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Risk analysis of seasonal stream water quality management

Manoj Jha and Roy Gu

ABSTRACT

Seasonal discharge programs, which take advantage of temporal variation of stream assimilative capacity, are cost effective. However, these seasonal discharge control programs should not increase the risk of water quality violations. A method is presented to estimate the allowable pollutant loads under both seasonal and non-seasonal discharge control programs for a single discharger that maintains the same level of risk of water quality violation. An enhanced in-stream water quality model QUAL2E-UNCAS was applied to a 39-km river reach of the Des Moines River below Des Moines Sewage Treatment Plant (DMSTP) in Iowa. The model was calibrated for dissolved oxygen (DO), biological oxygen demand (BOD), and ammonia as nitrogen with standard errors of 10, 17, and 23% by comparing with the observed water quality data. Monte-Carlo simulation technique was then implemented for seasonal and non-seasonal discharge program to assess the water quality violation risk and the allowable pollutant load. The results indicated that the four-seasonal program offers about 136% increase in BOD loading and 61% increase in ammonia loading when compared with the non-seasonal program without any increase in the violation probabilities, whereas the two-seasonal program only offers 13% decrease in BOD loading and 56% increase in ammonia loading. It is found that the multi-discharge program was beneficial for both water quality indicators, and thus provides a way of reducing the overall cost of waste treatment.

Key words | ammonia nitrogen, BOD, Des Moines River, in-stream water quality management, QUAL2E-UNCAS, seasonal discharge program

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INTRODUCTION

Stream water quality management problems have been addressed as multiobjective optimization problems in several earlier studies (Louie *et al.* 1984; Tung & Hathhorn 1989). Several waste load allocation models have been developed to determine the required pollutant treatment levels at a number of point sources to attain a satisfactory water quality response in a receiving water body in an economically efficient manner. These models are typically designed on the basis of critical stream conditions such as annual low flows and high summer temperatures (Lence *et al.* 1990). However, the discharge limit based on pre-determined constant conditions is not cost effective for rivers with significant seasonal variations in flow (Kao & Bau 1996). Seasonal management programs, which consider the dynamic waste assimilative capacity of a river and allow for different levels of waste treatment during different seasons of the year, have been shown to be more cost-effective than non-seasonal uniform treatment programs (Reheis *et al.* 1982; Eheart *et al.* 1987; Rossman 1989; Lence & Takyi 1992; Ng *et al.* 2006; Chen & Ma 2008). Under seasonal discharge programs, allowable discharge rates are indexed to the calendar date, with the expectation that the assimilative capacity of the receiving water body will vary from one period to another. The rate of waste discharge

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allowed at a given time is determined by considering water quality goals and the acceptable probability of achieving those goals. Reheis *et al.* (1982) reported the economic efficiency of seasonal discharge control program indicating capital cost savings of up to 16% and the annual operating cost savings of up to 19% compared to the constant year-round discharge limit. Eheart *et al.* (1987) demonstrated significant cost savings from seasonal discharge program as long as there is adequate flexibility in treatment options.

Although the economic efficiency of seasonal discharge programs has been demonstrated, the increased risk of water quality violation, the increased information requirement, and the increased operational difficulty remains a concern. Eheart *et al.* (1987) pointed out that the risk in a seasonal water pollution control program arose primarily from uncertainty of the flow rate. Rossman (1989) described an approach for designing risk equivalent seasonal discharge limits for single-discharger stream segments, and found that under a fixed pollutant discharge level, the risk of violating water quality standards is related to the statistical variations of environmental factors such as streamflow, temperature, pH, hardness, and background pollutant concentration. Several optimization methods have been developed incorporating the issues of uncertainty due to both randomness of the stream flow and imprecision in management goals of obtaining seasonal fraction removal levels (Kao & Bau 1996; Suresh & Mujumdar 1999; Sasikumar & Mujumdar 2000; Burn & Yulianti 2001; Yandamuri *et al.* 2006). Kao & Bau (1996) performed risk analysis of discharge management programs, which is based on design flows determined from the flow duration curve method, using Monte-Carlo simulation with a water quality simulation model QUAL2E to assess the risk of water quality violation of seasonal program. Sashikumar & Mujumdar (2000) addressed the management problems using a fuzzy multiobjective optimization model while Mujumdar & Vemula (2004) developed a simulation-optimization approach that integrates the fuzzy optimization model within the framework of simulation model QUAL2E and unconstrained genetic algorithm.

This paper presents a simplified approach for designing a seasonal discharge program based on the lowest 7-day average flow with 10-year return period (7Q10) as design flow for a river reach receiving a single discharge. A risk equivalent seasonal discharge program was developed for a 39-km river reach of the Des Moines River in Iowa below the sewage treatment plant (DMSTP). An objective function of maximizing pollutant loads was established for two water quality indicators - BOD and ammonia, which are recognized as significant pollutants for Des Moines River (Gu & Dong 1998). The physical processes of the river reach were modeled using an in-stream water quality simulation model QUAL2E (Brown & Barnwell 1987). Risk analysis for seasonal and non-seasonal discharge program was performed using Monte-Carlo simulation approach inbuilt in the enhanced version of the QUAL2E model called QUAL2E-UNCAS (Brown & Barnwell 1987). The seasonal discharge program was compared with a non-seasonal discharge program by examining the calculated pollutant discharge limits with the same risk of water quality violations.

MATERIALS AND METHOD

Modeling domain and water quality model

A 39-km segment of Des Moines River in Iowa below DMSTP was selected to study the risk equivalent seasonal waste discharge control program. The reach begins at the outfall of the treatment plant. The Des Moines River is the largest interior water body in Iowa. The reach below Des Moines city is classified as Class A (primary contact recreation) and Class B (WW) (significant resource warm water) by Environmental Protection Commission of State of Iowa. There are no criteria specified for DO and ammonia for Class A, but for Class B (WW), the criteria for DO is more than 5.0 mg/L and for ammonia is less than 1.9 mg/L (for pH = 8.0 and T = 25°C) and 2.0 mg/L (for pH = 8.0 and T = 10°C or 15°C).

The stream water quality model, QUAL2E (Brown & Barnwell 1987), is a comprehensive and versatile one-dimension steady state model. It simulates major components of the nutrient cycle, algal production, benthic and carbonaceous demand, atmospheric reaeration and their effects on the dissolved oxygen balance. It can be applied for waste load allocations, discharge permit determinations, and other conventional pollutant evaluations.

The model is capable of simulating up to 15 water quality constituents in dendrite streams that are well mixed laterally and vertically. This is the best suited in-stream model for point sources of pollutants and has limitation when simulating rivers that experience temporal variations in streamflow in polluting load over a diurnal of a shorter time period. The model is extensively documented in the user manual (Brown & Barnwell 1987) which explains the theory behind the model and the way in which it may be implemented.

The conceptual representation of a stream used in the QUAL2E formulation is a stream that has been divided into a number of sub-reaches or computational elements of equal lengths equivalent to finite difference elements. For each computational element, hydrologic balance (in terms of flow), heat balance (in terms of temperature), and material balance (in terms of concentration) are conducted. Both advective and dispersive transports are considered in the material balance. The model uses a finite-difference solution of the advective-dispersive mass transport and reaction equations and a special steady-state implementation of an implicit backward difference numerical scheme which gives the model an unconditional stability (Walton & Webb 1994).

Most determinants are simulated as first-order decays but DO, nitrate, and phosphate are represented in more details. The model includes sediment processes, but only as a sink for substances (for example it includes a settling rate for BOD but not a re-suspension rate) or as a source of oxygen demand. The algal model consists of growth (by photosynthesis), respiration and the settling of algae onto the sediments of the river bed. The nitrogen cycle is represented by the transformations affecting organic nitrogen, ammonium, nitrite and nitrate. The phosphorus cycle is represented by the transformations affecting organic and dissolved phosphorus fractions. Both organic nitrogen and phosphorus are produced by algae but organic nitrogen is removed by hydrolysis to ammonium and settling, while organic phosphorus is removed by simple decay and settling. The DO model incorporates the effects of the algal, nitrogen, phosphorus and BOD processes, but the DO concentration will also be influenced by atmospheric re-aeration and sediment oxygen demand. Temperature is modeled by performing a heat balance on each element.

An extension of the model called QUAL2E-UNCAS allows users to perform uncertainty analysis on the steady state water quality simulations by investigating model sensitivity to changes in one variable at a time (sensitivity analysis) or all the variables at once (first-order error analysis) or by using Monte Carlo techniques. When undertaking first-order error analysis, all variables are assumed to act independently, and the relationship between the parameter and the output is assumed to be linear. This is not always correct, but does provide a useful approximation. Monte Carlo simulation for uncertainty analysis provides summary statistics and frequency distributions for the water quality parameters at specific locations in the system. This technique has the advantage of there being no assumption of linearity, but at a cost of greatly increased run times. The cumulative frequency distributions are useful in evaluating overall dispersion in the model predictions and in assessing the likelihood of violating a water quality standard. The input requirement for Monte Carlo simulation option in QUAL2E-UNCAS consists of the variance of the input variable, the probability density function of the input variable and the number of simulations to be performed. The number of Monte Carlo simulations must be enough to avoid large errors in the estimated values of output variance, yet small enough to avoid unduly long computation times.

Modeling and assessment

The low flow condition in 1997 offers an excellent opportunity to calibrate the model since severe drought conditions were experienced in Central Iowa during the summer of 1997. The historical streamflow data for 1997 was obtained from the U.S. Geological Survey (USGS) website for gage station number 05485500, which is located 35 km upstream of the simulation reach. Data on DO, BOD, and ammonia from upstream of the reach were collected from Des Moines River Water Quality Network operated by Iowa State University and supported through the Rock Island District of Army Corps of Engineers (Lutz 2004). It can be observed from the historical water quality data that no obvious variations exist during different seasons and thus assumed constant throughout. Data collected on July 13 of 1997 for DO (4.2 mg/L), BOD (10.8 mg/L), and ammonia (8.0 mg/L) were considered as the upstream boundary conditions for the modeling purpose. Here, BOD represents Total BOD.

The QUAL2E model was applied to simulate the concentrations of DO, BOD, and ammonia in the 39-km reach of the Des Moines River below DMSTP. It was assumed that there are no other significant sources of pollution including nonpoint sources, and no significant horizontal and/or vertical dispersion of flow within the modeling reach of the river. The model was first calibrated using the observed water quality data of the river assuming steady state condition. The river design flow, temperature, and the background values of BOD, DO, and ammonia of upstream boundary condition were used as inputs to the model. The model result was evaluated using standard error method. The calibrated model was then applied to estimate the preliminary allowable pollutant load for each of the seasonal discharge programs.

An important criterion of seasonal discharge programs is that the degree of water quality protection achieved under such programs be the same as that achieved under an accepted or existing non-seasonal discharge program for the same river basin. This condition is referred to as the "risk equivalency" condition (Rossman 1989). A risk equivalent seasonal discharge program that meets a maximum total pollutant discharge objective function is given as:

$$\text{Maximize} \quad z = \sum_{i=1}^{s} d_i w_i \qquad (1)$$

subject to limit on risk equivalency condition,

$$\prod_{i=1}^{s} p_i(a_i w_i(s_i^*)) \geq 1 - P \qquad (2)$$

limit on water quality of river,

$$0 \leq a_i w_i \leq s_i^* \qquad (3)$$

and limit on allowable discharge at given time,

$$W_i^1 \leq w_i \leq W_i^u \qquad (4)$$

where z is total pollutant load (kg), w_i is the discharged pollutant load from the discharger (Sewage Treatment Plant) in season i (kg/day), d_i is the days in season i, a_i is the impact coefficient of pollutant load on water quality at the critical point in the river in season i, $a_i w_i$ is the concentration of the pollutant at critical point in the river (mg/L), P is the probability of incurring one or more water quality violations in any year specified by the river basin authority, s_i^* is the water quality standard of the river in season i (mg/L), W_i^1 is the raw pollutant load of discharger in season i, and W_i^u is the upper limit of treatment for the discharger in season i (kg/day), which is predefined by treatment technology of the treatment plant.

For seasonal waste discharge management, three different schedules were considered: non-seasonal (i.e. year-round), two-seasonal discharge, and four-seasonal discharge. The seasonal discharge programs were based on flow variations over an annual cycle. The seasons for two-seasonal program were April to June (high flow) and July to March (low flow). The seasons for four-seasonal program were January to March, April to June, July to September, and October to December. The design flow and design temperature data were selected from the 7-day average low flow values and the mean temperature for each season. For a given season, the 7Q10 low flow and the highest seasonal average temperature were selected to account for the critical stream conditions.

The preliminary allowable pollutant load which meets the constraints given by Equations (3) and (4) was found through the numerical experiments by changing the amount of pollutant load. The model simulates both ammonia nitrification and BOD decay. Both processes consume dissolved oxygen in the river.

Although the preliminary allowable pollutant loads for each of the seasonal discharges has been acquired, the risk equivalent condition described by Equation (2) in the risk equivalent seasonal discharge program may not be maintained under such a load. Risk analysis was performed using Monte-Carlo simulations. The 7% incurring probability of one or more water quality violations in any year is assumed to be the acceptable risk of water quality violations. Risk analysis requires probability density function and associated parameters of seasonal design flow of each seasonal discharge program. The diagnostics on the Log-normal distribution of the average 7-day lowest flow for all of the seasons indicated that all of the Kolmogorov-Simirnov (K-S) tests were satisfied at a significant level of 5% or more, and thus Log-normal distribution function was used to determine the probability density function. About two thousand simulations were implemented for each season using samples of design flows randomly sampled based on the distribution function. BOD loadings were determined according to the dissolved oxygen criteria and risk level of water quality violations, whereas Ammonia loadings for both seasonal and non-seasonal discharge programs were determined according to the in-stream ammonia criteria and water quality risk.

Although the model is very well suited for its intentional use, it has a lot of limitations. It is a one-dimensional stead state model and therefore is suited for streams that are well mixed vertically and laterally. The modeling results will not hold true if there are significant temporal variations over a short period of time in streamflow as well as in nonpoint source loads.

RESULTS AND DISCUSSION

The QUAL2E model developed for the 39-km Des Moines River reach was initially run with the model's recommended default values of parameters for all of the chemicals and biological reactions that are simulated by the model. List of parameters and their default and recommended values are listed in the user manual, specifically Table III-2 on page 53 (Brown & Barnwell 1987). The model simulates the changes in flow condition along the stream by computing a series of steady-state surface water profiles using an implicit finite-difference numerical solution method to solve equations for flow and then the solutes for each of the elements sequentially.

The QUAL2E model was calibrated for the concentrations of DO, BOD, and ammonia under steady state condition. The calibration was performed using actual flow data for summer of 1997 (July through September) and using upstream values of DO, BOD, and ammonia as boundary condition. Final calibrated values of the model calibration parameters were found to be 1.0 day^{-1} for ammonia oxidation coefficient, 0.2 mg O_2/L for nitrification inhibition coefficient, and 0.4 day^{-1} for BOD decay rate. Figure 1 shows comparison of observed and simulated concentrations of DO, BOD, and ammonia nitrogen at several locations up to 29 km river reach below DMSTP. Field data (measured) values represent the average concentrations at respective locations. Visual inspection shows that the model simulated values closely followed the field or measured data. Further statistical evaluation yielded standard error values of 10, 17, and 23% for DO, BOD and ammonia respectively.

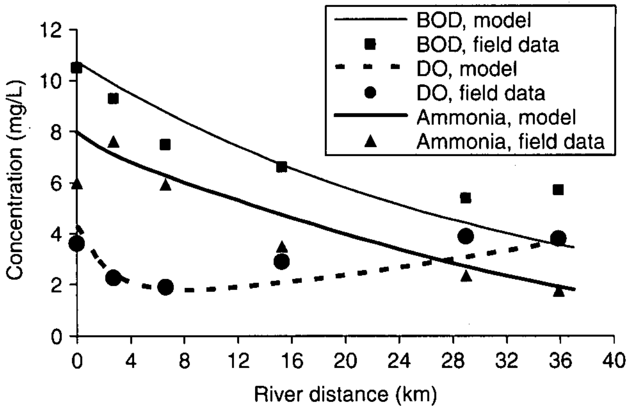

Figure 1 | Measured and QUAL2E simulated average concentrations of DO, BOD, and ammonia in the 39-km Des Moines River segment below Des Moines Sewage Treatment Plant (DMSTP).

Table 1 presents the calculated design flow (7Q10) and design temperature for each of the seasons. The calibrated model was applied to the simulations of the preliminary allowable pollutant load for each of the seasonal discharge programs. The preliminary allowable pollutant load was determined by changing the amount of pollutant loads to satisfy Equations (3) and (4).

About two thousand samples of design flows were randomly sampled from the log-normal distribution function for QUAL2E simulations for each season. The number of water quality criterion violations divided by the total number of simulations is defined as the water quality risk of that season. For the seasonal discharge program, the combined violation probability was calculated from the left side of risk equivalency condition constraint as shown in

Table 1 | Design flow and temperature values for seasonal discharge programs

Seasonal Discharge Program		Design flow, 7Q10 (m^3/s)	Design temperature (°C)	Variance of average 7-day lowest flow*
Non-seasonal	Jan-Dec	2.8	25	0.144
Two-seasonal	Apr-Jun	16.4	25	0.122
	Jul-Mar	3.2	25	0.148
Four-seasonal	Jan-Mar	3.2	10	0.160
	Apr-Jun	16.4	25	0.122
	Jul-Sep	4.5	25	0.142
	Oct-Dec	3.6	15	0.161

*Based on log-transformed seasonal flow values.

Equation (2). If this risk is greater than 7%, the preliminary allowable pollutant load is reduced for each season and the model is re-run for the new load. The procedure is repeated for several times until Equation (2) is satisfied. The final pollutant load is the solution for the risk equivalent seasonal discharge program, which has the maximum load, and the risk is not greater than the non-seasonal discharge program.

Figure 2 shows monthly ammonia loadings for each of the three seasonal programs. The total annual ammonia loadings are 292 (non-seasonal), 456 (two-seasonal), and 469 (four-seasonal) metric tons. The four-seasonal and two-seasonal discharge programs offer about 61 and 56% increase in ammonia loadings than non-seasonal discharge program without any increase in the violation probabilities.

Figure 3 shows the monthly BOD loadings for each of the three seasonal programs. With respect to annual BOD loading, four-seasonal program offers 136% increase (3,250 metric tons), and two-seasonal program offers 13% decrease (1,200 metric tons) while comparing with the non-seasonal program (1,378 metric tons). This situation can be explained by the interaction of ammonia nitrification and BOD decay. Both processes consume dissolved oxygen in the river. Temperature plays an important role in determining BOD loading while flow rate has greater effect on ammonia loading.

For the four-seasonal program, there are no significant advantages of ammonia loading for two seasons: Jan–Mar (3.8 mg/L) and Oct–Dec (4.115 mg/L) over the non-seasonal program (3.745 mg/L). However, the other two seasons are very effective for ammonia loading because of higher design flows (16.4 m^3/s for Apr–Jun; 4.5 m^3/s for Jul–Mar) than that of the non-seasonal (2.8 m^3/s) program. Therefore, the combined ammonia loading for the four-seasonal program is 1.61 times the non-seasonal ammonia loading. Similarly, BOD loadings have no advantages in two seasons, Apr–Jun and Jul–Mar, since the design temperatures are the same as that of non-seasonal. However, design temperatures for Jan–Mar and Oct–Dec are much lower than that of the non-seasonal program and hence BOD concentrations are much higher (85.3 mg/L for Jan–Mar; 56.33 mg/L for Oct–Dec) than that of the non-seasonal program (17.67 mg/L). The combined BOD loading of the four-season discharge program is about 1.36 times higher than that of the non-seasonal program.

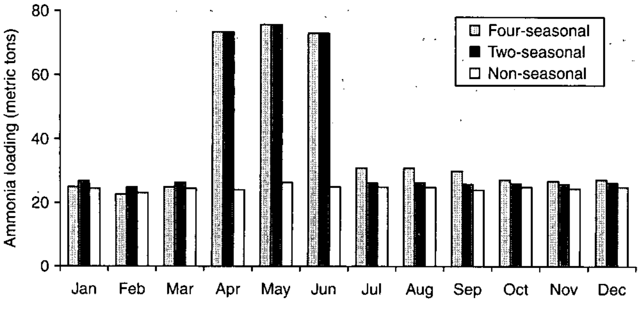

Figure 2 | Monthly ammonia as nitrate loadings from DMSTP for different seasonal discharge programs.

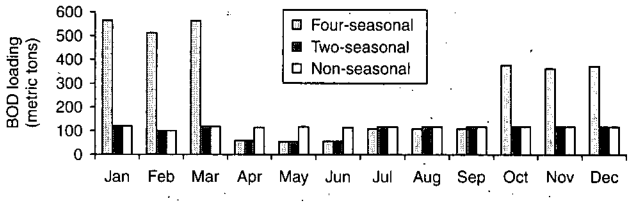

Figure 3 | Monthly BOD loadings from DMSTP for different seasonal discharge programs.

Ammonia loading of the two-seasonal program has some advantages over that of the non-seasonal program because design flows are higher (Table 1). The ammonia concentrations are 11.5 mg/L and 3.965 mg/L for the two seasons whereas the value for the non-seasonal program is 3.745 mg/L. The ammonia loading for the two-seasonal program is 1.56 times that of the non-seasonal. However, the BOD loading for the two-seasonal program is smaller because the design temperatures are the same for both programs. Although the river under the two-seasonal program has more assimilative capacity, more is used by ammonia loading and less can be used by BOD decay. So, the BOD loading is 13% less than that of the non-seasonal program.

Overall, the river under the four-seasonal program has much higher assimilative capacity than that of the two-seasonal program and non-seasonal program. The primary reason is higher design flow in two seasons and lower design temperatures in the other two seasons. This study demonstrates the usefulness of seasonal water quality management while considering the risk of water quality violations. Accurate analysis and successful implementation will help reduce the overall cost of waste management.

CONCLUSION

The cost of waste pollutant control can be reduced by means of seasonal waste discharge control programs based on temporal variation in stream assimilative capacity. However, it should be guaranteed that the probability of water quality violation under such programs is the same as that under non-seasonal discharge programs. This paper presents a method to estimate allowable pollutant loads for a single discharger under both seasonal and non-seasonal discharge control programs that maintain the same risk of water quality violation. This method used the maximum pollutant load as the objective function. The flow rate, which affects the receiving water assimilative capacity, was treated as a random variable whose distribution can be estimated from long-term historical data. A water quality model QUAL2E was employed to simulate a 39-km reach of Des Moines River in Iowa, downstream of DMSTP. Monte-Carlo simulation was adopted to assess the water quality violation risk and determine the allowable pollutant loads based on the risk for two critical pollutants, BOD and ammonia. Results indicated that the four-seasonal discharge program was beneficial for both pollutant loads. The four-seasonal and two-seasonal discharge programs offer about 61 and 56% increase in ammonia loadings, respectively, than the non-seasonal discharge program without any increase in the violation probabilities. Similar results were found for BOD loading with four-seasonal program being at 136% increase and two-seasonal program being at only 13% increase in loading. The allocation of river assimilative capacity between ammonia and BOD depends on several factors such as economic efficiency and technical issues of treatment at the facility. Overall, it was found that the river under the four-seasonal program has much higher assimilative capacity than that of the two-seasonal program and non-seasonal program while maintaining the same risk of violations. The method is promising in reducing overall cost of waste management through a seasonal discharge management program.

While water quality modeling is useful in providing the solution, it is important to understand the limitations of the model and the underlying assumptions. QUAL2E assumes constant emissions in steady state condition, which may not hold true under conditions such as non-point source pollution, precipitation-driven pollution, and others. Increase in loadings will cause reduced level of DO and higher levels of nutrients in the water, which will have further implications. Higher nutrient concentrations not only degrade local water quality but also trigger growth of aquatic plant communities and ultimately lead (or adds) to low DO conditions such as hypoxic zone (dead zone), an oxygen-depleted condition (less than 2 mg/L) adverse for aquatic lives to survive.

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