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RISK ANALYSIS FOR FLOW DURATION CURVE BASED SEASONAL DISCHARGE MANAGEMENT PROGRAMS

KAO JEHNG-JUNG[Ⓜ]* and SHYANG-FU BAU

Institute of Environmental Engineering, National Chiao Tung University, 75 Po-Ai Street, Hsinchu, Taiwan, 30039 Republic of China

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Abstract—A non-seasonal discharge standard may be too stringent and not cost-effective for a season of large flow, if the variation of seasonal streamflow of a river is significant. Seasonal discharge programs established based on streamflow variation were therefore explored in this work. A design procedure using the flow duration curve method, two total-mass-load based discharge programs, linear programming, and Monte-Carlo analysis is proposed for determining and analyzing the pertinent seasonal division of a two-season discharge management program. The flow duration curve method was used to compute the design low flow. The maximal total waste load and uniform treatment programs were the two total-mass-load based programs analysed. Linear programming models were established to determine the optimal division of seasons based on the objective of maximally allowable total waste load. Monte-Carlo simulation with QUAL2E-UNCAS was implemented to assess the risk of violation of water quality of seasonal programs. The proposed procedure is demonstrated in a case study of the Tung-Kang River basin in Taiwan. Copyright © 1996 Elsevier Science Ltd

Key words—seasonal discharge program, Monte-Carlo simulation, optimization, risk analysis, water quality model, design low flow

INTRODUCTION

Regulations of effluent discharge based on total waste mass load was recently promulgated by the EPA, Taiwan, for improving the quality of natural water bodies. A design low flow, occasionally called a critical flow, is suggested to determine the maximally allowable waste load. The discharge limit determined based on a unique design low flow of a river with significant seasonal variation of streamflow is however not cost-effective in a season of large flow and is inappropriate for a season of low flow. The limitation may be too stringent for periods with large flow rate. Seasonal discharge programs (SDP) are therefore explored in this work.

The economic efficiency of SDP is previously reported (Reheis *et al.*, 1982; Boner and Furland, 1982; Ferrara and Dimino, 1985; Herbay and Smeers, 1983). By means of seasonal discharge programs, the overall cost of water quality control might be decreased substantially without violation of water quality standards, if the characteristics of a river are suitable to implement such a seasonal program. As to the risk assessment in discharge management, Eheart *et al.* (1987) asserted that the risk in a seasonal program arose primarily from uncertainty of the flow rate. Rossman (1989), while defining the risk as the probability of violating the water quality standard once or more in a year, investigated management of a single pollutant source under the limitation that the seasonal risk is not greater than that of the non-seasonal condition. Lence *et al.* (1990) proceeded to apply this risk equivalent approach for multiple pollutant sources. Lence and Takyi (1992) applied also a sensitivity analysis to analyze seasonal programs. To avoid administrative complexity, SDP of two seasons were proposed in most investigations. Their designate low flows are, however, based on 7Q10 rather than Q_{90} or Q_{75} used in Taiwan. 7Q10 is computed based on the recurrence interval of low flow frequency, whereas Q_{90}/Q_{75} are computed mainly based on a flow duration curve without considering temporal serial correlation. The failure frequency of a discharge program arranged on the basis of Q_{90}/Q_{75} is not obvious; therefore the risk is obscure and more difficult to evaluate. It is thus necessary to find an adequate process for risk assessment for Q_{90}/Q_{75} before a seasonal program can be proposed. Furthermore, in previous studies, a systematic procedure was unavailable to evaluate the suitability of a river for implementing a seasonal program. Such a procedure is required in Taiwan because artificial control or redirection of flow by hydraulic constructions typically exist. If such an artificial effect cannot be adequately estimated and incorporated into a seasonal discharge program, the implementation of the seasonal program becomes difficult or impossible. A procedure is thus proposed with a preliminary analysis for the applicability of a two-season SDP for a river in Taiwan.

*Author to whom all correspondence should be addressed (Fax: 886 35 728 251; *e-mail*: jjkao@green.ev.nctu.edu.tw).

THE PROPOSED SDP ANALYSIS PROCEDURE

A proposed SDP analysis procedure is shown in Fig. 1. The procedure consists essentially of four major steps: preliminary analysis of discharge management programs; evaluation of the applicability of SDP; analysis of an appropriate division of the two seasons of a SDP; risk analysis of SDP. Preliminary analysis includes verification of compliance with regulations and establishment of mathematical models to simulate water quality and to analyze discharge management programs. SDP applicability is evaluated based on both the variation of the monthly design low flow and whether there are artificial effects on the variation. Seasonal interval division is determined by an optimization approach. An assessment approach employing Monte-Carlo simulation is adopted in this research for analyzing the water quality violation risk of SDP. These steps are explained as follows.

Preliminary analysis of discharge management programs

The previous policy of water quality control was based primarily on effluent concentration. This method is simple, easily understood and based on the assumption that good water quality can be secured by ensuring a low level of pollutants. Such a low effluent concentration, however, does not invariably ensure good water quality of a river. The water quality can deteriorate significantly as a result of a large waste volume at low concentration. The principal goal of discharge management, although more restrictive than the method of effluent concentration, is to determine the maximally allowable pollutant discharge without violation of the water quality standard. The status of compliance with regulations must be verified and mathematical models may need to be established to evaluate the efficiency of a non-seasonal discharge program. Whether the more stringent program of discharge management is applicable to a water body should be decided at the end of this step.

Verification of compliance with regulations. According to Taiwan Water Pollution Control Act, when the entire or part of a water body is highly populated by industrial pollution, and if the water quality cannot meet the standard according to the effluent concentration method, the provincial (or municipal) authorities should regulate the water body with regard to discharge management based on the assimilative capacity of the water body. When the status of water quality requires discharge management, relevant information should be collected so as to define clearly the domain of the problem and to help understand the background and extent of the pollution for forthcoming analyses and assessments.

Water quality model and impact coefficients. If a river is determined to be applicable for discharge management, the next task is to set up a water quality model for the river to determine its assimilative capacity. In the case study of this research, QUAL2E (Brown and Barnwell, 1987) is employed as the water quality model. As effects on locations

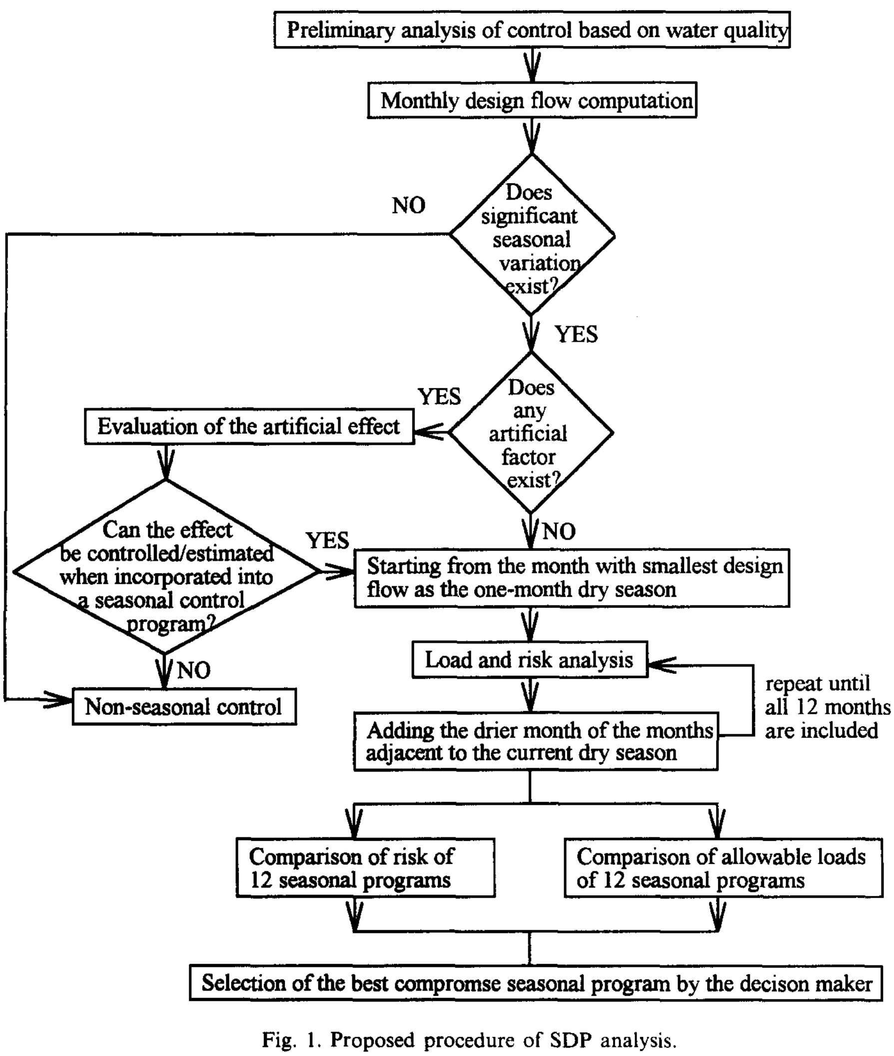

Fig. 1. Proposed procedure of SDP analysis.

for BOD or DO deficit from pollution loads at other locations have relations of linear superposition in the steady state (Thomann and Mueller, 1987), the extent of impact from a pollution load at a certain location to others can be expressed with a coefficient. The coefficient times the pollutant load of a certain pollution source is the pollution impact of that location from that pollution source. The impact coefficients are used to establish the linear programming models for discharge management programs described below.

Mathematical models of discharge management programs. There are several methods available for discharge management, such as maximum total waste load, uniform treatment, zone uniform treatment, least cost, transferable discharge permit (Eheart *et al.*, 1987), and so forth. In this work, two methods of maximum total waste load (TWL) and uniform treatment (UT) (Chadderton and Kropp, 1985) were adopted. The TWL model is used as a substitute for the generally used least-cost model. The substitution is valid because at the least-cost solution the TWL is generally at its maximum. This model is however not practical because bias exists in allocating discharge permits and the model is generally employed only as an ideal basis for comparing other alternative programs. The UT model is commonly utilized because of its fairness. This model assures the equity by requiring a uniform treatment level across all dischargers. The formulations of the TWL and UT models follow.

Total waste load (TWL) model:

$$\max \sum_{n=1}^{n} wqpl_i,$$

subject to

$$O \leqslant wqp_j \leqslant S^* \quad \text{for all } j;$$

$$wqp_j - \sum_{i=1}^{n} IC_{ij}{}^*wqpl_i = WQP_j^b \quad \text{for all } j;$$

$$(1 - R_i^u)^* WQPL_i^* \leqslant wqpl_i \leqslant WQPL_i^* \quad \text{for all } j;$$

other constraints, where wqp_i is the concentration of the water quality parameter at element j (mg/l); $wqpl_i$ is the finally discharged waste load from discharger i (kg/day); $WQPL_i^*$ is the raw waste load of discharger i; WQP_j^b is the background concentration at element j; IC_{ij} is the pollutant impact coefficient for discharger i on element j (mg/l/kg/day); R_j^u is the upper limit of the level of treatment for discharger i; S^* is the water quality standard; n is the number of dischargers.

Uniform treatment (UT) model:

$$\max \sum_{i=1}^{n} (1-r)^* WQPL_i^*$$

subject to

$$O \leqslant wqp_j \leqslant S^* \quad \text{for all } j;$$

$$wqp_j - \sum_{i=1}^{n} IC_{ij}{}^*(1-r)^* WQPL_i^* = WQP_j^b \quad \text{for all } j;$$

$$R_l \leqslant r \leqslant R^u$$

other constraints, where r is a uniform treatment level to be found; R^u is the treatment upper limit level; R^l is the lower limit of the level of treatment.

Both TWL and UT models are linear. The two linear programming models are solved with XMP (Marsten, 1988), a FORTRAN library, to evaluate the efficiency of a discharge management program.

Assessment of the applicability of SDP

In order to assess whether a river is applicable for discharge management by means of a seasonal approach, monthly design low flows are first determined. From the variation of the flows, we can discover whether there is any obvious cycle of wet and dry seasons. One objective of applying a SDP is to find a more economical alternative under the premise that the varied assimilative capacities in dry and wet seasons can be effectively utilized while still meeting the water quality requirement. As a result, if the variation among monthly flows is not obvious, the seasonal approach is inadequate in such a case. Moreover, we must notice whether such variation is affected by any artificial factor. For example, the construction of a dam upstream or water uptake at some location of a river can significantly alter the flow variation. A SDP is inappropriate if any such artificial factor exists and cannot be effectively incorporated into the program analysis, although seasonal variation may still be obvious.

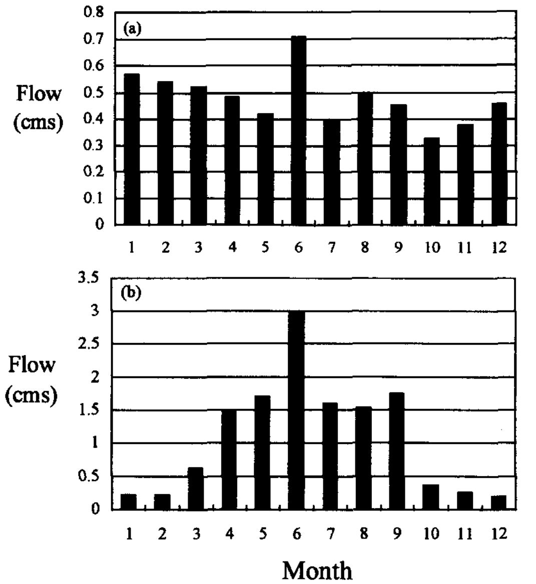

Fig. 2. Monthly Q_{90} for: (a) Pao-Chiao gauge station; and (b) San-Ying gauge station.

Monthly design low flow. As the worst water quality cases generally occurs under low flow, the design flow for discharge management is generally based on such a low flow, also called a critical flow. In Taiwan, the flow duration curve method is used to determine this design low flow. In applying the method, a curve of flow duration is plotted from a set of sorted flow data of a river over past years. Then, the annual design low flow at some desired duration is obtained from the plot. For example, Q_{75} is the low flow of which 25% of the flow data is less than it. The monthly design low flow is calculated in an approach similar to the annual one. The daily flow data in the same month are gathered together, sorted in ascending order, and a monthly Q_{75} or Q_{90} is determined with a plot of the sorted monthly data. This procedure is repeated for each month until all monthly design low flows are obtained.

Adequacy of SDP. According to the monthly design flows, the variation in flow of a river can be observed. Figure 2(a) shows the results from flow records at Pao-Chiao Station on Ching-Mei Stream. The flow of Ching-Mei Stream have no obvious variation and is inappropriate to implement a seasonal approach. Figure 2(b) shows a similar plot for San-Ying station on a Da-Han Stream that reveals an obvious variation of dry and wet seasons. Several artificial factors, however, exist for the stream. The Stone Gate Reservoir is located upstream, and Ho-Chi Weir, Yuan-Shang Weir and Ban-Hsin Uptake are located in non-tidal sections. The more water is withdrawn or stored upstream, the less is the flow of the stream. Figure 3 shows the trend in flows of Da-Han Stream calculated by a moving method for a moving period equal to 5 yr, according to which the flow decreased year by year. As a result, a seasonal approach

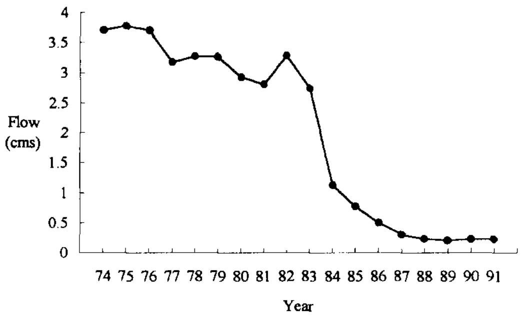

Fig. 3. Five year Q_{90} for San-Ying gauge station.

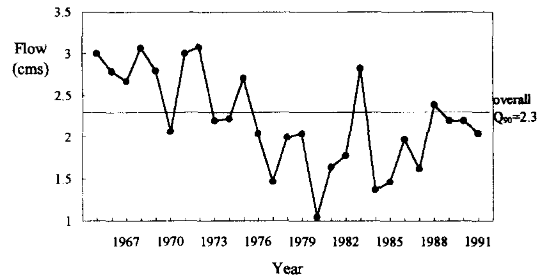

Fig. 4. Annual Q_{90} for Choutro gauge station.

is inappropriate because estimating the violation risk due to the artificial hydraulic operations is difficult.

Analysis of the appropriate seasonal division.

If the seasonal variation in flow of a river is obvious and no artificial factor exists, such a river is suitable for further analysis for finding an appropriate SDP. Because transitory operation makes variations inefficient at wastewater treatment facilities, it is not adequate to divide into too many seasons. Moreover, dividing thus would increase the complexity of management and may offset the economic benefits from a SDP. We therefore explored a SDP with two seasons, dry and wet.

Division of seasons. The purposes of dividing seasons is to set varied standards for varied assimilative capacities in different seasons. The division of two seasons is determined based on variation of monthly design flows. The steps adopted in this work to determine the division follow:

(1) The method described previously are used to calculate monthly design flows for all 12 months.
(2) According to these 12 design flows, the month with least flow is chosen as the dry season and the other 11 months constitute the wet season. The design flow is computed for both the dry and wet seasons.
(3) One of the 2 months of the wet season adjacent to the dry season that has the smaller design flow is put into the dry season. The design flow is computed again for both the new dry and wet seasons.
(4) The previous step is repeated until all possible seasonal divisions are obtained, 12 possible divisions in total. Accordingly, the dry season would eventually last 12 months that is the same as the non-seasonal program.

Total amount of allowable discharge. After the seasonal design flows are computed for the 12 possible divisions, criteria must be set for selecting the optimal division. In this work, the allowable amount of pollution discharge and the water quality risk, described in the next section, of each division are used for this purpose. By incorporating water quality models and mathematical models for discharge management, the total allowable amount of pollution discharge can be computed. Various sets of impact coefficients of dry and wet seasons for varied seasonal divisions are re-determined with QUAL2E, which are then used with the TWL and UT models to solve for the allowable discharge amounts for each season with XMP. The sum of discharges of both seasons is the total annual allowable pollutant discharge. Based on the discharge amounts of each seasonal division, the one with maximal discharge can be treated as the best seasonal division that can utilize the assimilative capacity to the best extent.

The causes of variation of discharge amount for varied seasonal divisions can be illustrated in two parts: extended dry season and shortened wet season. When the dry season becomes longer, the design flow of the season increases correspondingly, so does the allowable pollutant discharge. The length of the wet season decreases with the extended dry season, which results in decreased allowable pollutant discharge in the wet season. In the process of seasonal division, if the increased allowable discharge in the dry season is greater than the decrease in the wet season, the net amount increases, and vice versa.

The seasonal alternative utilizes the assimilative capacity at high flows, whereas the allowable pollutant discharge at low flows is less than that of the non-seasonal alternative. The seasonal alternative can therefore improve the water quality at low flows, in addition to the economic benefits.

Risk analysis

According to the flow duration curve method, there is intended to be only a portion of time in which the flows are less than the design value. The design flow, however, for each year does not always occur as we expect. This condition causes the risk in managing water quality. Fluctuations exist in low flows from year to year. In this work, the water quality risk of SDP with varied seasonal divisions are analyzed by means of a Monte-Carlo simulation.

The source and definition of the risk. Figure 4 shows the results of flow analysis at Choutro station on Tung-Kang River. The annual design flow (Q_{90}) is 2.3 $m^3 s^{-1}$. According to the curve of design flows, discrepancies exist between design flows in some years and 2.3 $m^3 s^{-1}$. In years when the design flow is lower less than 2.3 $m^3 s^{-1}$, the discharge management program may not achieve its water quality goals, whereas the frequencies of design flows obtained with the flow duration curve method are less obvious. It is thus necessary to analyze such risk prior to the implementation of a SDP. For an annual design flow, there is a corresponding allowable discharge pollutant discharge that allows for a portion of time during a year in which the water quality violates the standards. If in some year the flow is less than the design value, the portion of time in violation of the water quality standard would exceed the portion mentioned. We thus conclude that discharge management in that year fails. In a SDP risk analysis, a conservative criterion is used herein; any failure in one season would be regarded as a failure for the entire year.

Monte-Carlo simulation. Monte-Carlo simulation is an effective method for assessing the uncertainties and nonlinearities of a model. The likelihood of an effect caused by uncertainties and nonlinearities can be statistically determined based on the distribution of numerous simulation results. Monte-Carlo simulation is implemented by first sampling the values of one of several analyzed model parameters according to a pre-determined probability distribution. The sampled values are then input to the analysis model to compute the associated result. This sampling process is repeated for many times until a stable distribution of associated results is obtained. QUAL2E expanded its function to include Monte-Carlo simulation and in the new version called QUAL2E-UNCAS; it consists of 16 FORTRAN subroutines and a data file that links the uncertainty analysis module to QUAL2E. The statistical analysis of a series of results obtained from repeated Monte-Carlo simulation can help us understand properties of the uncertainty of a problem.

As each Monte-Carlo simulation requires two QUAL2E simulations and four linear programming optimization steps for the TWL and UT models for two seasons, the process takes much time, but sufficiently numerous Monte-Carlo simulations should be implemented to obtain a stable distribution of results. As a compromise, the Monte-Carlo simulation is implemented 2000 times. Before any simulation is implemented, a probability distribution of design flow is determined based on historical data. The procedure of applying the Monte-Carlo simulation to assess the risk of water quality of SDP follows:

(1) For each seasonal division, we gather the design flows of the dry and wet seasons for past years and find the probability distribution of flows in each set.
(2) 2000 design flows are sampled from each distribution for each season.
(3) QUAL2E is applied for the design flows and the allowable pollutant discharges previously determined in a SDP. If violation of the water quality standard occurs in any season, then the simulation is regarded as a failure.
(4) The risk is calculated as the number of failures divided by the total number of simulations.
(5) The procedure is repeated until risks of all season-dividing scenarios are obtained.

In the real world, when naturally occurring low flow is actually less than the design flow, it does not necessarily result in a failure of water quality. In addition to the extent to which the low flow is less than the design flow, the program of discharge management itself is also an important factor in the extent of risk. For example, the UT method used in this work is more stringent to limit pollutant discharge than the TWL method; the resulting risk is generally smaller.

Table 1. Major waste loads for Tung-Kang River

Discharger No.	Distance to river mouth (km)	Flow (m^3s^{-1})	BOD (mg/l)	Waste load in BOD (kg/day)
1	32.5	0.07	8.43	51
2	28.0	0.18	5.72	89
3	26.3	0.53	3.39	180
4	23.5	0.07	5.13	31
5	18.4	0.04	30.09	104
6	18.2	0.07	25.46	154
7	17.2	0.88	18.12	1378
8	15.3	0.11	14.94	142
9	14.9	0.03	9.65	25
10	14.3	0.05	75.23	325
11	13.0	4.83	7.41	3093
12	12.3	0.71	8.66	531
13	11.0	0.09	16.59	129
14	5.7	1.77	6.12	936

A CASE STUDY

A case study was implemented for the basin of Tung-Kang River to exemplify the proposed procedure for SDP analysis and associated risk assessment. Tung-Kang River is one of 21 major rivers in Taiwan. The relevant hydraulic and water quality data of the river are based on the study by Wen (1989). There are 14 major dischargers, of which the pollutant loads are listed in Table 1. Figure 5 shows the locations of the basin, major waste discharges, regular water quality monitoring locations, and gauge stations. The estuarine portion of the river is up to about 4.5 km to the river mouth. This portion is not included in this

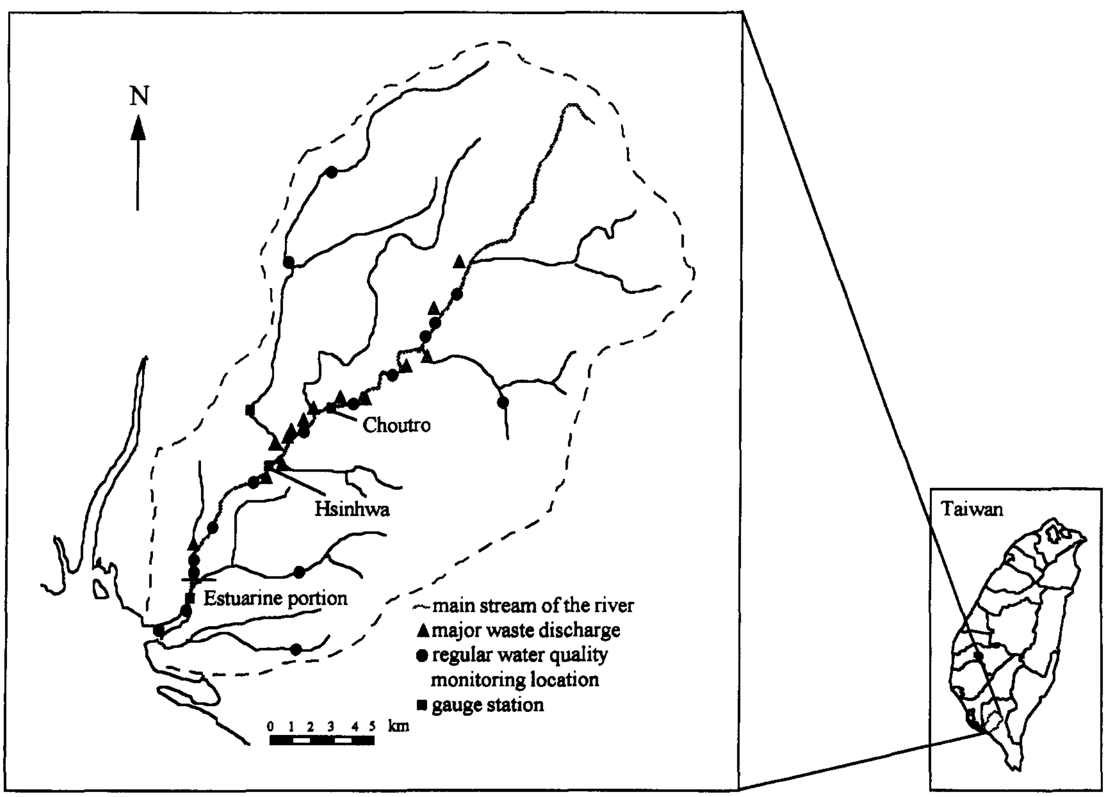

Fig. 5. The basin of Tung-Kang River.

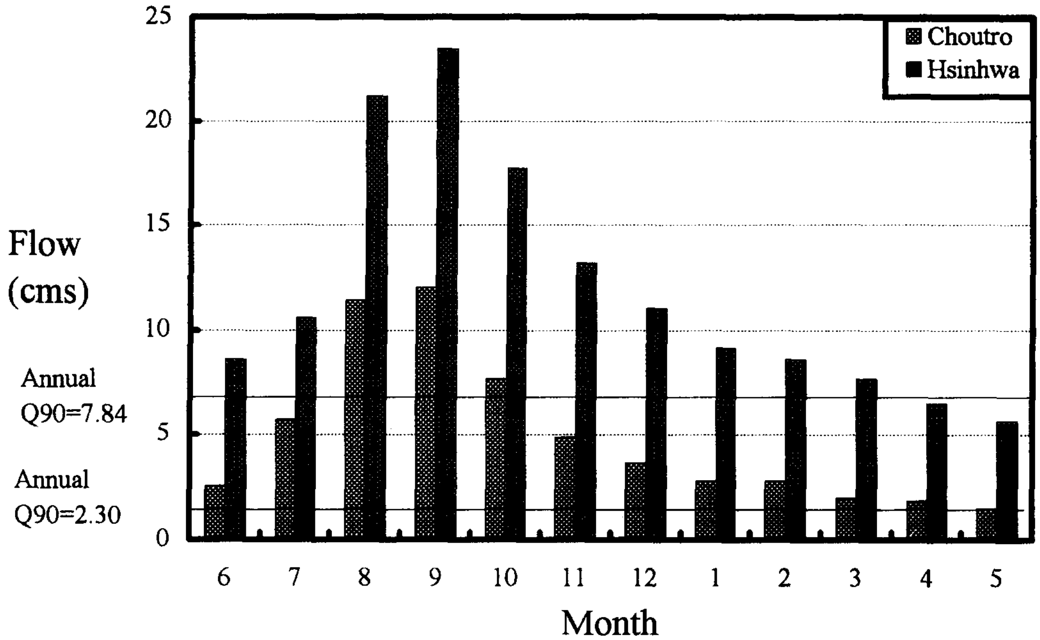

Fig. 6. Monthly Q_{90} for Choutro and Hsinhwa gauge stations.

study because the water quality modeling task required for this portion is much more complex than that for a non-estuarine portion. Because of the rapid velocity and steep slope, reaeration is generally effective for this river. It is generally believed that removal of BOD loads can improve DO; thus BOD is chosen as the major parameter for water quality analysis in this work. Water quality data for the river are collected regularly, 1–3 times per month, at the locations shown in Fig. 5. The water quality of the waste influent from each major discharger was also sampled during the studied period. The historical flow data for the river are provided by the Water Resources Committee, Ministry of Economics, Taiwan. Flow data for locations of major discharges were measured by Hydraulic Laboratory, National Cheng Kung University, Taiwan during the studied period.

Monthly design flow

Calculated monthly and annually Q_{90} for Choutro and Hsinhwa stations on the river are shown in Fig. 6, which exhibits a clear trend of wet and dry seasons. To make the cycle prominent, the plot starts at May. This plot and similar plots for other stations on the river are used to determine the seasonal division as described below.

Seasonal division

The month of May, which has the smallest design flow, is chosen as the first dry season, with the other 11 months as the wet season. Q_{90} for both seasons are re-computed. Then, comparison of the design flow of 2 months adjacent to May indicate April to have a smaller design flow. April is then combined into the dry season (hence comprising 2 months), whereas the wet season consists of 10 months. The design flow for both new seasons are re-calculated. According to the same pattern, the procedure is repeated until the dry season contains the entire 12 months, which is the same as the non-seasonal scenario. The various divisions of seasons and their associated seasonal design flows at Choutro station are listed in Table 2.

Allowable pollutant discharges for each seasonal division

Upon obtaining 12 divisions of seasons, the allowable pollutant discharges under each division are computed according to the TWL and UT models. Water quality standards of BOD = 4 mg/l and BOD = 2 mg/l are used in the computation. QUAL2E is first applied to determine the impact coefficients. Then the TWL and UT models are solved with XMP. The annual allowable pollutant discharges under seasonal discharge management are the sum of discharges of both seasons. The results are shown in Figs 7 and 8. With the TWL method and a BOD standard equal to

Table 2. Q_{90} for varied seasonal divisions

Dry season length (months)	Months in dry season	Q_{90} (m^3s^{-1})	
		Dry season	Wet season
1	5	1.47	2.50
2	4 ~ 5	1.47	2.83
3	3 ~ 5	1.65	3.26
4	2 ~ 5	1.80	3.74
5	2 ~ 6	1.81	3.80
6	1 ~ 6	1.87	4.86
7	1 ~ 6,12	2.00	6.33
8	1 ~ 6,11 ~ 12	2.05	8.00
9	1 ~ 7,11 ~ 12	2.06	9.70
10	1 ~ 7,10 ~ 12	2.15	11.70
11	1 ~ 8,10 ~ 12	2.20	12.0
12	1 ~ 12	2.30	—

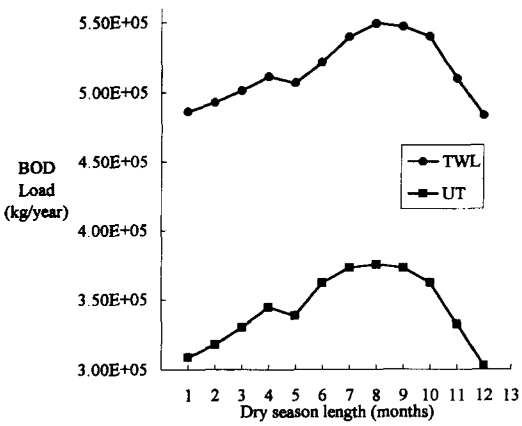

Fig. 7. Allowable loads for TWL and UT programs (BOD standard = 2 mg/l).

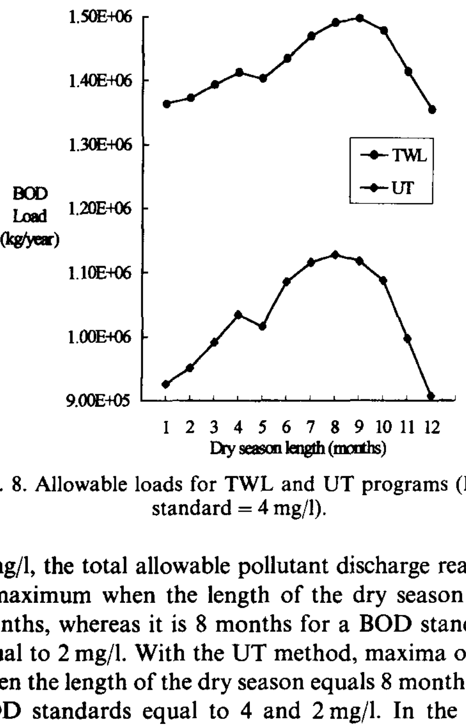

Fig. 8. Allowable loads for TWL and UT programs (BOD standard = 4 mg/l).

4 mg/l, the total allowable pollutant discharge reaches a maximum when the length of the dry season is 9 months, whereas it is 8 months for a BOD standard equal to 2 mg/l. With the UT method, maxima occur when the length of the dry season equals 8 months for BOD standards equal to 4 and 2 mg/l. In the case study, when the dry season length increases from 4 to 5 months, the design flows of both seasons have no obvious increase. The increase in allowable pollutant discharge in the dry season is insufficient to compensate the decrease resulting from the diminished length of in the wet season. When the dry season is 8 or 9 months, the total allowable pollutant discharge attains a maximum. If the allowable pollutant discharge is the only criterion for division of seasons, then the best division would be when the dry season length equals 8 or 9 months.

According to the above results, for the best division of seasons the allowable pollutant discharge under the TWL method increases about 10% relative to a non-seasonal scenario, whereas the increase under the UT method is about 20%. After a trial-and-error procedure, we found that the total allowable pollutant discharge at Q_{90} for a seasonal program roughly equals that at Q_{80} for the non-seasonal scenario. Hence instead of decreasing the requirement from Q_{90} to Q_{80}, the seasonal alternative can be employed to diminish the total cost.

Risk of SDP

The design flow determined according to the flow duration curve method cannot reveal the frequency of the low flow events as precisely as that by the frequency analysis method. Hence the risk of a SDP is less clear in the former case. The magnitude of risk level indicates the suitability of the method to manage water quality and is important for a SDP analysis. In this work, the risk assessment of SDP is implemented with massive Monte-Carlo simulations.

Prior to analyzing the risk in SDP, the probability distributions and associated parameters of seasonal design flows of each division listed in Table 2 are determined from historical flow data. Log-normal distribution function is applied in this work to determine the probability density function. 2000 samples of design flows are randomly sampled based on the previously determined distribution. In total 2000 QUAL2E simulations are implemented for each set of samples. With the same pollutant loads determined in the analysis of seasonal divisions, results of QUAL2E simulation are used to determine whether randomly produced flows would result in compliance of water quality standard(s). The number of occasions of violation of the standard(s) divided by the total number of simulations, 2000, is defined as the water quality risk of that season. The union of occasions in violation in both seasons is used to calculate the risk of the entire year for a division of seasons. Once any season fails, the entire year fails. Monte-Carlo simulations are implemented for 12 divisions of seasons, two methods of TWL and UT, and two water quality standards of BOD equal to 4 and 2 mg/l. The risk levels and corresponding allowable pollutant discharges of each division of seasons are illustrated in Figs 9 and 10. Each point represents a season division.

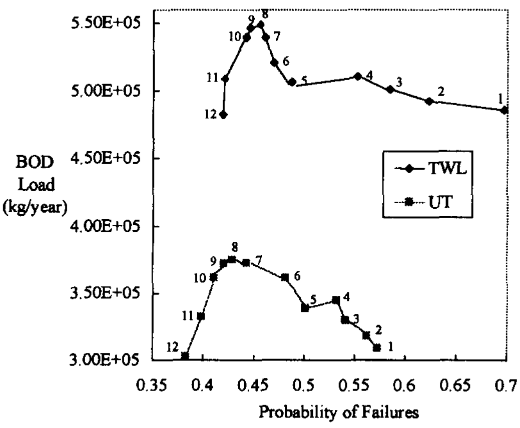

Fig. 9. Risk for TWL and UT programs (BOD standard = 2 mg/l).

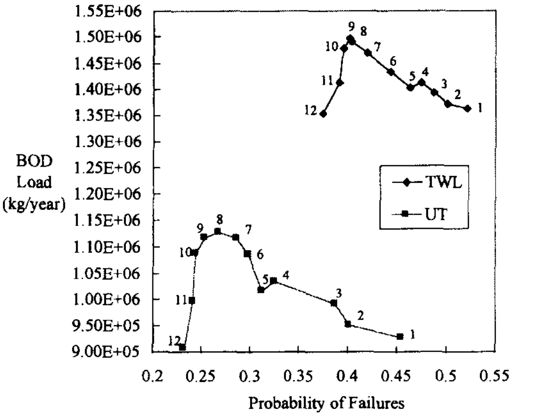

Fig. 10. Risk for TWL and UT programs (BOD standard = 4 mg/l).

In the figures, a peak is clearly observed. For the points at the right of the peak, the risk increases as the allowable pollutant discharge decreases. These alternatives are therefore not worthy of further analysis. The points at the left of the peak reflect the trade off between the allowable pollutant discharge and the risk. That is, an increased risk induces an increased allowable pollutant discharge. For example, in Fig. 10, the risk for the dry season of length 8 months is only 3.5% greater than that of a non-seasonal situation (a dry season of length 12 months), but the allowable discharge of pollutants increases by about 2.25×10^5 kg/yr (increase of 25%). This trade off relationship offers a basis to choose the best compromise division of seasons. According to the figures, varied discharge management programs affect the risk levels. The UT method is clearly more stringent than the TWL method and thus has a smaller risk. This risk information, even whether or not a seasonal alternative is adopted, has great value for an water quality management authority to assess the discharge management.

CONCLUSION

For discharge management programs based on design flows determined from the flow duration curve method, a procedure is developed in this work to determine a pertinent division of seasons and to assess the water quality risk of a SDP. Through seasonal management, the social cost in water quality control can be diminished, and pollution sources may be more willing to comply. Hence it would be beneficial for both environmental protection and economic growth. From the case study of Tung-Kang River, the total allowable discharge of pollutants for the seasonal alternative at Q_{90} is about the same as that for the non-seasonal Q_{80}. Through assessment of the risk with Monte-Carlo simulation, the suitability of a SDP can be assessed. As the results reveal, the risk under the TWL method exceeds that under the UT method. The resulting allowable discharges of pollutants and the corresponding levels of risk can serve as two criteria to decide the best compromise division of seasons or whether or not to adopt a seasonal option.

The characteristics of each river are unique, hence no single management is applicable to every river. Seasonal management operates according to the variation of the river flow, but such variations depend markedly on the rivers. Therefore, the process of seasonal management program and the determination of management approach should be unique for each river. The approaches proposed herein to divide seasons and to assess water quality risk are inapplicable to rivers affected by artificial factors such as dams and water uptakes.

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