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WASTE LOAD SCHEDULING – AN ALTERNATIVE APPROACH TO STREAM WATER QUALITY MANAGEMENT

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Abstract*: Achieving water quality standards to desirable levels under low flow conditions is very difficult and requires application of a combination of various water quality management measures to the stream. If it is desired that the proposed waste load allocation under such conditions should also be equitable, then the problem can become more complicated. In the present paper a methodology which we call as waste load scheduling (WLS) is being proposed. Scheduling is very widely practiced in irrigation management especially for low flow conditions. Hence the idea is to apply the concept of rotation based irrigation scheduling to water quality management problem. The model was applied to a case study. From results it was observed that with WLS model we can achieve the desired water quality standards even when the stream flow is very low, which is not possible with daily effluent treatment alone.*

Keywords*: Water quality management; scheduling; waste load scheduling.*

INTRODUCTION

Water quality management is one of the important aspects of overall water resources planning and management. There are many water quality management techniques available and depending on the availability of funds and technological options, any one or combinations of them can be applied at a particular stream for achieving desired water quality standards. The available water quality control techniques can be broadly classified into two categories, namely: direct source control methods and indirect methods. Examples for direct control at the source include, effluent treatment, process change/ process modifications, in-stream reaeration, low flow augmentation, by-pass piping. Indirect measures include effluent charges, discharge permits, taxation, incentives for pollution reduction etc. Each of the aforementioned methods has their own advantages and disadvantages. Apart from the control measures listed above, there exist methods where the effluent is stored in retention basins and is then discharged into the stream whenever the stream conditions are favorable for effluent discharge. Such control measures are known as controlled effluent discharge (CED). The CED can be achieved in various ways, like HCR (Hydrograph Controlled Release) method, real-time effluent discharge, and[1] long term effluent discharge. One of the major concerns of water quality management is the effluent discharge under low flow conditions and effects of externalities. In water quality management the problem of effluent discharge during low flow conditions is addressed by augmenting the stream flow by releasing sufficient quantity of water into the stream from a reservoir for dilution. Other methods include in-stream artificial

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reaeration and controlled effluent discharge (i.e., storing the effluent during low flows in the stream and discharge it when stream condition is favorable).
Externality effect in water quality arises due to negative impact caused in the downstream reaches when effluent is discharged by an upstream polluter. This gives rise to conflicts among the polluters, resolving which may require some innovative water quality management practice, which can take care of such conflicts. Such conflicts can be observed in all the cases where a scarce resource (like surface water, groundwater, forests, natural minerals etc.) is exploited by some users which in turn have a negative impact on all the users who are dependent on that source for their usage. Relevant to our water resources problem is the exploitation of groundwater and surface water by users for irrigation or drinking purpose.

In irrigation water management we come across issues of externalities when the upstream farmers/irrigators divert water indiscriminately from the canals thereby causing a water deficit to the downstream users. This leads to system inequity and dissatisfaction among the downstream users. Irrigation management planners try address this issue by adopting rotation based irrigation scheduling. In rotation based irrigation scheduling, each farmer is allotted certain time interval during which he can withdraw water from the irrigation canal for his irrigation purpose. This method ensures that all the farmers get equal opportunity to irrigate their crops. Hence the method is more equitable and it also helps in keeping check on any defaulters.

The problem in water quality management is somewhat similar to the one observed in irrigation management, i.e. as in irrigation water use the effect of waste load discharge by an upstream polluter has more negative impact on the downstream reaches. Hence the purpose of this paper is to apply the concept of rotation based irrigation scheduling to waste load allocation among the polluters. In the succeeding sections we will first give a brief overview of various water quality management and water quality control techniques available, then we will give a brief description of concept behind waste load scheduling along with mathematical formulation. The developed mathematical model will be applied to a study area and finally we will conclude the paper with results and discussions.

WATER QUALITY MANAGEMENT ALTERNATIVES AND WATER QUALITY CONTROL TECHNIQUES

Effluent treatment is one of the earliest methods of water quality control. Treating the effluent before discharging it into the stream was believed to be the best way in which the stream water quality can be maintained. However it was felt that effluent treatment alone may not be sufficient for maintaining water quality especially during low stream flow conditions. Hull and Carbaugh (1959) were the first to propose low flow augmentation as an alternative water quality control measure. The approach gained popularity among several modelers and further work on low flow augmentation was expanded by Geyer and Hull (1963), Worley et al. (1965), recognized the benefits of low flow augmentation as a water control alternative along with effluent treatment. Rinaldi et al. (1979), however pointed out some of the drawbacks of low flow augmentation stating that its effectiveness strongly depends on the type of the pollution source and of the reservoir. In the case of suspended solids, an increase of the flow would improve the conditions near the source and worsen them further downstream, since the augmented velocity and reduced flow time negatively affect sedimentation. Low flow augmentation however will not lead to reduction of concentration in conservative pollutants. Also the effects of the reservoir storage itself on water quality must be taken into account.

Other methods of water quality control include bypass piping which was first suggested by Graves et al. (1969). The idea behind bypass piping is to design the effluent discharge points in such a way that the effect of effluent on DO level is the minimum. When DO is the only limiting parameter in a reach and also when the reach length is considerably shorter, artificial reaeration can be more cost effective than any advanced waste treatment method. Various modelers such as Cleary (1966), Susag et al. (1966), Whipple and Yu (1971), Orlanto (1972) etc. have shown the effectiveness of artificial in-stream reaeration as an alternative water quality control measure.

Controlled effluent discharge (Young and Beck, 1974; Zirschsky, 1987; Cook, 1989) is also one of the widely used water quality control technique. In this method, the effluent is stored in lagoons or any such detention basins and whenever the stream conditions are favorable (i.e. stream discharge is very high), the effluent is discharged into the stream. The effluent control procedure can vary from simple direct effluent discharge to a more complicated hydrograph controlled effluent discharge.

All the water quality control techniques listed above have their own advantages and disadvantages. In the aforementioned control measures some control methods can be used as stand-alone method (bypass piping and controlled effluent discharge), whereas some methods can be used only as an alternative along with effluent treatment (low flow augmentation, artificial stream reaeration). However we feel that there is still scope to come up with alternative water quality management methods which can be used even under low flow conditions. In the present paper we have made an attempt to come up with a new water quality management measure known as waste load scheduling. The succeeding sections provide a glimpse of the proposed methodology.

WASTE LOAD SCHEDULING

Concept behind waste load scheduling

Like in irrigation water use, the idea behind waste load scheduling is to minimize the exploitation of stream water by the upstream users thereby minimizing the disadvantage for the downstream users. In irrigation scheduling, this is accomplished by allotting each farmer/irrigator a time interval during which he can divert water from main canal to his requirements. This method is more equitable because it ensures that all the farmers get equal opportunity to irrigate their fields, which may not be the case under continuous irrigation scheme and also avoids the exploitation of stream water by any upstream users. Similar concept is being tried to apply for waste load management. In waste load allocation, often the downstream polluters receive polluted stream due to effluent discharge by upstream users. By developing a waste load schedule which will tell a polluter when to discharge his effluent and how much effluent to discharge, we can reduce the problem of externalities in WLS to some extent. Before going to derive mathematical formulation for WLS, it will be helpful to find some analogies between irrigation scheduling and WLS. Table 1 below shows some analogous points between WLS and irrigation scheduling.

Table 1 Comparison between irrigation scheduling and waste load scheduling

	Irrigation Scheduling	Waste Load Scheduling (WLS)
Objective	When to irrigate and how much to irrigate	When to discharge the effluent and how effluent to discharge
Constraints	The water delivered to a farmer	The effluent discharged by a polluter

	during his scheduled time should meet the crop water requirement of the farmer.	in the stream should meet the water quality standards at downstream checkpoints
Decision variable	Irrigation interval (duration between starting and ending time of irrigation)	Time of storage (which is assumed to be equal to the time of effluent discharge) and treatment level

Once we have observed some similarities between irrigation scheduling and WLS, we can formulate a mathematical model for WLS.

Mathematical formulation for WLS
Assumptions in the model

a) Only one polluter is allowed to discharge the effluent in the stream during a given scheduled time.
b) The effluent storage time is equal to the time of effluent discharge and includes the process time of effluent treatment.
c) The schedule starts from downstream most polluter

Decision variables
The decision variables in the WLS problem are the time of effluent discharge and level of treatment to be achieved by the polluter to meet the water quality standards. Hence the decision variables can be defined as:
EDT_i – Effluent discharge time for polluter i
x_i – Treatment level to be achieved by polluter i

Objective function
The objective of the model is to minimize the effluent storage volume and treatment level for each polluter. Mathematically, the objective function may be written as:

$$\min z = \sum_{i=1}^{n} V_i + \sum_{i=1}^{n} W_i x_i \quad (1)$$

$$V_i = Q_i Ts_i \quad (2)$$

$$W_i = \frac{W_{ei}}{1 + k_i Ts_i} \quad (3)$$

V_i = Effluent storage volume in cubic meters
W_i = BOD entering the treatment plant (in kg/d of BOD_5)
x_i = Treatment level to be achieved by polluter i
Q_i = Influent flow rate in m^3/days
Ts_i = Total storage time in the storage basin in days.
W_{ei} = Influent BOD load in kgs/d
k_i = Reaction coefficient in the storage basin and n is the number of polluters

Constraints
The constraints for the model are the upper and lower bounds on the treatment level for each polluter, and satisfaction of desirable DO levels at checkpoints. Mathematically they can be expressed as:

$$Ts_{i-1} \geq Ts_i + tr_i \quad (4)$$

$$\frac{W_i(1-x_i)}{Q_{ti}+Q_{ri}} f_i + C_i \leq DO_i^{sat} - DO_i^{std} \quad (5)$$

$$x_i^{lb} \leq x_i \leq x_i^{ub} \quad (6)$$

Ts_{i-1} – Storage time for polluter *i-1* (upstream polluter), in days
Ts_i – Storage time for polluter *i* (downstream polluter) in days
tr_i – Travel time from the discharge point of polluter *i* to the end of the stream in days
Q_{ti} – Effluent discharge in m^3/sec
Q_{ri} – Stream discharge in m^3/sec
f_i – Transfer coefficient, which is a function of *ka* (stream re-aeration coefficient), *kd* (de-oxygenation coefficient) and *tr* (travel time in a reach) and is given by:

$$f_i = \frac{k_{di}}{k_{ai}+k_{di}}\left(e^{-k_{di}tr_i} - e^{-k_{ai}tr_i}\right) \quad (7)$$

C_i – DO deficit in reach *i* due to due to initial BOD and DO deficit in the stream
DO_i^{sat} - Saturation DO level in reach *i*, in mg/l
DO_i^{std} - Desirable DO standard for reach *i* in mg/l
x_i^{lb} - Lower bound on the treatment level, signifying that a municipality should have at least a primary treatment plant
x_i^{ub} - Upper bound on the treatment level, signifying the maximum possible treatment level that can be achieved with available treatment technology

APPLICATION OF MODEL TO A CASE STUDY

Study area description

The proposed waste load scheduling model was applied to the Tambraparni river basin. The study area lies in the southern region of the Tamil Nadu state between 8^0 8' and 9^0 23' N latitude and 77^0 9' & 77^0 54' E longitude. The total length of the river from its origin to destination is about 120 Km. There are four major tributaries namely, Servalar, Manimuthar, Gadana and Chittar, which contribute to the stream flow at various points along the main stream course. The river is dotted with many towns and a few industries along its course. However in Tambraparni river basin, domestic sewage pollution is more severe than the industrial pollution because of lack of flow during summer and limited self purification capacity of the river.

Pollution status of the Thambraparni river

The major share of pollution in the river is due to uncontrolled disposal of domestic sewage and non point source pollution from agricultural runoff. There are no existing treatment plants for any of the major or minor towns in the river basin. This makes the effect of domestic sewage on the river water quality even more pronounced. Most of the small towns and villages in the basin area have no drainage (sewerage) facilities. The only towns which have partial sewerage system are Tirunelveli, V.S.Puram, Ambasamudram, Cheranmahadevi, Palayamkottai, Melapalayam and Srivaikundam. The Government of India has sanctioned about Rs. 700 millions to implement underground sewerage system in Tirunelveli Corporation area (Micro-level Status Report for Tambraparni River Basin, 2003). The DO in river varies from a lowest value of 1.7 mg/l during the month of March to a highest value of 6.8 mg/l during the monsoon seasons of August and September whereas the BOD varies from 0.13 mg/l to 10.2 mg/l. As the population of the towns will increase there will be more withdrawal from stream and hence more stress on the river water quality. Hence there is a need to come up with a practical effluent management technique so that the stream water quality will not deteriorate in the future. Table 2 shows the waste load and stream flow characteristics for each reach.

Table 2 Waste load and stream flow characteristics for each reach

Polluter	Mileage (km)	BOD load (kg/d)	Effluent discharge (m^3/sec)	Distance (in km)	Saturation DO (in mg/l)	Deoxygen coefficient Kd (d^{-1})	Reaeration coefficient Ka (d^{-1})
R1	13	7781	0.081	9	7.35	0.280	0.735
R2	22	3950	0.041	17	7.16	0.294	0.827
R3	39	10385	0.108	13	7.03	0.324	1.041
R4	52	7962	0.083	3	7.03	0.324	1.079
R5	55	11380	0.119	3	7.03	0.324	1.079
R6	58	18550	0.193	24	7.03	0.324	1.079
R7	82	7788	0.081	14	7.03	0.324	1.088
R8	96	2025	0.021	19	6.90	0.340	1.142

Results and Discussion

In order to show the flexibility of the proposed model, the waste load schedule was developed for a mean, minimum and maximum flow rates. Table 3 shows the mean, minimum and maximum flow rate values for the stream. It is assumed that the proposed schedule for mean, minimum and maximum flow rates will be valid for any flow rates occurring between minimum and maximum flow rates. It is also assumed that no new polluter will enter the stream, because with the entry of any new polluter a schedule will have to be derived. With these assumptions, a schedule was developed stating when a polluter should discharge his effluent (in days: hours: minutes), and how much waste load he can discharge on that day.

Table 3 Minimum, mean and maximum flow rate values in the stream

Reach	Stream flow rate (in m^3/sec)		
	Q_{min}	Q_{avg}	Q_{max}
R1	0.34	3	11.47
R2	0.54	3.3	12.17
R3	0.62	4.86	12.97
R4	0.62	4.86	12.97
R5	0.62	4.86	12.97
R6	0.62	4.86	12.97
R7	0.64	5.33	13
R8	0.64	5.33	13

From results it was observed that the parameter affecting the schedule most is the flow rate in the stream, whereas the variation of DO standards at downstream checkpoints does not affect the schedule in any way. Comparing the results obtained from WLS with traditional least cost treatment solution, we find that there is a considerable decrease in annual O&M cost with WLS model. However on the flip side the initial capital cost for WLS will be considerably higher in case of WLS when compared to daily effluent treatment plants. It can be seen from the results that one of the advantages of WLS approach when compared to daily effluent treatment is that with WLS the desired water quality standards can be achieved even when the stream flow rate is very low (without resorting to any other water quality management alternative). One of the advantages of the WLS method is that the stream will have more time for recuperation (i.e. time for regaining its assimilative capacity). Also the model is relatively more equitable since the downstream polluters do not have to bear the pollution load from upstream polluters. In other words the quantity of effluent a downstream polluter can discharge is no more limited by how much effluent upstream polluter discharges, and is dictated only by the water quality standard that is to be achieved at downstream points.

Table 4 Least cost solution for min, mean and max flow rates and under a desirable DO levels of 5 mg/l and 4 mg/l

Polluter	Q_{min}		Q_{avg}				Q_{max}			
	2 mg/l		5 mg/l		4 mg/l		5 mg/l		4 mg/l	
	TRL	O&M cost	TRL	O&M Cost	TRL	O&M cost	TRL	O&M Cost	TRL	O&M cost
P1	98.0	0.076	98.0	0.076	84.4	0.066	30.0	0.023	30.0	0.023
P2	88.0	0.035	44.0	0.017	30.0	0.012	30.0	0.012	30.0	0.012
P3	98.0	0.102	98.0	0.102	98.0	0.102	98.0	0.102	46.8	0.049
P4	98.0	0.078	85.2	0.068	68.6	0.055	54.1	0.043	30.0	0.024
P5	98.0	0.112	98.0	0.112	98.0	0.112	98.0	0.112	98.0	0.112
P6	98.0	0.182	98.0	0.386	98.0	0.386	98.0	0.182	98.0	0.182
P7	84.9	0.066	77.3	0.060	63.5	0.049	75.5	0.059	30.0	0.023
P8	37.5	0.008	30.0	0.006	30.0	0.006	30.0	0.006	30.0	0.006
Annual O&M cost in Rs (*10^6)		24.02		30.18		28.72		19.64		15.7

Table 4 above gives the least cost solution for various flow conditions. From table it can be observed that when flow is minimum, effluent treatment alone will not be sufficient to achieve the desired water quality standards in the stream. We will have to resort to other management options like low flow augmentation, effluent storage or artificial reaeration. Table 4 and Table 5 show waste load schedule and treatment level for each polluter for minimum and average discharge values. Cycle 1 refers to the schedule which is to be followed at the beginning of the scheduling process. Cycle 2 will start again from downstream most polluter when the effluent discharged by upstream most polluter, reaches to the end of the stream. It can be observed from Table 5 that by WLS it is possible to achieve a DO level of 4 mg/l in the stream even when the flow rate is very low. Hence it can be argued that the proposed methodology of WLS can be adopted as a stand-alone management measure when the flow rate is very low. Also the model is comparatively more equitable when compared to the traditional least cost solution.

Conclusion

A waste load scheduling has been proposed in the present paper. The inspiration for the model was the rotation based irrigation scheduling which is widely practiced in irrigation water management especially under deficit flow conditions. However we have taken a very simplistic case by making many assumptions. The model however can be solved for complicated cases like when many new polluters are entering into the stream how it may

Table 4 Waste load schedule for Q_{avg}.

Polluter	Cycle 1			TRL in %		Effluent load (kg/d)		Cycle 2			TRL in %		Effluent load (kg/d)	
	Day	Hour	Minute	5 mg/l	4 mg/l	5 mg/l	4 mg/l	Day	Hour	Minute	5 mg/l	4 mg/l	5 mg/l	4 mg/l
P1	20	7	14	77.2	63.4	4238	6803	44	7	14	75.0	59.8	4787	7698
P2	15	18	31	58.6	33.0	3606	5836	39	18	31	56.8	30.1	4019	6503
P3	12	14	27	81.5	68.8	3724	6281	34	14	27	75.6	58.8	5463	9225
P4	8	22	23	82.3	70.1	2559	4323	32	22	23	77.4	61.8	3880	6558
P5	6	3	40	86.9	77.8	2401	4069	30	3	40	81.5	68.8	4539	7655
P6	4	2	57	95.4	92.2	2165	3670	28	2	57	87.5	78.9	10616	17962
P7	2	17	7	60.6	35.5	1943	3180	26	17	7	76.6	61.8	3758	6135
P8	1	20	0	30.0	30.0	982	982	25	20	0	48.4	30.0	2155	2923

Table 5 Waste load schedule for Q_{min}

Polluter	Cycle 1			TRL in %		Effluent load (kg/d)		Cycle 2			TRL in %		Effluent load (kg/d)	
	Day	Hour	Minute	4 mg/l	3 mg/l	4 mg/l	3 mg/l	Day	Hour	Minute	4 mg/l	3 mg/l	4 mg/l	3 mg/l
P1	28	23	47	93.8	89.9	1228	2008	64	7	14	90.1	80.4	1636	3239
P2	23	1	28	89.0	81.9	1015	1643	58	18	31	82.9	72.2	1297	2109
P3	16	22	52	91.9	85.6	1746	3125	52	14	27	74.9	57.4	4390	7451
P4	13	5	21	90.0	84.8	1580	2449	49	22	23	81.1	67.9	2513	4268
P5	7	23	50	93.0	88.7	1453	2242	43	3	40	82.7	70.7	3288	5569
P6	4	1	31	97.7	96.4	1326	2018	40	2	57	84.5	73.6	10196	17367
P7	2	5	36	90.0	84.5	673	1050	38	17	7	79.4	68.3	2580	3971
P8	1	20	0	30.0	30.0	421	982	37	20	0	75.0	62.9	814	1208

affect the initial schedule (or how to accommodate new polluters in the schedule). Also of interest can be how to develop a schedule when stream flow rate is considered as a random variable. Another advantage of WLS is that there can be considerable reduction in annual O&M cost when compared to daily effluent treatment and discharge.

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