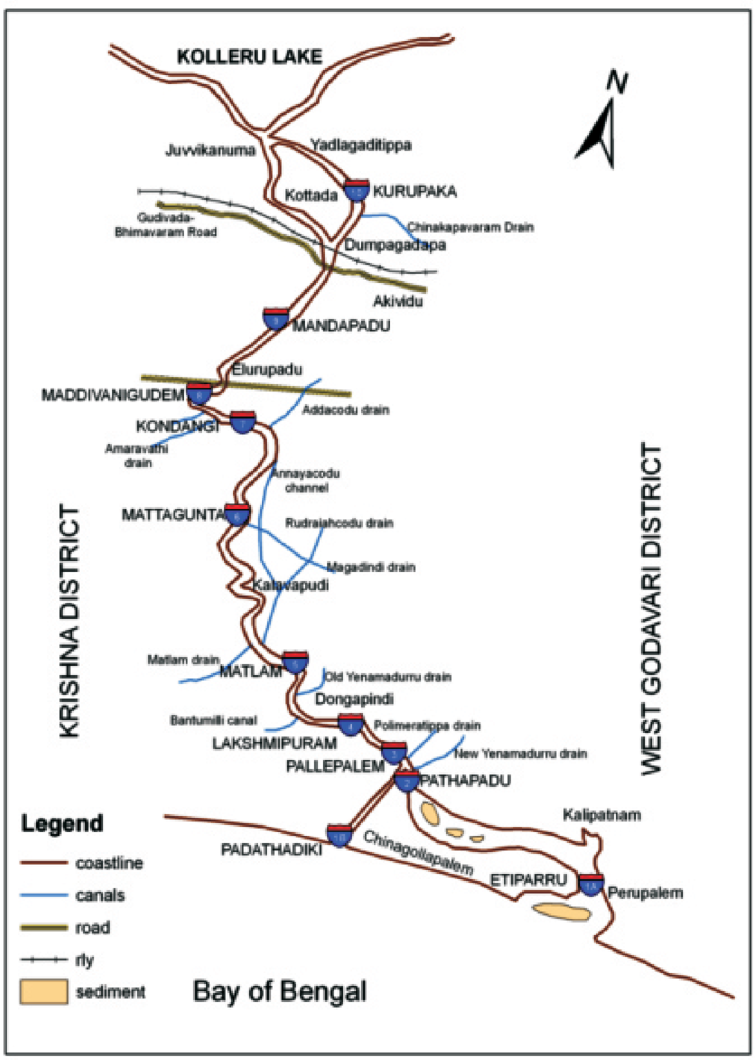

Fig. 1. Study area - Course of Upputeru channel; numbers indicate stations in the upstream from mouths.

100m. The maximum and minimum channel depths of about 9.8m and 4.2m have been encountered at Station 3 (Pallepalem) and Station 6 (Mattagunta) respectively. The average depth and width of the study area are 6m and 190m respectively. The channel is very shallow and wide between the stations 1A and 2. The width depth ratio is almost constant after the station 3. The stations 8, 9 and 10 are visited seasonally to study the salinity intrusion into the channel.

III. MATERIALS AND METHODS

The stations were occupied usually around full moon day in every month and data for 13 hours (from 0600 hrs to 1800 hrs) i.e., over a complete tidal cycle has been collected. Average distance between the consecutive stations has been limited to 4-5km which is greater than or equal to the tidal excursion. The stations were divided into two groups consisting of 4 stations in each group. The data from all the stations have been collected within two days during the study (17). In order to confirm stations locations, a Handheld GPS has been used. Salinity and Temperature observations have been made at surface, mid depth and bottom at each station by using a T-S bridge instrument (accuracy: —+0.01psu). Eulerian method of current measurements has been carried at each station using Lawrence current meter. The instruments have been calibrated before each survey following standard methods. Discharge and rainfall data have been obtained from the Drainages Sub-Division, Akividu, West Godavari District, A.P., India.

IV. RESULTS AND DISCUSSION

A. Fresh water fraction and Flushing time

An overall view of the rate of mixing in an estuary is given by the concept of the "Flushing Time" defined as the average time taken by a particle of fresh water to pass through the estuary (14). Its determination requires an adequate knowledge of the distribution of salinity, in horizontal and with depth within the estuary, as well as of the channel flow. In the simplest estimate of flushing time, fresh water is used as a tracer and it is assumed that fresh water is removed by flushing at the same rate as it is being added by Lake discharge. The fraction of fresh water method is adopted for the computation of flushing time.

The flushing time 't' is given by $t = F/R$, where R is the rate of influx of fresh water and F is the total volume of fresh water accumulated in the estuary. If S_0 is the salinity of the undiluted sea water which is available for mixing and S is the salinity at any point, then the fresh water content 'f' at that point is given by $f = (S_0 - S)/S_0$. To determine F, the total volume of fresh water accumulated in the estuary, the estuary is divided into a suitable number of segments of volume V and the appropriate value of 'f' assigned to each element. The total fresh water content is then given by $F = f \times V$ where the summation is carried out over the total volume 'V'. The variation of flushing times with respect to the fresh water discharge is shown in Fig 2.

The flushing time is smaller i.e., 1.81 tidal cycles when the discharge is highest. The flushing time is highest of about 5.61 tidal cycles when the discharge is very less.

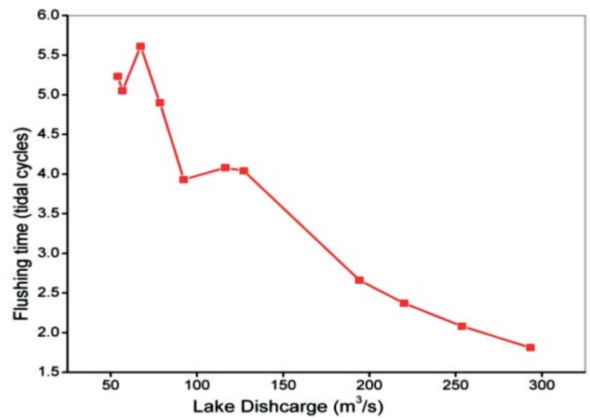

Fig. 2. Flushing times of Upputeru channel with respect to fresh water discharge.

Flushing time decreases rapidly with increasing fresh water flow and thereafter decreases gradually. Similar results were observed for Bostan harbor (12) and for Azhikode estuary (6).

B. Circulation and Mixing

A quantitative means of classifying and comparing estuaries, and one which requires measurements of salinity and velocity only, has been developed by Hansen and Rattray (1966). Here, two dimensionless parameters have been used to characterize estuaries. The Stratification parameter $\delta S/S_0$ is defined as the ratio of the surface to bottom difference in the salinity (δS) and the mean cross-sectional salinity (S_o). The Circulation parameter u_s/u_f is defined as the ratio of the net surface current to the mean cross-sectional velocity. Here, when the net flow is upstream, the values of U_S or U_f becomes negative. The stratification and circulation parameters have been computed and plotted station wise, in the Stratification and Circulation diagram according to Hansen and Rattray scheme. The results for four months (June & November of 2010 and January & March of 2011) representing four different seasons are mensioned in Table 1.

Table 1. Stratification and Circulation Parameters.

Stn.No.	U_s	U_f	U_s/U_f	S_o	dS	dS/S_o	class
JUNE, 2010							
1B	– 10	– 10	1	21.4	12.8	0.6	1b
3	10	2	6	20.1	10.4	0.52	2b
4	13	7	1.8	15.8	10.9	0.69	2b
5	7	1	5.2	6.72	3.62	0.54	2b
6	4	1	4	4.27	3	0.7	2b
7	– 1	– 1	1	1.8	0.01	0.01	1a
NOVEMBER, 2010							
IB	33	22	1.5	5.33	7.85	1.47	4
III	42	41	1	1.06	1.56	1.48	4
IV	44	33	1.3	0.47	0.03	0.06	1a
V	38	29	1.3	0.46	0.02	0.03	1a
VI	43	35	1.2	0.41	0.04	0.1	1a
VII	47	39	1.2	0.39	0.03	0.08	1a
JANUARY, 2011							
IB	7	7	1	15.72	2.85	0.18	1b
III	27	15	1.8	9.72	9.29	0.96	2b
IV	18	17	1	1.16	0.35	0.31	1b
V	17	12	1.3	0.61	0.08	0.13	1b
VI	24	18	1.3	0.51	0.07	0.14	1b
VII	28	20	1.4	0.43	0.03	0.07	1a
MARCH, 2011							
IB	7	5	1.5	24.7	0.19	0.01	1a
III	10	3	3.3	19.0	4.74	0.25	2b
IV	3	1	2.3	11.9	3.99	0.34	2b
V	3	1	2.3	5.36	1.26	0.24	2b
VI	11	9	1.2	1.55	0.39	0.25	1b
VII	15	10	1.5	0.68	0.09	0.14	1b

The classification according to Hansen and Rattray scheme during the four representative months have been shown in fig. 3.

For the month of June 2010 the data at station 1B falls into type 1b i.e. well mixed with appreciable stratification and the remaining part of the channel falls almost into 2b i.e. partially mixed with high stratification. For the month of November 2010 the data at Stations 1B and 3 fall into type 4 i.e. Salt wedge type where the stratification reaches to maximum and the remaining part of the channel falls into type 1a i.e. laterally well mixed with a very less stratification.

For the month of January 2011 the data along the channel almost falls into type 1b in the diagram i.e. well mixed with appreciable stratification. For the month of March 2011 the data at station 1B falls into type 1a and almost the remaining stations fall into type 2b.

Hence, the following conclusions may be drawn from the data. When the lake discharge is moderate stratification dominates along the channel. When the lake discharge is very high the stratification becomes greater and the fresh water flows out over an almost stationary deep layer with very little interation.

When the lake discharge is less the channel becomes well mixed with a weak interaction between sea and fresh water. When the lake discharge is very less the station near the mouth became laterally well mixed with the sea water and stratification dominated at the remaining stations with a weak interaction between sea and fesh water. Similar results were observed for upper estuary of Vouga channel under very less fresh water discharge (1).

C. Salinity along the channel

The mean of tidally averaged salinity at different depths which is termed as 'Tidal Depth Mean Salinity' at every location has been computed. The variation of 'Tidal Depth Mean Salinity' along the channel for four months (June & November of 2010 and January & March of 2011) representing four different seasons viz., SW monsoon, NE monsoon, Post monsoon and Pre monsoon is given in Fig. 4. During June 2010, the salinity has intruded almost up to (27km) last station of the study area. The salinity during NE and Post monsoon seasons is almost negligible from 10 km. Salinity intrusion has been again increased during Pre monsoon season (March 2011) and extended beyond 25 km upstream.

The longitudinal distribution of 'Tidal Mean Salinity' (tidally averaged salinity) along the study area for the representative months of four seasons has been

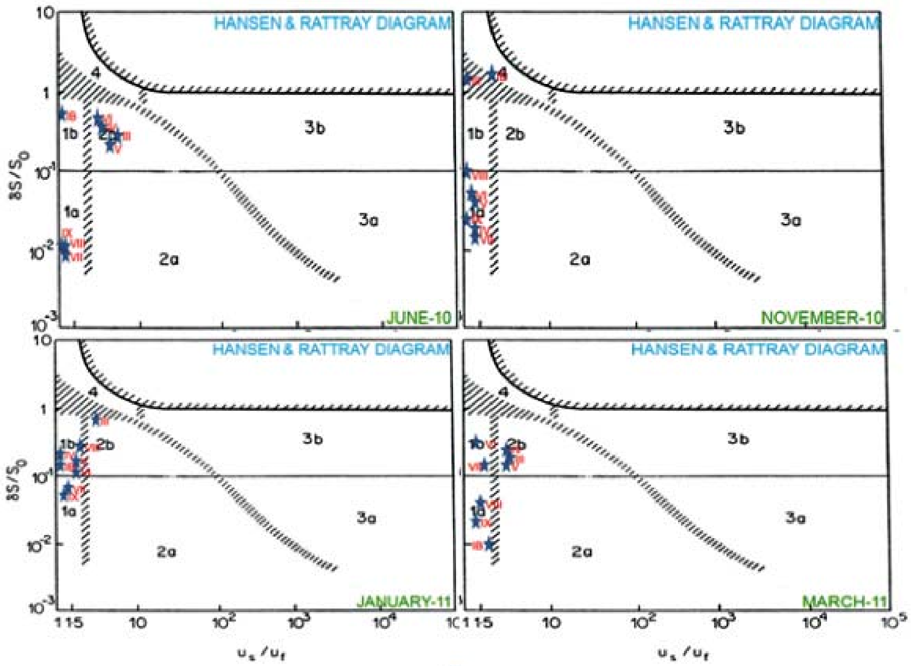

Fig. 3. Stratification and Circulation parameters in Hansen and Rattray diagram.

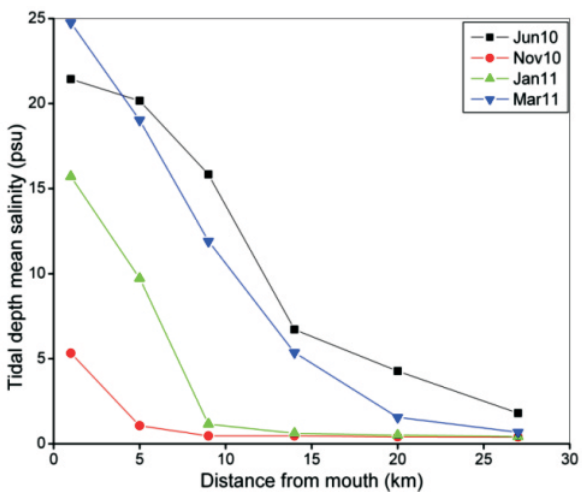

Fig. 4. Longitudinal variation of Tidal depth mean salinity

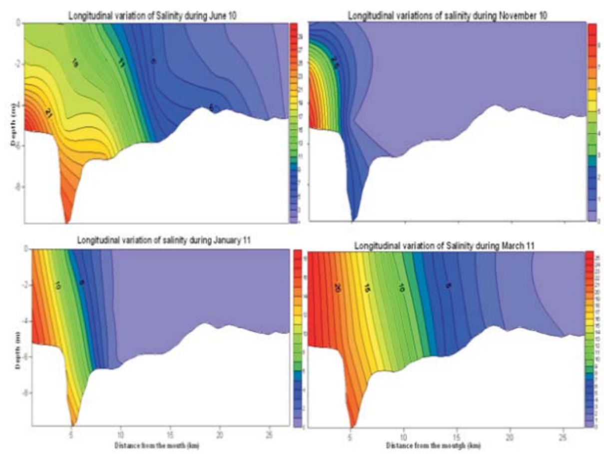

Fig. 5. Distribution of Tidal Mean Salinity

presented in fig. 5. The distribution of salinity along the channel has shown marked variability during different seasons.

The channel has been observed to be partially mixed (appreciable stratification) during June 2010. Most of the channel is filled with fresh water and the salinity intrusion is limited to a very lesser distance upstream when the lake discharge is very high. The vertical variation in salinity undergoes marked changes from season to season (10) (11). The vertical gradient of salinity was observed to be higher i.e. more stratification at the mouth during SW and NE monsoon seasons. During Post and Pre monsoon seasons the laterally homogeneous conditions (less stratification) have been prevailed all along the channel.

D. Salt budget

In order to predict the estuarine characteristics, it is necessary to be able to quantify the mixing processes. This is done by considering the budget of salt within sections of the estuary, by adding up the mass of salt being carried into a particular volume and equating it with what comes out, and the change of salinity within the volume (16). The variation of Total salt along with the monthly mean runoff is shown in fig. 6.

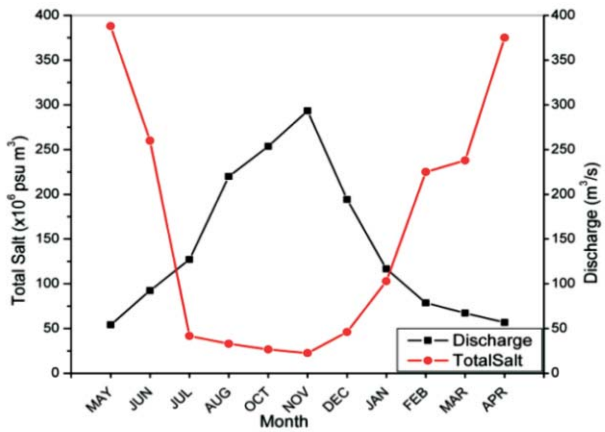

Fig. 6. Month wise Variation of Total Salt along with lake discharge

For estimating the salt budget, the 'Depth Mean Salinity' (S) has been used as a continuous function of the upstream distance (x) from the mouth of the channel. If 'A' is the area of cross section of data collecting location, then the total salt in the channel during a particular field observation is given by

$$S_{tct} - \int_{x}^{\infty} 5\,(x)\,A\,(x)\,dx \qquad (1)$$

The upper limit is the far upstream end of the channel where salinity S vanishes. Monthly loss is maximum i.e., 83.9% from June to July 2010. This may be due to the precipitation in addition to the lake discharge during SW monsoon season. Monthly gain is maximum i.e., 122.4% from December 2010 to January 2011. The channel loses about 94.2% of salt from May to November 2010. When the runoff decreased in the subsequent months the channel has regained about 94.0% of salt by April 2011.

E. Horizantal Diffusion Coefficients - One-Dimensional Advection Diffusion Model

Bowden (1963) (20) based on the early concepts given by Stommel (1953) (21) pointed out that it was unprofitable to attempt to the forecast the mixing processes form first principles, in terms of parameters such as the tidal range, channel flow and geometry of the estuary. The estimation of Horizontal Diffusion Coefficients along the channel axis can be made by adopting the following equation.

$$\int_{x}^{\infty} S\,(x)\,A\,(x)\,dx = K_x A \frac{\partial S}{\partial x} + RS \qquad (2)$$

Where S (x), K_x, R, t and A are Total Salinity as a function of upstream distance (x) from the mouth of the channel, the axial Diffusion Coefficient, channel runoff, time period and cross sectional area respectively. Here, assumptions have been made that the observation time is much greater than the mixing time (15). In view of this, one can easily adopt the One-Dimensional Advection Diffusion Model (1-D AD). The above input parameters have been seasonally integrated (18) for the monthly period starting from May 2010 to April 2011.

The mean values were observed to be varied between 953 and 2.08×10^5 m^2/s during the study period from May 2010 to April 2011. The spatial and temporal variations of horizontal diffusion coefficients of the channel during the study period have been shown in Fig. 7 and 8 respectively.

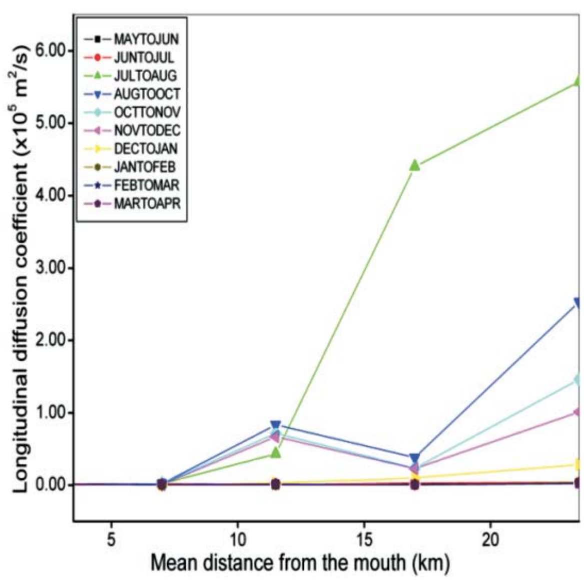

Fig. 7. Spatial variation of horizontal diffusion coefficients

During June-July, the values of diffusion coefficients varied upstream between 654 and 4030m^2/s along the channel. During November-December, the variation among the values was very much high between 626 and 1.01×10^5 m^2/s. Maximum variation has been observed during July – August 2010 i.e., from 323 to 5.57×10^5 m^2/s.

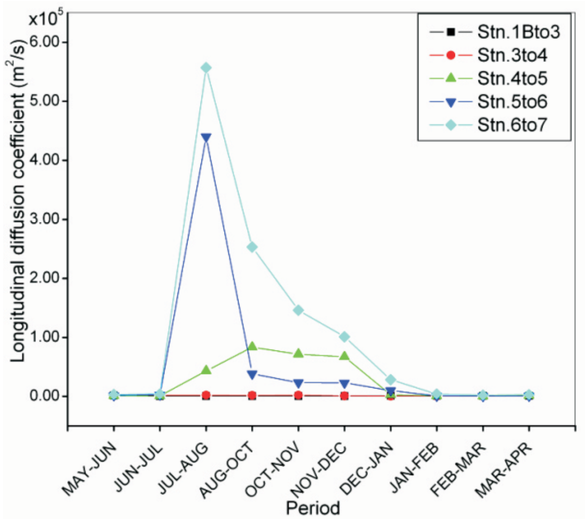

Fig. 8. Temporal variation of horizontal diffusion coefficients

The mean values of Diffusion coefficients increases gradually from mouth to head of the channel. The rise or fall of the values of diffusion coefficient is much greater for a greater change in the upland drainage. Similar results were observed for Gautami Godavari (8) and Vasishta Godavari estuaries (2), (3).

Regression equations for the special (y_{ix}) and temporal (y_{it}) diffusion coefficients can be established by least square method and using One Dimensional Advection Diffusion model (4). The computed values of diffusion coefficient (K_x) for different months show the trend in variation of K_x with distance from the mouth. Regression equations for diffusion coefficients for four months (June & November of 2010 and January & March of 2011) representing four different seasons viz., SW monsoon, NE monsoon, Post monsoon and Pre monsoon seasons have been established. These equations are given below.

Spatial:

$Y_{1x}(x) = -7015.48 + 4102.57x - 615.91x^2 + 35.54x^3 - 0.67x^4$

(Jun – Jul)

$Y_{2x}(x) = 211363.6 - 121708.9x + 20742.5x^2 1272.9x^3 + 25.6x^4$

(Nov –Dec)

$Y_{3x}(x) = 2991.01 - 1177.45x + 182.70x^2 - 11.07x^3 + 0.23x^4$

(Jan Feb)

$Y_{4x}(x) = 1632.95 - 445.39x + 66.64x^2 - 4.10x^3 + 0.08x^4$

(Feb – Mar)

Temporal:

$Y_{1t}(t) = 1359 - 1194.16t + 564.5t^2 - 75.33t^3$

(IB – III)

$Y_{2t}(t) = 5484 - 4666.66t + 1410t^2 - 137.33t^3$

(III -- IV)

$Y_{3t}(t) = -396050 + 628519t - 264608t^2 + 33068t^3$

(IV -- V)

$Y_{4t}(t) = -124222 + 201835.66t - 85520t^2 + 10716.33t^3$

(V—VI)

$Y_{5t}(t) = -576020 + 917953.33t - 386085t^2 + 48181.66t^3$

(VI—VII)

Here, Y(x) is the spatial diffusion coefficient, function of distance from the mouth and Y(t) is the temporal diffusion coefficient, function of time. These equations would be more useful to get diffusion coefficients for any point along the channel axis, which in turn, helps to compute the concentration of pollutant along the axis of the channel. Thus these studies help to predict the impact assessment for any point along the channel axis.

V. CONCLUSION

The study on Upputeru channel under different discharge conditions reveals that the channel exhibits the characteristics of an 'estuary'. It falls into type 4 i.e. salt wedge estuary during periods of very high discharge conditions i.e., during July - November '10. But, during periods of moderate discharge conditions the channel falls into type 2b, i.e., the channel appeared to be partially mixed with appreciable stratification. During the periods of the very less discharge, the channel falls into 1b or 1a i.e. well mixed with high degree of stratification or well mixed in which the mean flow is seaward at all depths and the upstream transfer of salt is by diffusive processes respectively.

The flushing time has been varied from a minimum of 1.81 tidal cycles during November 2010 to a maximum of 5.61 tidal cycles during March 2011. The flushing time decreases rapidly with increasing fresh water flow and for higher flow the fall is gradual. This shows that the flushing time is directly attributed to the fresh water discharge.

The channel losses salt during the period May 2010 – November 2010 and gained during the period November 2010 – April 2011. The Total Salt in the channel varies inversely with the Lake discharge.

During June 2010 the salinity has intruded almost up to (27km) last station of the study area. The salinity during NE and Post monsoon seasons was almost negligible from 10km upstream. Salinity intrusion has been again increased during Pre monsoon season (March 2011) and extended beyond 25km upstream.

The channel has been observed to be partially mixed (appreciable stratification) at the beginning of SW monsoon. Most of the channel is filled with fresh water and the salinity intrusion is limited to a very lesser distance upstream when the lake discharge is very high. The vertical gradient of salinity was observed to be higher i.e. more stratification at the mouth during SW and NE monsoon seasons. When the Lake discharge is very less i.e. during Post and Pre monsoon seasons the laterally homogeneous conditions (less stratification) have been prevailed all along the channel.

The mean values of longitudinal diffusion coefficients were observed to be varied from 953 and 2.08×10^5 m^2/s during the study period i.e., from May 2010 to April 2011. Maximum variation has been observed during July – August 2010 i.e., from 323 to 5.57×10^5 m^2/s. This shows that the value of K_x varies as that of lake discharge. The channel being narrow and shallow, the diffusion coefficients are found to be dependent on the bottom topography.

VI. ACKNOWLEDGEMENT

The authors are grateful to thank Natural Resources Data Management System (NRDMS), Department of Science and Technology (DST) for providing for providing funds to carry out this work. APV expresses his gratitude to UGC for providing Teacher Fellowship under FDP. Mr. Arun extends thanks to CSIR, New Delhi.

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