Chapter 8
Sensitivity Analysis for Stream Water Quality Management

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Abstract The sensitivity equations of stream water quality parameters are presented, and their practical applications to stream pollution control scientifically illustrated. Non-tidal streams are classified into: (a) clean or slightly polluted swift non-tidal streams, (b) moderately polluted swift non-tidal streams, (c) heavily polluted swift non-tidal streams, (d) clean or slightly polluted, intermediate non-tidal streams, (e) moderately polluted intermediate non-tidal streams, (f) heavily polluted intermediate non-tidal streams, (g) clean or slightly polluted

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L.K. Wang, C.T. Yang and M.-H.S. Wang (eds.), *Advances in Water Resources Management*, Handbook of Environmental Engineering, Vol. 16,
DOI 10.1007/978-3-319-22924-9_8

slow non-tidal streams, (h) moderately polluted slow non-tidal streams, and (i) heavily polluted slow non-tidal streams.

Tidal streams are classified into: (a) clean or slightly polluted tidal streams, (b) moderately polluted tidal streams, and (c) heavily polluted tidal streams. The characteristics and water quality parameter ranges of different types of receiving streams are presented. The significance of water quality sensitivities and dissolved oxygen deficits for water quality management are systematically identified by the author's mathematical models.

Keywords Water resources • Environmental management • Sensitivity • Dissolved oxygen deficit • Systems analysis • Water quality • Stream pollution control • Non-tidal streams • Tidal streams • River management

Nomenclature

B	Bottom deposit uptake rate, mg/L-day
C	Concentration of dissolved oxygen, mg/L
D	Total dissolved oxygen deficit, mg/L
Do	Initial concentration of dissolved oxygen deficit, mg/L
D_B	Dissolved oxygen deficit caused by bottom deposit uptake, mg/L
D_D	Dissolved oxygen deficit caused by initial DO deficit, mg/L
D_L	Dissolved oxygen deficit caused by BOD, mg/L
D_N	Dissolved oxygen deficit caused by nitrification, mg/L
D_α	Dissolved oxygen deficit reduced by photosynthesis reaction, mg/L
E	Longitudinal dispersion coefficient, km^2/day
J_1	$(U/2E) + \left(U^2/4E^2 + K_1/E\right)^{0.5}$
J_2	$(U/2E) - \left(U^2/4E^2 + K_2/E\right)^{0.5}$
J_n	$(U/2E) - \left(U^2/4E^2 + K_n/E\right)^{0.5}$
K	one of water quality parameters, such as K_1, K_2, K_n, α, E or B
K_1	Deoxygenation coefficient (base e), day^{-1}
K_2	Reaeration coefficient (base e), day^{-1}
K_n	Nitrification rate coefficient (base e), day^{-1}
K_r	BOD removal rate constant (base e), day^{-1}
L	Concentration of remaining carbonaceous biochemical oxygen demand (CBOD), mg/L
L_o	Initial concentration of remaining CBOD, mg/L
m_1	$\left(U^2 + 4K_1E\right)^{-0.5}$
m_2	$\left(U^2 + 4K_2E\right)^{-0.5}$
m_3	$\left(U^2 + 4K_nE\right)^{-0.5}$
N	Concentration of ammonia nitrogen, mg/L
N_O	Initial concentration of ammonia nitrogen, mg/L
n_1	$\partial J_1/\partial E = -(J_1/E + 2\,K_1m_1)$

n_2	$\partial J_2/\partial E = -(J_2/E + 2\ K_2 m_2)$
n_n	$\partial J_n/\partial E = -(J_n/E + 2\ K_n m_n)$
$S_{C,K}$	Sensitivity of C to K for non-tidal streams
$S_{C,K,\ t}$	Sensitivity of C to K for tidal streams
$S_{D,\ B}$	Sensitivity of D to B for non-tidal streams, day
$S_{D,\ K1}$	Sensitivity of D to K_1 for non-tidal streams, mg-day/L
$S_{D,\ K2}$	Sensitivity of D to K_2 for non-tidal streams, mg-day/L
$S_{D,\ Kn}$	Sensitivity of D to K_2 for non-tidal streams, mg-day/L
$S_{D,\ \alpha}$	Sensitivity of D to α for non-tidal streams, day
$S_{D,\ B,\ t}$	Sensitivity of D to B for tidal streams, day
$S_{D,\ E,\ t}$	Sensitivity of D to E for tidal streams, mg-day/L-km^2
$S_{D,\ K1,\ t}$	Sensitivity of D to K_1 for tidal streams, mg-day/L
$S_{D,\ K2,\ t}$	Sensitivity of D to K_2 for tidal streams, mg-day/L
$S_{D,\ Kn,\ t}$	Sensitivity of D to K_n for tidal streams, mg-day/L
$S_{D,\ \alpha,\ t}$	Sensitivity of D to α for tidal streams, day
$S_{D,\ K}$	Sensitivity of D to K for non-tidal streams, day
$S_{D,\ K,\ t}$	Sensitivity of D to K for tidal streams
$S_{L,\ K1}$	Sensitivity of L to K1 for non-tidal streams, mg-day/L
$S_{L,\ K1,\ t}$	Sensitivity of L to K1 for tidal streams, mg-day/L
$S_{L,\ E,\ t}$	Sensitivity of L to E for tidal streams
t	Flow time of pollutant, day
U	Mean velocity of streams, Km/day
X	The downstream distance from the point of effluent discharge, km
α	Photosynthesis rate, mg/L-day

1 Introduction

The authors have developed practical formulas for calculating the following sensitivities of critical water quality parameters: (a) the sensitivities of biochemical oxygen demand (L) to deoxygenation coefficient (K_1) and to longitudinal dispersion coefficient (E), and (b) the sensitivities of dissolved oxygen deficit (D) to deoxygenation coefficient, longitudinal dispersion coefficient, reaeration coefficient (K_2), photosynthesis rate (α), and bottom deposit uptake rate (B). It was also concluded that the sensitivity of dissolved oxygen (C) to any water quality parameter ($S_{C,K}$ or $S_{C,K,t}$) is equal to the negative sensitivity of dissolved oxygen deficit ($S_{D,k}$ or $S_{D,K,t}$) specific parameter (K).

$$S_{C,K} = -S_{D,K} \tag{8.1}$$

$$S_{C,K,t} = -S_{D,K,t} \tag{8.2}$$

where K in the subscripts represents any one of the water quality parameters, K_1, K_2, K_n, E, α or B; t in the subscripts stands for tidal streams. $S_{D,k}$, $S_{D,K,t}$, $S_{C,K}$ and $S_{C,K,t}$ are all defined clearly in the NOMENCLATURE section.

In this chapter, the sensitivity equations of stream water quality parameters are summarized and presented. Practical applications of the sensitivity equations are proposed and illustrated in detail. Receiving waters are classified according to the hydraulic characteristics and the degree of pollution as follows:

Non-tidal Receiving Streams.;

a. clean or slightly polluted swift non-tidal streams
b. moderately polluted swift non-tidal streams
c. heavily polluted swift non-tidal streams
d. clean or slightly polluted intermediate non-tidal streams
e. moderately polluted intermediate non-tidal streams
f. heavily polluted intermediate non-tidal streams
g. clean or slightly polluted slow non-tidal streams
h. moderately polluted slow non-tidal streams
i. heavily polluted slow non-tidal streams

Tidal Receiving Streams;

a. clean or slightly polluted tidal streams
b. moderately polluted tidal streams
c. heavily polluted tidal streams

The hydraulic characteristics and the water quality parameters of the aforementioned [1] types of receiving streams are scientifically assigned. The sensitivities of water quality (L, D, and C) to various water quality parameters (K_1, K_2, K_n, E, α, and B) are systematically analyzed and compared with one another for determination of relative environmental significance. Recent development in stream pollution control and the sensitivities of water quality parameters is introduced [1–17]. Finally important conclusions are drawn for water quality control in receiving streams.

2 Water Quality Models and Sensitivity Equations

The formulas of sensitivities have been theoretically derived from four steady state water quality models. The derivation of the sensitivity formulas can be found elsewhere [2], The steady state water quality models, two for non-tidal streams and two for tidal streams, are summarized in Appendix 1. The derived sensitivity equations for non-tidal streams and tidal streams are summarized in Appendices 2 and 3, respectively [15]. All terms are defined clearly in the NOMENCLATURE section.

3 Significance of Sensitivities for Non-tidal Streams

When a realistic set of consistent stream water quality parameter values need to be developed and/or identified, the sensitivities of these water quality parameters must be evaluated and discussed. Though the sensitivities are different from stream to stream, and from distance to distance within a stream, they can be generalized and compared with one another under specified stream conditions. The non-tidal streams are classified into swift, intermediate, and slow streams, according to their hydraulic characteristics. Each type of stream is further classified into clean or slightly polluted, moderately polluted, and heavily polluted streams according to their degrees of pollution.

The water quality of common receiving streams can be generalized as follows: (a) the initial concentration of remaining ultimate carbonaceous biochemical oxygen demand (CBOD) ranges from 3 to 30 mg/L; (b) the initial concentration of dissolved oxygen deficit (D) ranges from 1 to 8 mg/L; (c) the deoxygenation coefficient (K_1, base e) ranges from 0.1 to 6.0 day^{-1}; (d) the reaeration coefficient (K_2, base e) ranges from 0.1 to 20 day^{-1}; (e) the bottom deposit uptake rate (B) ranges from 0 to 2 mg/L-day; and (f) the photosynthesis rate (α) ranges from 0 to 2 mg/L-day. The sensitivities of various stream water quality parameters are discussed according to the classification and ranges of parameters stated previously.

Of the five most important water quality parameters for non-tidal streams (K_1, K_2, K_n, α, and B), only K_1 affects the Biochemical Oxygen Demand Model vindicated in Eq. 8.14, Appendix 1, and the sensitivity of L to K_1 ($S_{L,K1}$, indicated in Eq. 8.18, Appendix 2). Accordingly $S_{L,K1}$ is the only and the most important sensitivity term for biochemical oxygen demand. No evaluation and further discussion on other sensitivity terms are attempted in this research.

The total dissolved oxygen deficit for non-tidal streams (D, indicated in Eq. 8.15, Appendix 1) can be divided into five terms as follows:

$$D = D_L + D_N + D_B + D_\alpha + D_D \tag{8.3}$$

where

$$\begin{aligned} D_L &= \text{dissolved oxygen deficit caused by biochemical oxygen demand, mg/L} \\ &= K_1 L_O (K_2 - K_1)^{-1} [\exp(-K_1 t) - \exp(-K_2 t)] \end{aligned} \tag{8.4}$$

$$\begin{aligned} D_N &= \text{dissolved oxygen deficit caused by nitrification, mg/L} \\ &= K_n N_O (K_2 - K_n)^{-1} [\exp(-K_n t) - \exp(-K_2 t)] \end{aligned} \tag{8.5}$$

$$\begin{aligned} D_B &= \text{dissolved oxygen deficit caused by bottom de posit uptake, mg/L} \\ &= B(K_2)^{-1} [1 - \exp(-K_2 t)] \end{aligned} \tag{8.6}$$

$$\begin{aligned} D_\alpha &= \text{dissolved oxygen deficit reduced by photosynthesis reaction, mg/L} \\ &= -\alpha [1 - \exp(-K_2 t)] \end{aligned} \tag{8.7}$$

$$\begin{aligned} D_D &= \text{dissolved oxygen deficit caused by initial DO deficit, mg/L} \\ &= D_O [\exp(-K_2 t)] \end{aligned} \tag{8.8}$$

Accordingly D, D_L, D_N, D_B, D_α, D_D and all sensitivity terms $S_{D,K}$ will be analyzed and discussed in detail in Sect. 3.

The sensitivity of dissolved oxygen to a water quality parameter $S_{C,K}$ is simply the negative sensitivity of dissolved oxygen deficit to the same water quality parameter $S_{D,K}$ (Eq. 8.1); therefore $S_{C,K}$ is not included in the systems analysis.

3.1 Swift Non-tidal Streams

Non-tidal swift streams are generally shallow, rocky and/or sandy with mean stream velocity ranging from 0.3 to 1 m/s. Since the stream velocity is high, plankton blooms are difficult to grow, and the photosynthesis reaction almost can be neglected. The sensitivities of stream water quality parameters are discussed in the subsequent sections.

3.1.1 Clean or Slightly Polluted Swift Non-tidal Streams

Since stream water is clean or slightly polluted, its CBOD concentration is usually under 5 mg/L; the deoxygenation coefficient (K_1, base e) is under 0.23 day^{-1}; the reaeration coefficient (K_2, base e), which is proportional to velocity, is in the range from 5 to 20 day^{-1} or even higher. The stream bed is sandy or rocky; therefore, the bottom deposit uptake rate (B) is very small and can be neglected. Ammonia nitrogen concentration should be very low because of good stream water quality; therefore, the nitrification can be neglected. Let the initial concentration of remaining CBOD (L_O) be equal to 3 mg/L, the initial concentration of dissolved oxygen deficit (D_O) be equal to 1 mg/L, K_1 (base e) be equal to 0.15 day^{-1}, and bottom deposit uptake rate (B), photosynthesis rate (α), initial concentration of ammonia nitrogen (N_O), and nitrification coefficient (K_n) all be equal to zero. K_2 values (base e), however, are assigned to be equal to 5, 10 and 20 day^{-1}. Substituting those values into Eqs. 8.15, and 8.19–8.22 (See Appendices 1 and 2) for calculating the sensitivities and dissolved oxygen deficits under various flow times (t), one can obtain the results shown in Fig. 8.1. The sensitivity of dissolved oxygen deficit to reaeration coefficient ($S_{D,K2}$) is negative for this kind of river. It is important to know that sensitivity is a slope of water quality to a stream parameter, thus, may be positive or negative. Each sensitivity should be evaluated in accordance with its absolute value. Therefore the absolute value of the sensitivity $|S_{D,K2}|$ is plotted in Fig. 8.1. From the figure it can be seen that the sensitivity of D to K_1 ($S_{D,K1}$) is greater than the absolute value of $S_{D,K2}$. However, the value of dissolved oxygen deficit due to the term (D_D) is larger than that of due to deoxygenation term (D_L). The sensitivities of $S_{D,K1}$ and $|S_{D,K2}|$ decrease when K_2 increases. $S_{D,K1}$ increases with increasing flow time (t). When t increases, $|S_{D,K2}|$ increases to a peak point and then decreases. From above discussion, one can see that K_1 and K_2 are the two most important stream parameters for clean or slightly polluted swift non-tidal streams.

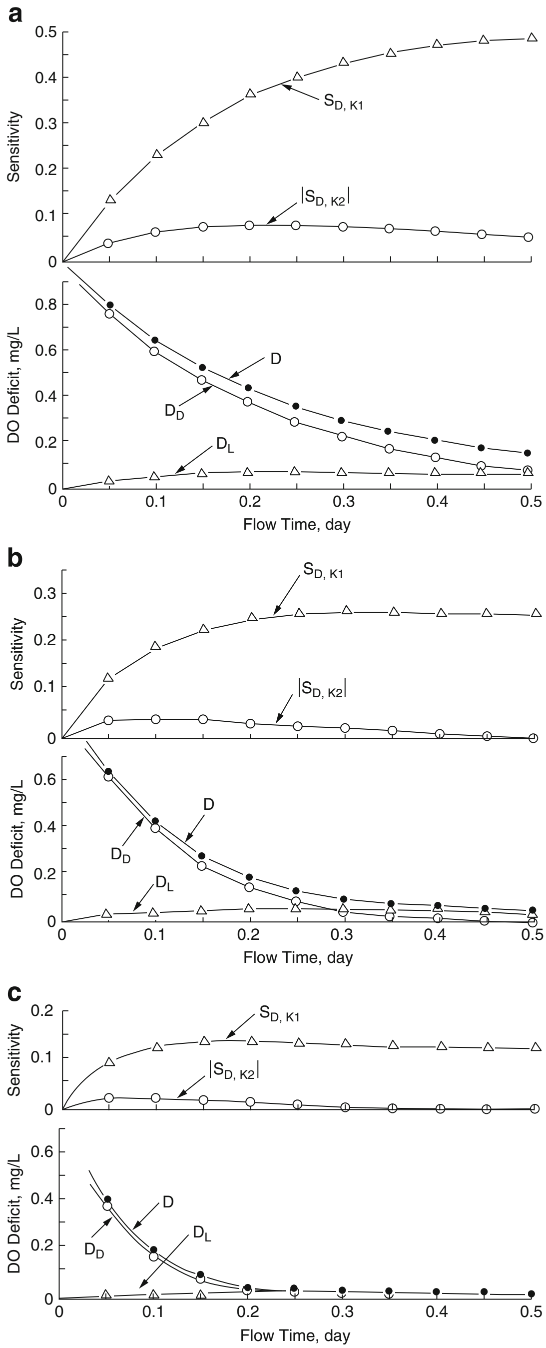

Fig. 8.1 (**a**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted swift non-tidal stream.($K_2 = 5$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted swift non-tidal stream ($K_2 = 10$ 1/day). (**c**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted swift non-tidal stream ($K_2 = 20$ 1/day)

3.1.2 Moderately Polluted Swift Non-tidal Streams

For this kind of stream water, the initial concentration of remaining carbonaceous biochemical oxygen demand (L_O) is about 10 mg/L; initial dissolved oxygen deficit (D_O) ranges from 1 to 3 mg/L; deoxygenation coefficient (K_1) ranges from 0.2 to 0.5 day^{-1} (base e); the range of reaeration coefficient (K_2) is same as that for clean or slightly polluted swift streams; the bottom deposit uptake rate (B) is under 0.1 mg/L-day. Let $L_O = 10$ mg/L, $D_O = 3$ mg/L, $K_1 = 0.345$ day^{-1}, and neglect the photosynthesis and nitrification effects (i.e., $B = 0.1$ mg/L-day, and $\alpha = K_n = N_O = 0$), one can plot Fig. 8.2 with Eqs. 8.15, and 8.19–8.22. Figure 8.2 indicates that the $S_{D,K1}$ is the most sensitive. The sensitivities of dissolved oxygen deficit to reaeration coefficient $|S_{D,K2}|$, to nitrification coefficient ($S_{D,Kn}$), and to bottom deposit uptake rate ($S_{D,B}$) are relatively insensitive. All sensitivities rapidly reduce with increasing K_2 values from 5 to 20 day^{-1}. Figure 8.2 also indicates that the most part of dissolved oxygen deficit is contributed by D_D term when the flow time (t) is short. The percentages of dissolved oxygen deficit due to nitrification (D_N) and bottom deposit uptake (D_B), are very small. In conclusion, the nitrification and bottom deposit uptake can be neglected, and K_1 and K_2 must be carefully and accurately measured for the moderately polluted swift non-tidal streams.

3.1.3 Heavily Polluted Swift, Non-tidal Streams

Generally for this type of streams the remaining CBOD of the stream is about 20 mg/L, or more. Wastewaters which discharge into the receiving stream of this type can even be untreated wastes. The deoxygenation coefficient (K_1, base e) is greater than 0.5 day^{-1}. The dissolved oxygen concentration of the stream water is very low. Initial dissolved oxygen deficit (D_O) ranges from 3 to 8 mg/L. There are sludge banks in the slow water segments of the stream. The range of bottom deposit uptake rate (B) is about from 0.1 to 1.0 mg/L-day. When the stream is heavily polluted, the nitrification bacteria cannot compete with the saprophyta; therefore, the nitrification effect can be neglected. Let $L_O = 20$ mg/L, $D_O = 5$ mg/L, $K_1 = 1.0$ day^{-1} (base e), $K_n = N_O = \alpha = 0$, and $B = 0.5$ mg/L-day. Substituting those values into Eqs. 8.15, and 8.19–8.22 for calculating sensitivities and dissolved oxygen deficits under various flow times (t), one can then plot Fig. 8.3. The figure indicates that the $S_{D,K1}$ is the most sensitive among the sensitivities evaluated. The $|S_{D,K2}|$ is less sensitive than $S_{D,K1}$. The $S_{D,B}$, b is very inert especially under the condition of high K_2 value. All sensitivities rapidly decline when K_2 increases from 5 to 20 day^{-1}. Figure 8.3 also indicates that the most part of dissolved oxygen deficit is contributed by D_D term when t value is small. The percentage of dissolved oxygen deficit due to bottom deposit uptake (D_B) is so small that it can be neglected.

In summation, the order of sensitivity (from very sensitive to insensitive) for swift streams is in the order of $S_{D,K1}$, $|S_{D,K2}|$, $S_{D,B}$ and $S_{D,Kn}$. The major sources or

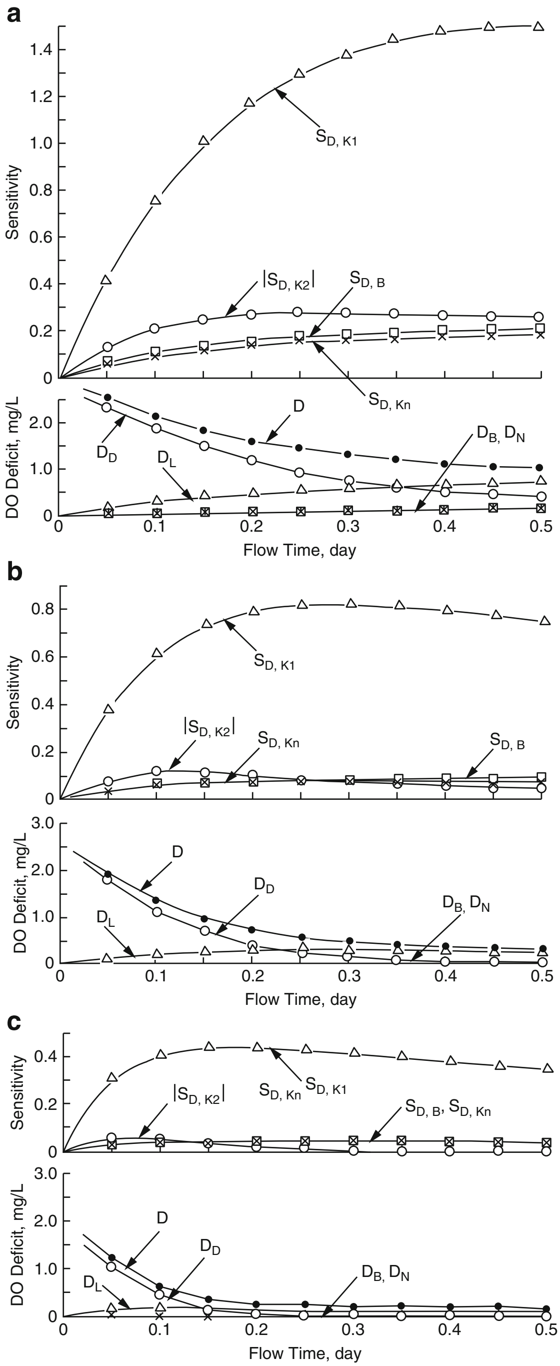

Fig. 8.2 (**a**) The sensitivities and dissolved oxygen deficits for moderately polluted swift non-tidal stream ($K_2 = 5$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for moderately polluted swift non-tidal stream ($K_2 = 10$ 1/day). (**c**) The sensitivities and dissolved oxygen deficits for moderately polluted swift non-tidal stream ($K_2 = 20$ 1/day)

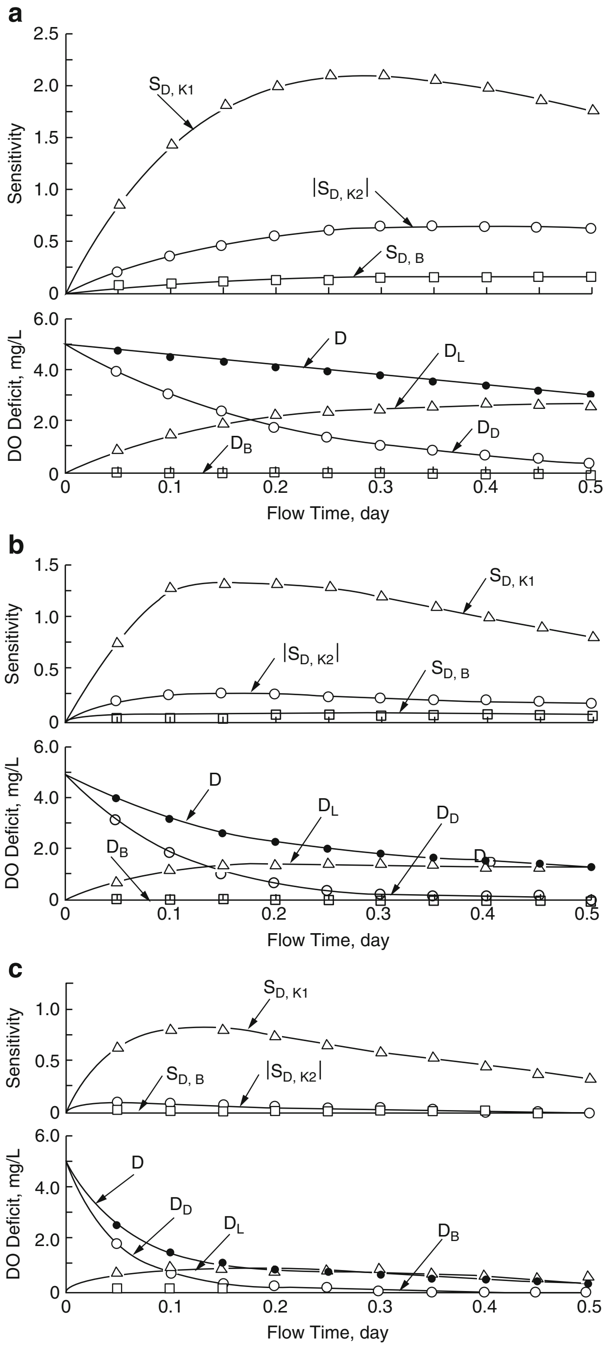

Fig. 8.3 (**a**) The sensitivities and dissolved oxygen deficits for heavily polluted swift non-tidal stream ($K_2 = 5$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for heavily polluted swift non-tidal stream ($K_2 = 10$ 1/day). (**c**) The sensitivities and dissolved oxygen deficits for heavily polluted swift non-tidal stream ($K_2 = 20$ 1/day)

sinks of dissolved oxygen deficit (D) are deoxygenation and initial DO deficit, the percentage of dissolved oxygen deficit due to bottom deposit uptake (D_B) and nitrification (D_N) is not more than 2 %. Therefore, the parameters of K_1 and K_2 are the two important stream parameters which should be carefully determined. The parameters of B and K_n may be roughly measured or omitted for the swift streams.

3.2 Intermediate Non-tidal Streams

The mean velocity of intermediate non-tidal streams is generally in the range of 0.1 to 0.3 m/s. This kind of stream has a sandy or silty bed. Usually the bed would be sandy if mean velocity is higher than 0.2 m/s. If the mean velocity is lower than 0.2 m/s and the stream water is also polluted, the sludge will be settled in the bed, and the bottom deposit uptake will be significant. In this section, the sensitivities of intermediate non-tidal streams are analyzed and are discussed in following three conditions: clean or slightly polluted, moderately polluted and heavily polluted.

3.2.1 Clean or Slightly Polluted Intermediate Non-tidal Streams

When a stream is clean or slightly polluted, nitrification coefficient (K_n) and ammonia nitrogen concentration (N_O) of the stream water are almost equal to zero, thus, the nitrification can be neglected. The bottom deposit uptake and photosynthesis are also insignificant. The range of reaeration coefficient (K_1) which is a function of velocity and depth, is 0.25 to 15 day^{-1}. The flow through time (t) is longer than that of swift streams. Based on the above discussion, it is reasonable to assume that $L_O = 3$ mg/L, $D_O = 1$ mg/L, $K_1 = 0.15$ day^{-1}, $B = 0.1$ mg/L-day, $\alpha = 0.2$ mg/L-day, and $K_n = N_O = 0$. K_2 is assigned to be 0.5, 2.5 and 10 day^{-1}.

The sensitivities and the dissolved oxygen deficit at various flow times can be determined by substituting the L_O, D_O, K_1, B, α, K_n, N_O, and K_2 values into Eqs. 8.15, and 8.19–8.22. The results are plotted as Fig. 8.4 from which we can see that:

$$S_{D,K1} > S_{D,B} > |S_{D,K2}|$$

in the order of decreasing sensitivity.

All sensitivities decline when K_2 value increases. The dissolved oxygen deficit due to bottom deposit uptake is relatively small.

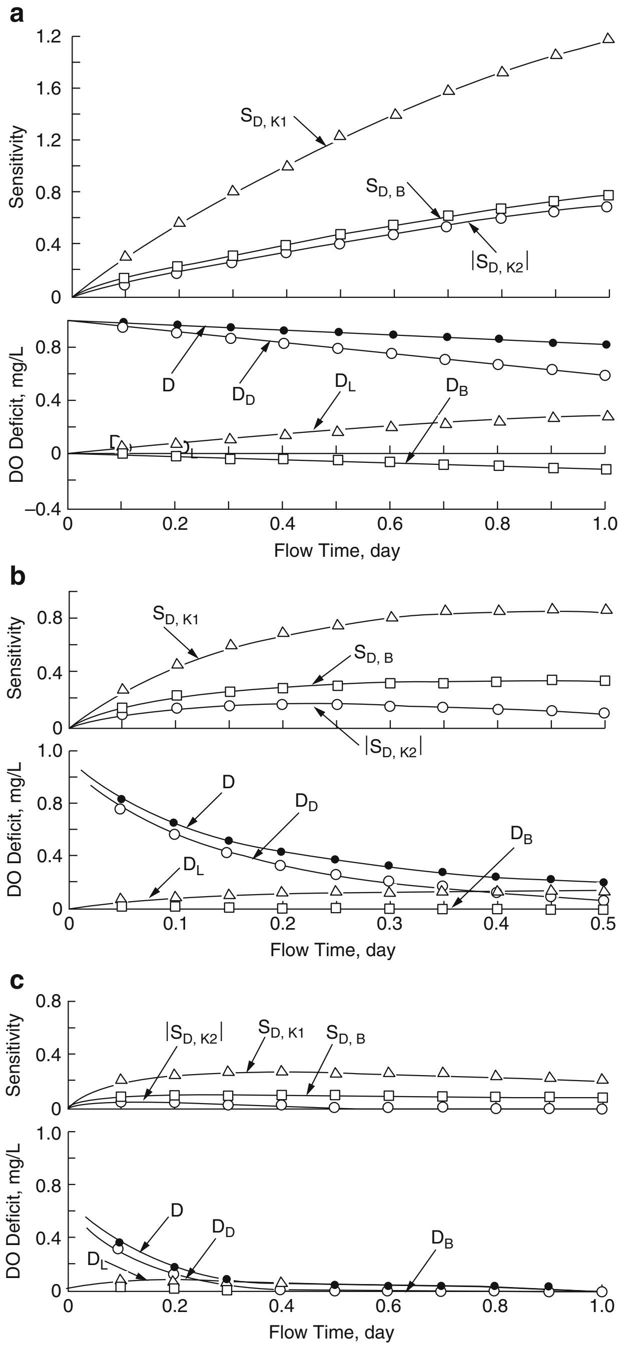

Fig. 8.4 (**a**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted intermediate non-tidal stream ($K_2 = 0.5$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted intermediate non-tidal stream ($K_2 = 2.5$ 1/day). (**c**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted intermediate non-tidal stream ($K_2 = 10$ 1/day)

3.2.2 Moderately Polluted Intermediate Non-tidal Streams

Nitrification may or may not exist under these stream conditions. If nitrification occurs in the stream water, the reactions follow:

$$2NH_3 + 3O_2 \rightarrow 2HNO_2 + 2H_2O \quad (8.9a)$$

$$2HNO_2 + O_2 \rightarrow 2HNO_3 \quad (8.9b)$$

The overall reaction is:

$$2NH_3 + 4O_2 \rightarrow 2HNO_3 + 2H_2O \quad (8.10)$$

The reactions of Eqs. 8.8 and 8.9 obey the first order reaction. The ranges of these two reaction coefficients are 0.01 to 0.50 day^{-1} (base e) and 0.50 to 2.00 day^{-1} (base e), respectively. [1] It is clear that the nitrification is controlled mainly by oxidation of NH_3 to HNO_2. The rate of oxygen uptake per unit of ammonia in oxidation ranges from 3 to 4 mg of O_2/mg of NH_3. Therefore, the range of nitrification coefficient in Appendices 1–3 is from 0.03 (i.e. 0.01×3) to 2.0 (i.e., 0.5×4) day^{-1} (base e).

The bottom deposit uptake of the stream under the stated environmental conditions is significant, and ranges from 0.1 to 1.0 mg/L-day [14]. Let $B = 0.5$ mg/L-day, $\alpha = 0$, $L_O = 10$ mg/L, $D_O = 3$ mg/L, $K_1 = 0.345$ day^{-1} (base e), $N_O = 1$ mg/L, $K_n = 0.345$ day^{-1} (base e), $K_2 = 0.5$, 1.5, and 10 day^{-1} (base e), and substitute these values into Eqs. 8.15, and 8.19–8.22. The sensitivities and the dissolved oxygen deficits at various flow times (t) are determined and illustrated in Fig. 8.5.

From Fig. 8.5, one can understand that the sensitivities of $S_{D,Kn}$ and $S_{D,B}$ are very small in comparison with the sensitivities of $S_{D,K1}$ and $S_{D,K2}$ when K_2 is 5 day^{-1}. The sensitivities of $S_{D,K2}$, $S_{D,Kn}$ and $S_{D,B}$ a11 approach to zero when K_2 is as high as 10 day^{-1}. All sensitivities rapidly decline when K_2 increases. The dissolved oxygen deficits due to nitrification (D_N) and bottom deposit uptake (D_B) are relatively small, under the conditions of high K_2 value, but the latter (D_B) is significant when K_2 value is as low as 0.5 day^{-1}.

3.2.3 Heavily Polluted Intermediate Non-tidal Streams

The point sources of pollution which discharge into this type of stream are mostly untreated wastes. The deoxygenation coefficient (K_1) is higher than 0.5 day^{-1} (base e). The concentration of dissolved oxygen of the stream water is usually very low, the initial concentration of dissolved oxygen deficit (D_O) ranges from 3 to 8 mg/L. There are sludge blankets in the slow water segment of the stream. The range of bottom deposit uptake rate (B) is about 0.1 to 1.5 mg/L-day. Since the stream is heavily polluted, the bacteria cannot compete with the saprophyta, therefore, the nitrification can be neglected. Let $L_O = 20$ mg/L, $D_O = 5$ mg/L,

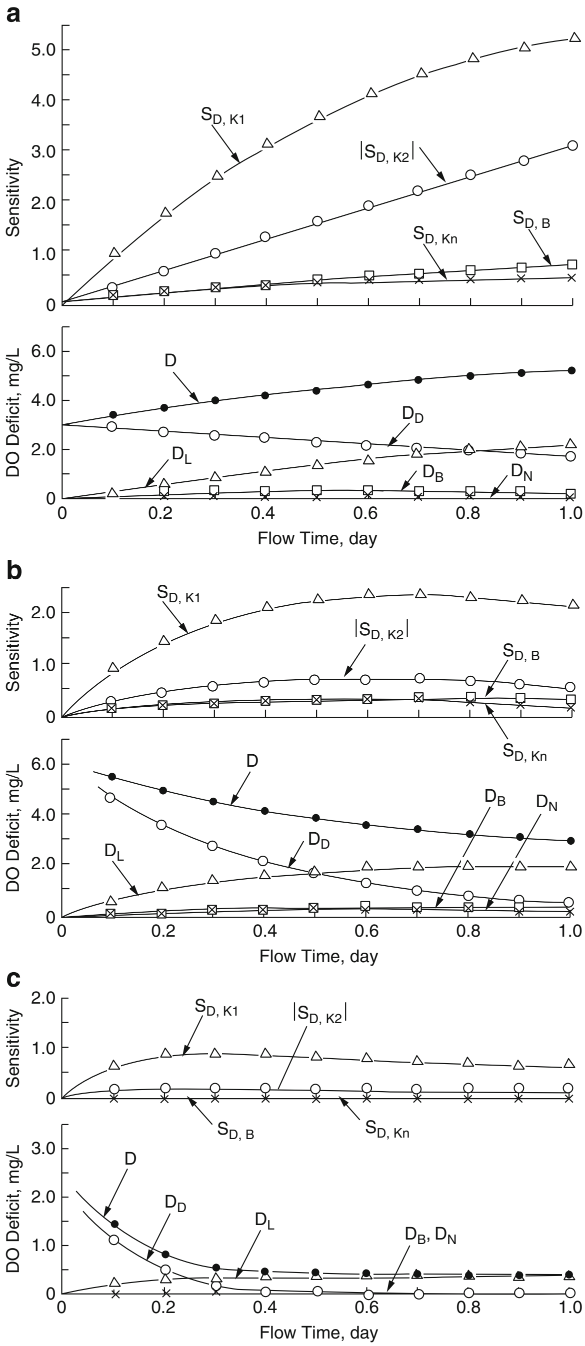

Fig. 8.5 (**a**) The sensitivities and dissolved oxygen deficits for moderately polluted intermediate non-tidal stream ($K_2 = 0.5$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for moderately polluted intermediate non-tidal stream ($K_2 = 2.5$ 1/day). (**c**) The sensitivities and dissolved oxygen deficits for moderately polluted intermediate non-tidal stream ($K_2 = 10$ 1/day)

$B = 1$ mg/L-day, $\alpha = 0$, $K_1 = 1.0$ day^{-1} (base e), $K_n = N_O = 0$, and $K_2 = 0.5$, 2.5 and 10 day^{-1} (base e). The calculated sensitivities and the dissolved oxygen deficits at various times (t) are illustrated in Fig. 8.6. The sensitivities at $K_2 = 0.5$ day^{-1} are not shown in Fig. 8.6 because of the low values. The stream water is in an anaerobic condition, and the existing models cannot be properly applied.

From Fig. 8.6, it can be understood that the $S_{D,K1}$ larger than $|S_{D,K2}|$, and $|S_{D,K2}|$ is larger than $S_{D,B}$. All sensitivities' decline when K_2 increases. The dissolved oxygen deficit due to bottom deposit uptake (D_B) is very low.

In summation, for the intermediate non-tidal streams, the sensitivity term of $S_{D,K1}$ is the most sensitive, $|S_{D,K2}|$ is next, $S_{D,B}$ and $S_{D,N}$ are relatively insensitive. The major sources or sinks of dissolved oxygen deficit are deoxygenation and initial dissolved oxygen deficit. The percentage of dissolved oxygen deficit due to bottom deposit uptake (D_B) and nitrification (D_N) is usually small. Therefore, the stream parameters of K_1 and K_2 are important for stream pollution control. B and K_n, however, are not significant.

3.3 Slow Non-tidal Streams

The mean velocities of slow non-tidal streams are generally under 0.1 m/s. For this kind of stream, the depth is deep, the reaeration coefficient (K_2) is very low ranging from 0.05 to 0.6 day^{-1} (base e). The sensitivities of this kind of stream are discussed in three pollutional conditions.

3.3.1 Clean or Slightly Polluted Slow Non-tidal Streams

When stream water is clean or slightly polluted, its nitrification can be neglected. The bottom deposit uptake and photosynthesis reactions do exist, but are very insignificant. Let $L_O = 3$ mg/L, $D_O = 1$ mg/L, $K_1 = 0.15$ day^{-1} (base e), $K_n = N_O = 0$, $B = 0.2$ mg/L-day, $\alpha = 0.4$ mg/L-day, and $K_2 = 0.2$ and 0.6 day^{-1} (base e). By substituting these values into Eqs. 8.15, and 8.19–8.22, one can determine the sensitivities and dissolved oxygen deficits at various flow times (t) and graphically illustrate the results in Fig. 8.7. From the figure, one can conclude that the $S_{D,K1}$ is the most sensitive, and $|S_{D,K2}|$ and $S_{D,B}$ (or $|S_{D,\alpha}|$) very sensitive too. The dissolved oxygen deficits due to combined action of bottom deposit uptake and photosynthesis ($D_B + D_\alpha$) are very significant, especially when K_2 value is low. Therefore, the photosynthesis and the bottom deposit uptake play an important role for clean or slightly polluted slow non-tidal streams.

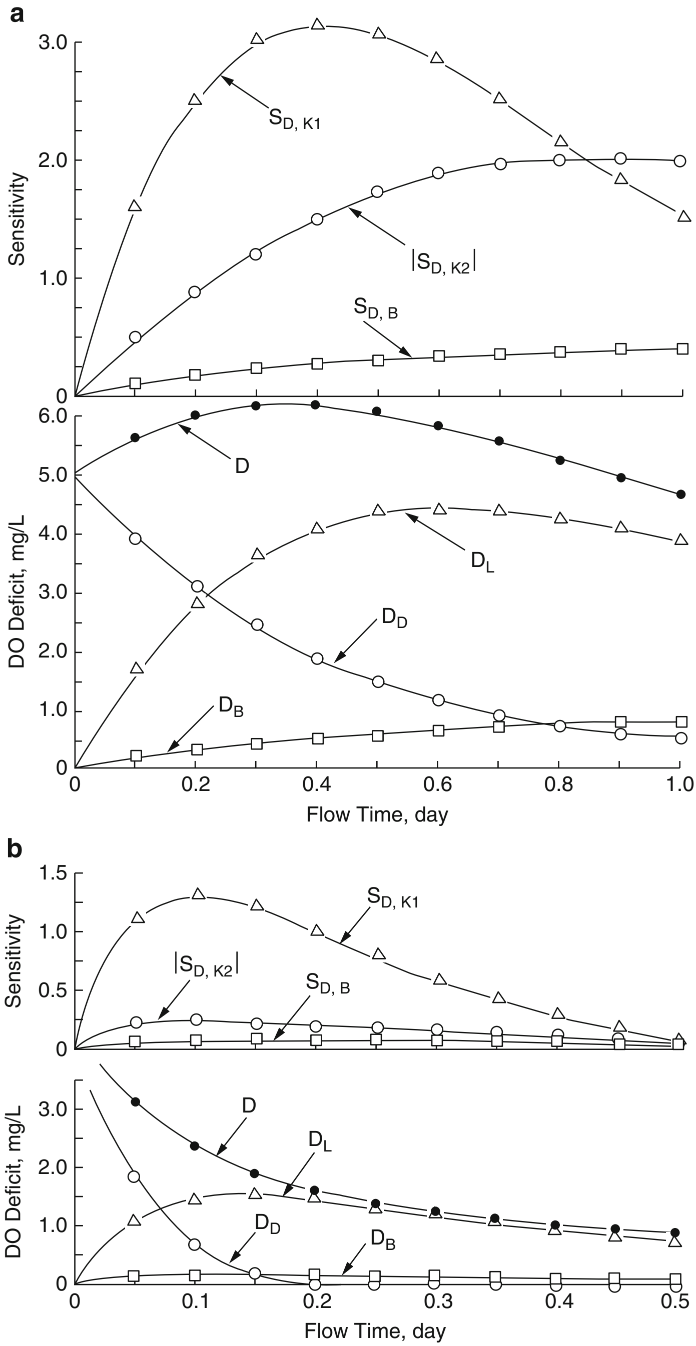

Fig. 8.6 (**a**) The sensitivities and dissolved oxygen deficits for heavily polluted intermediate non-tidal stream ($K_2 = 0.5$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for heavily polluted intermediate non-tidal stream ($K_2 = 2.5$ 1/day)

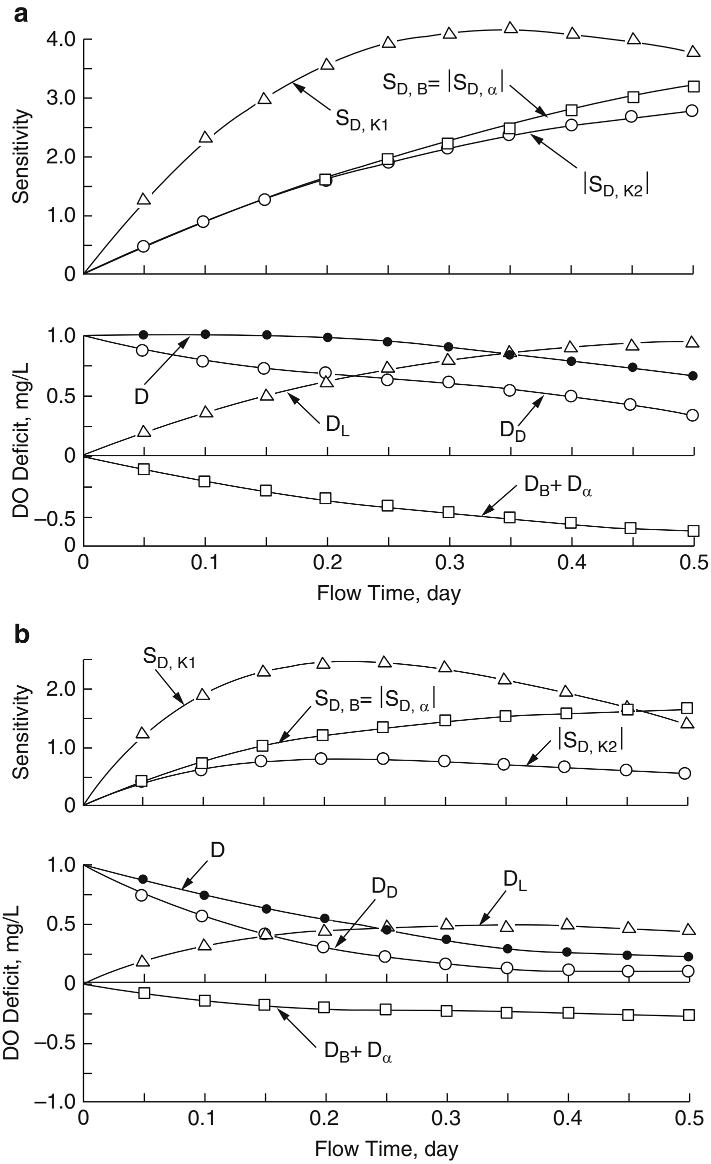

Fig. 8.7 (**a**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted slow non-tidal stream ($K_2 = 0.2$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted slow non-tidal stream ($K_2 = 0.6$ 1/day)

3.3.2 Moderately Polluted Slow Non-tidal Streams

Nitrification may or may not exist in a moderately polluted non-tidal stream. If nitrification occurs, the range of nitrification coefficient K_n is from 0.03 to

2.0 day^{-1} (base e). The bottom deposit uptake and photosynthesis are significant. Usually the bottom deposit uptake rate (B) ranges from 0.2 to 2 mg/L-day, and the photosynthesis rate ranges from 0.1 to 2.0 mg/L-day. Assuming $L_O = 10$ mg/L, $D_O = 3$ mg/L, $K_1 = 0.345$ day^{-1}, $K_n = 0.345$ day^{-1}, $K_2 = 0.2$ and 0.6 day^{-1} (base e), $\alpha = 2$ mg/L-day, $N_O = 1$ mg/L, and $B = 1$ mg/L-day, one can determine all sensitivities and dissolved oxygen deficit concentrations with Eqs. 8.15, and 8.19–8.22. Figure 8.8 illustrates the calculated results. From Fig. 8.8, one can see that the sensitivities of $S_{D,K1}$ and $|S_{D,K2}|$ are very high, whereas the $S_{D,Kn}$ and $S_{D,B}$ (or $|S_{D,\alpha}|$) are comparatively low. The dissolved oxygen deficit due to the combined effects of bottom deposit uptake and photosynthesis ($D_B + D_\alpha$) is significant, but that due to nitrification (D_N) is relative insignificant. The bottom deposit uptake and photosynthesis cannot be omitted in this type of streams.

3.3.3 Heavily Polluted Slow Non-tidal Streams

When a slow non-tidal stream is heavily polluted, K_1 is very high, which ranges from 0.5 to 5 day^{-1}, but the reaeration coefficient (K_2) is very low due to slow stream velocity. The dissolved oxygen is close to zero for the most part of the stream reach; therefore, the water quality models are difficult to be applied. The authors make no attempt to analyze the sensitivity at present. More research in this area is needed.

Section 4 starting below, presents only the significance of sensitivity analysis for three types of tidal streams. Important water quality models, nomenclature and references are also included in this Part.

4 Significance of Sensitivities for Tidal Streams

For tidal streams, the velocity is very slow and the water depth is relatively deep; therefore, the reaeration coefficient is smaller than that of non-tidal streams, thus K_2 ranges from 0.1 to 1.0 day^{-1} generally. Since the stream velocity is very low, suspended sludges are settled in the stream bed, and the algae blooms are dominant in the water. Therefore, bottom deposit uptake, and photosynthesis always occur in tidal streams. In addition, nitrification always occurs in tidal streams. The dispersion coefficient (E) ranges from 1 to 60 km^2/day. The sensitivities of water quality model for tidal streams should be controlled mainly according to the pollution loading, but not according to the stream velocity, because the range of velocity of tidal streams is narrow.

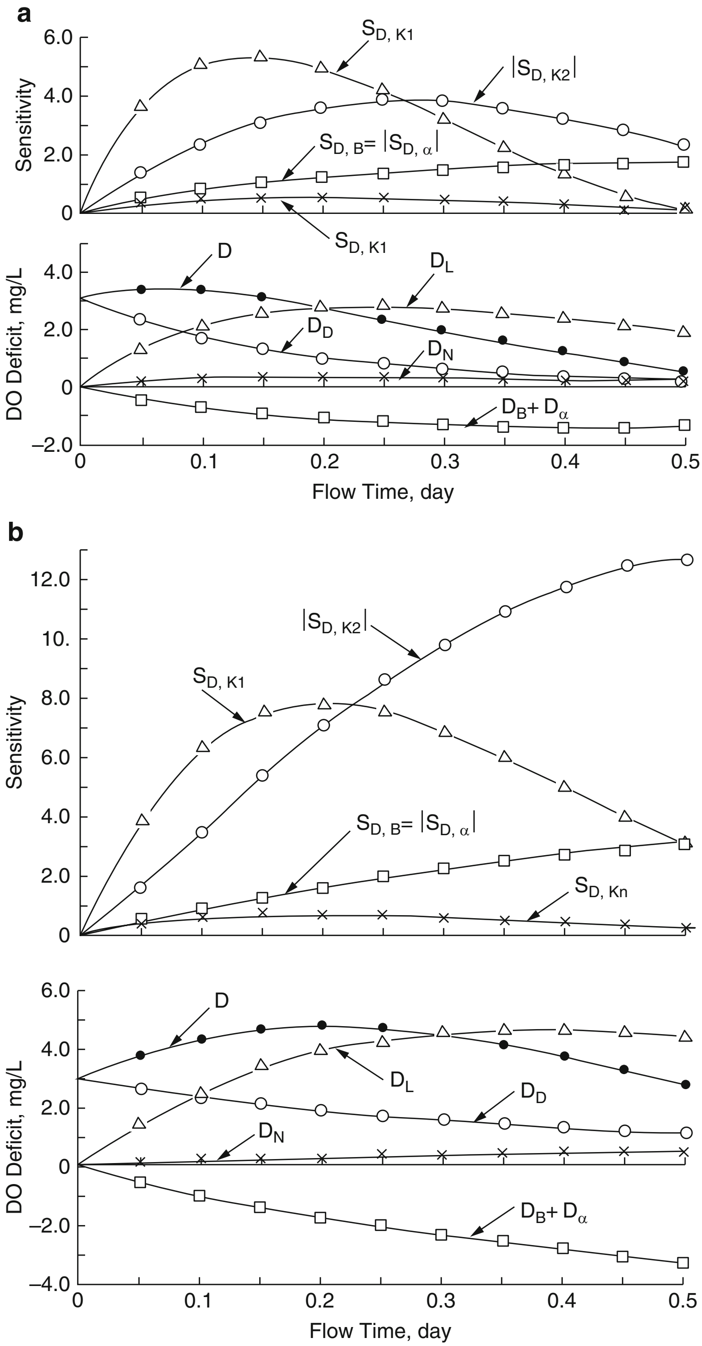

Fig. 8.8 (**a**) The sensitivities and dissolved oxygen deficits for moderately polluted slow non-tidal stream ($K_2 = 0.2$ 1/day). (**b**) The sensitivities and dissolved oxygen deficits for moderately polluted slow non-tidal stream ($K_2 = 0.6$ 1/day)

4.1 Clean or Slightly Polluted Tidal Streams

It is reasonable to assume the following figures for the major water quality parameters of clean or slightly polluted tidal streams: $L_O = 3$ mg/L, $D_O = 1$ mg/L, $K_1 = 0.15$ day^{-1} (base e), $K_n = N_O = B = 0$, $\alpha = 0.1$ mg/L-day, $K_2 = 0.4$ to 0.8 day^{-1} (base e), and U (Mean velocity of fresh water) = 0.5 km/day. Two values each are assigned for K_2 and U for the purpose of illustration. By substituting these values into Eqs. 8.17 and 8.25–8.29, one can determine the sensitivities and dissolved oxygen deficit and illustrate the results in Fig. 8.9. From the figure, we can see that $S_{D,K1,t}$ and $S_{D,K2,t}$ are extremely sensitive, $S_{D,\alpha,t}$ is moderately sensitive, and $S_{D,E,t}$ is relatively insensitive. All sensitivities increase in absolute values when freshwater velocity (U) increases, and rapidly decrease when K_2 increases. $S_{D,K1,t}$ is more sensitive than $S_{D,K2,t}$ when K_2 value is low, but is less sensitive than $S_{D,K2,t}$ when the K_2 value is high. The dissolved oxygen deficit is mainly contributed by initial DO deficit (D_D), deoxygenation (D_L), and combined action of photosynthesis and bottom deposit uptake (D_B and D_α). Therefore, the photosynthesis and deposit uptake cannot be neglected.

4.2 Moderately Polluted Tidal Streams

When sea water intrudes into a tidal stream, the concentration of remaining CBOD and initial dissolved oxygen deficit (D_O) are lower than that of a non-tidal stream for the same pollution loading. Let $L_O = 8$ mg/L, $D_O = 3$ mg/L, $K_1 = K_n = 0.345$ day^{-1} (base e), $B = 1$ mg/L-day, $\alpha = 2$ mg/L-day, $E = 10$ km^2/day, $N_O = 1$ mg/L, $K_2 = 0.4$ and 0.8 day^{-1} (base e), and $U = 0.5$ and 5 km/day. Substituting those values into Eqs. 8.17, and 8.25–8.29, one can obtain the sensitivities and dissolved oxygen deficits at various distances. All calculated results are presented in Fig. 8.10. Dissolved oxygen deficit declines to zero after 8 km from the river mouth at $U = 0.5$ km/day, thus the water quality models cannot be applied, and the sensitivities need not to be analyzed under this condition. $S_{D,K2,t}$ is extremely sensitive, while $S_{D,Kn,t}$ is very insensitive. The dissolved oxygen deficit associated with the nitrification (D_N) is also insignificant, thus the nitrification can be neglected. The sensitivity terms $S_{D,B,t}$ and ($|S_{D,\alpha,t}|$), are low when compared with $S_{D,K1,t}$. The dissolved oxygen deficit associated with the net action of photosynthesis and bottom deposit uptake ($D_\alpha + D_B$) is significant, thus the photosynthesis and bottom deposit uptake must be analyzed carefully for stream water quality control. Another sensitivity term, $S_{D,E,t}$ is in the same magnitude of $S_{D,K1,t}$; thus the longitudinal dispersion coefficient should not Be overlooked.

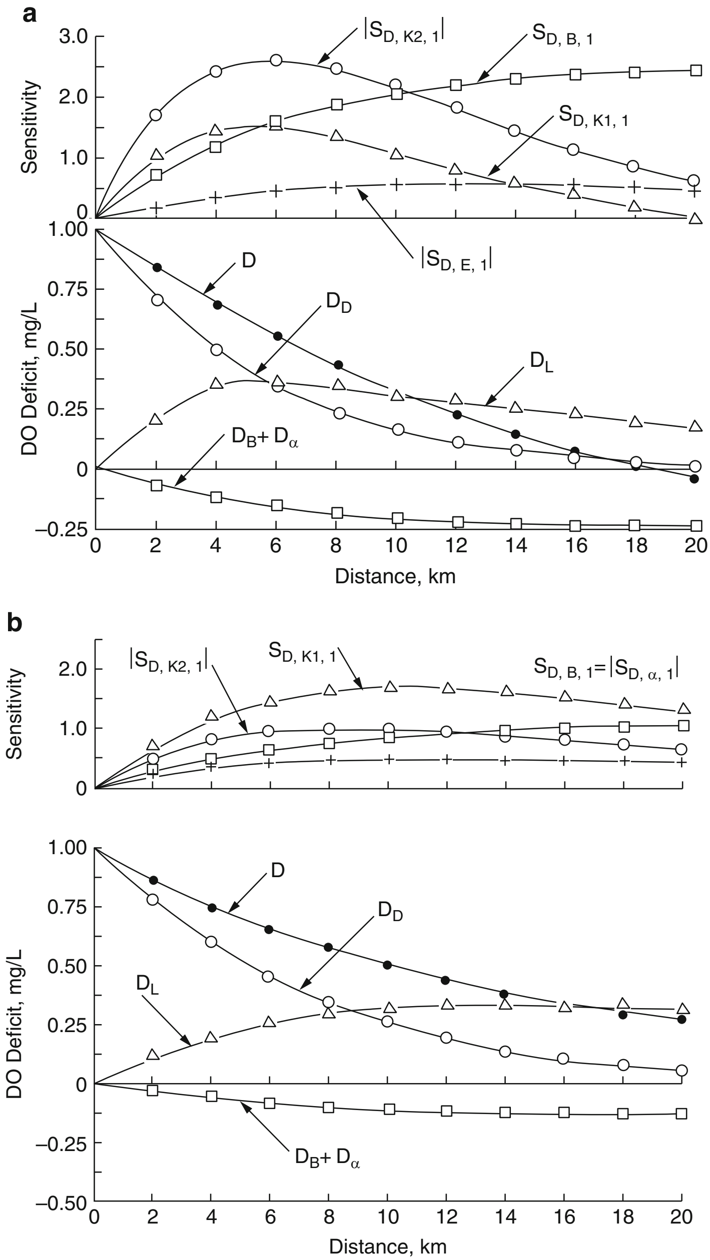

Fig. 8.9 (**a**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted tidal stream ($K_2 = 0.4$ 1/day and $U = 0$ km/day). (**b**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted tidal stream ($K_2 = 0.8$ 1/day and $U = 5$ km/day). (**c**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted tidal stream ($K_2 = 0.8$ 1/day and $U = 0.5$ km/day). (**d**) The sensitivities and dissolved oxygen deficits for clean or slightly polluted tidal stream ($K_2 = 0.4$ 1/day and $U = 5$ km/day)

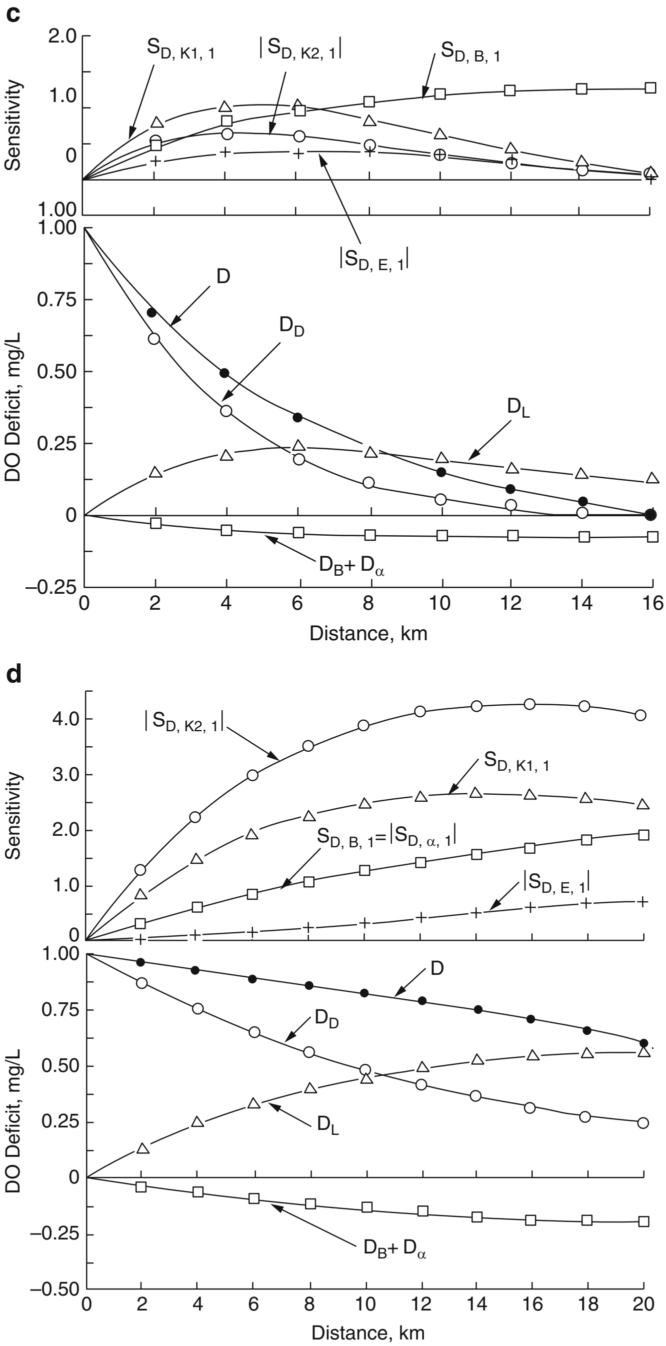

Fig. 8.9 (continued)

4.3 Heavily-Polluted Tidal Streams

The following water quality may be considered for heavily polluted tidal streams: $L_O = 15$ mg/L, $D_O = 5$ mg/L, $B = 3$ mg/L-day, $\alpha = 1$ mg/L-day, $K_1 = 1.0$ day^{-1} (base e), $K_2 = 0.4$ to 0.8 day^{-1} (base e), $K_n = 0$ day^{-1}, $N_O = 0$ mg/L, and $E = 10$ km^2/day. Choosing two K_2 values, 0.4 and 0.8 day^{-1}, and two U values, 0.5 and 5 km/day, and then substituting these values and L_O, D_O, B, α, K_1, K_n, N_O, and E values into Eqs. 8.17 and 8.25–8.29. The calculated sensitivities and

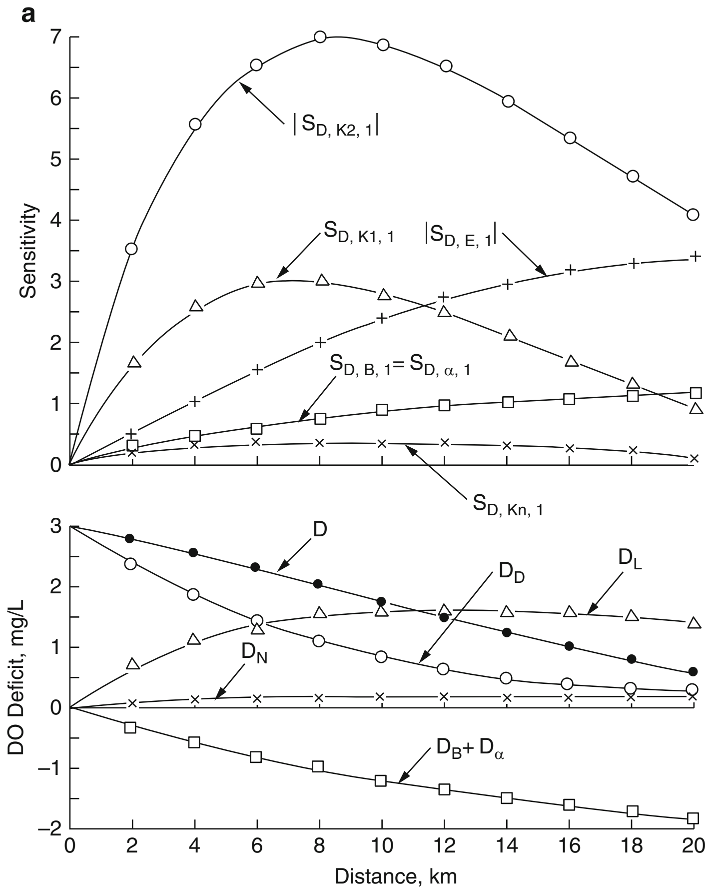

Fig. 8.10 (**a**) The sensitivities and dissolved oxygen deficits for moderately polluted tidal stream ($K_2 = 0.8$ 1/day and U = 5 km/day). (**b**) The sensitivities and dissolved oxygen deficits for moderately polluted tidal stream ($K_2 = 0.4$ 1/day and U = 5 km/day). (**c**) The sensitivities and dissolved oxygen deficits for moderately polluted tidal stream ($K_2 = 0.8$ 1/day and U = 0.5 km/day). (**d**) The sensitivities and dissolved oxygen deficits for moderately polluted tidal stream ($K_2 = 0.4$ 1/day and U = 0.5 km/day)

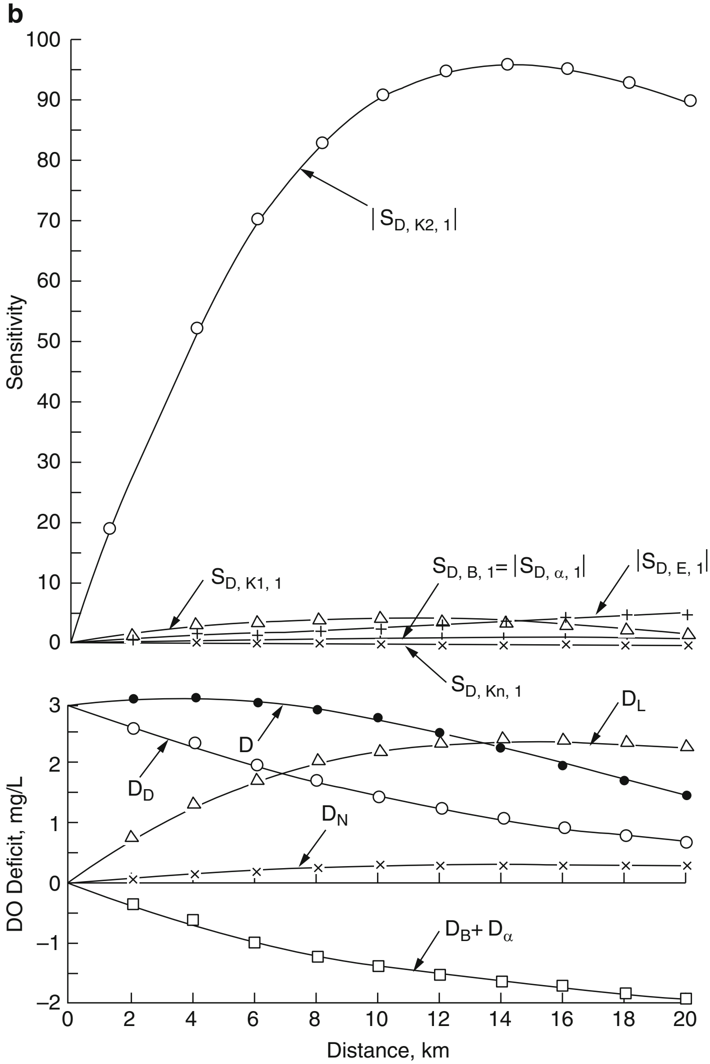

Fig. 8.10 (continued)

dissolved oxygen deficits are partially illustrated in Fig. 8.11. It should be noted that the sensitivities at $K_2 = 0.4\ \text{day}^{-1}$ are not shown in the figure. This is due to the fact that the total dissolved oxygen deficit at various X values is so high that the dissolved oxygen reduces to almost zero; in turn, the water quality models cannot be employed. It can also be seen that the sensitivity term $S_{D,K2,t}$ is extremely high,

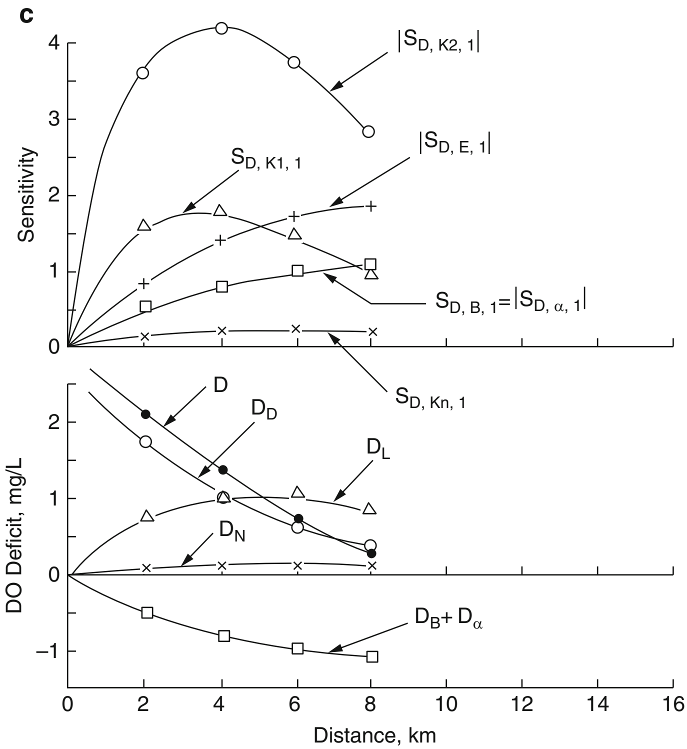

Fig. 8.10 (continued)

and $S_{D,E,t}$ is comparatively sensitive than $S_{D,K1,t}$ and $S_{D,B,t}$ (or $|S_{D,\alpha,t}|$). The dissolved oxygen deficit associated with photosynthesis and bottom deposit deficit $(D_\alpha + D_B)$ is significant, thus cannot be overlooked.

5 Discussions and Recommendation

This research divides the non-tidal streams into nine categories, and divides the tidal streams into three categories as follows, and presents the average hydraulic and water quality characteristics of each stream category:

Non-tidal Receiving Streams:

a. clean or slightly polluted swift non-tidal streams
b. moderately polluted swift non-tidal streams
c. heavily polluted swift non-tidal streams
d. clean or slightly polluted intermediate non-tidal streams
e. moderately polluted intermediate non-tidal streams

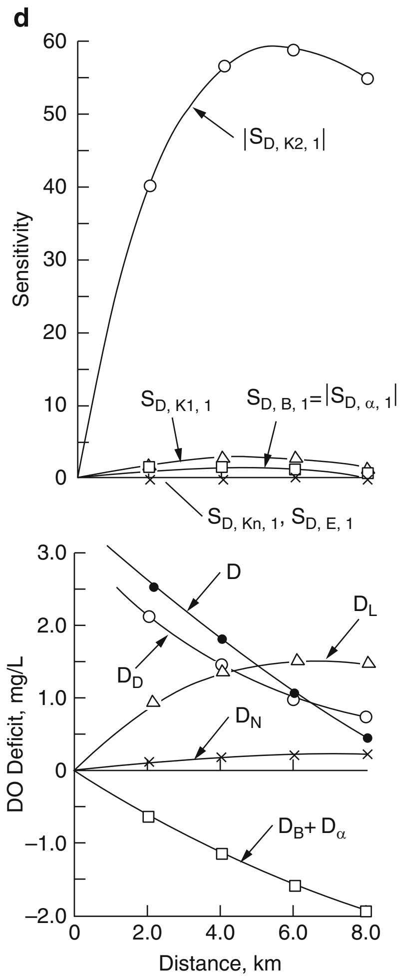

Fig. 8.10 (continued)

f. heavily polluted intermediate non-tidal streams
g. clean or slightly polluted slow non-tidal streams
h. moderately polluted slow non-tidal streams
i. heavily polluted slow non-tidal streams

Tidal Receiving Streams:

a. clean or slightly polluted tidal streams
b. moderately polluted tidal streams
c. heavily polluted tidal streams

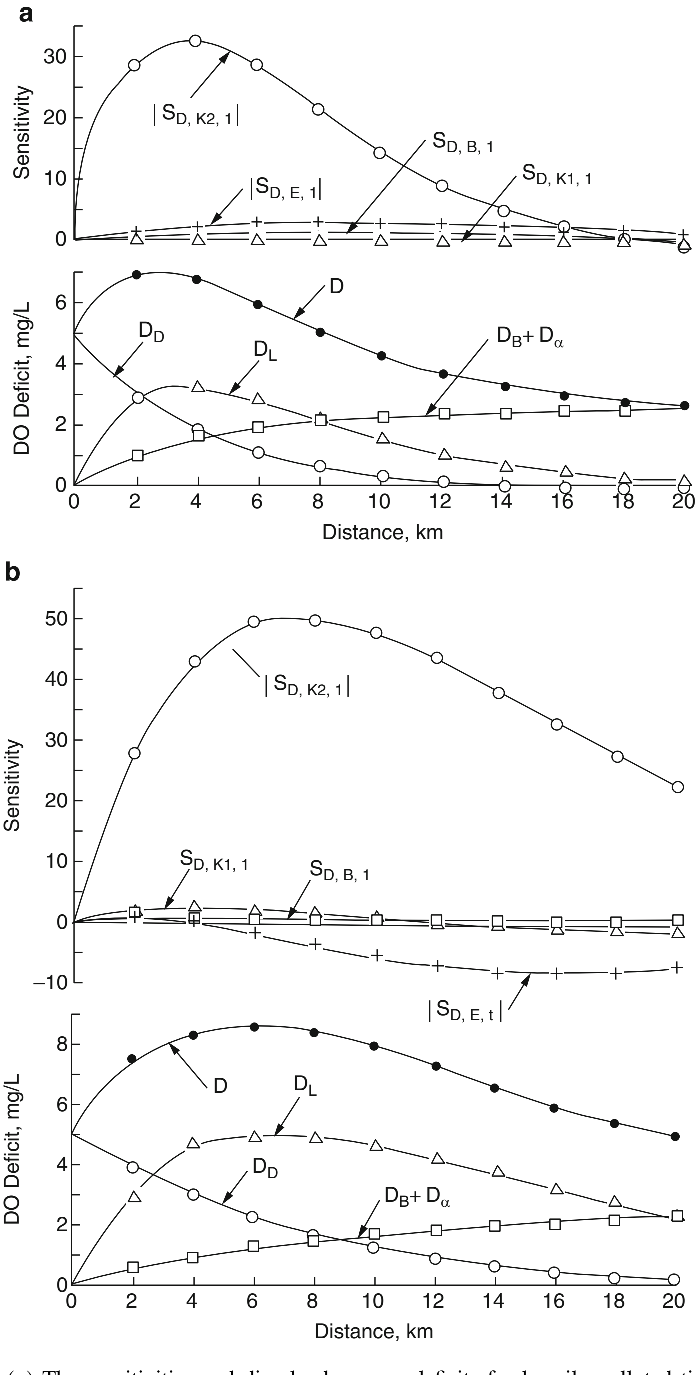

Fig. 8.11 (**a**) The sensitivities and dissolved oxygen deficits for heavily polluted tidal stream ($K_2 = 0.8$ 1/day and $U = 5$ km/day). (**b**) The sensitivities and dissolved oxygen deficits for heavily polluted tidal stream ($K_2 = 0.8$ 1/day and $U = 5$ km/day)

The sensitivity analysis can be a very useful scientific tool for stream water quality management. The results of this research identify the significance of water quality sensitivities and dissolved oxygen deficits systematically and graphically for each stream category. Knowing the category or type of a target stream (tidal or non-tidal; swift, intermediate or slow stream velocity; clean, moderately polluted, or heavily polluted), an environmental water resources engineer can determine/understand the sensitivity of each water quality/quantity parameter, and in turn, can better manage his/her stream pollution control projects.

Sensitivity analyses have been used by environmental water resources engineers extensively in recent years for environmental risk and decision analysis [18–21], ecological investigations [22–25], aquaculture site selection [26] and waterway management [27]. Its other applications may be further explored.

Further research in the area of sensitivity analysis of tidal streams may consider the effect of salinity because the salinity affects the reaeration coefficient [15–17, 28–30], in accordance with the following NCKU (National Cheng Kung University) equations.

$$K_{2s} = K_{2f} \exp\left(0.0127\ \text{Chlorinity}\right) \tag{8.11}$$

$$K_{2s} = K_{2f} \exp\left(0.0000127\ \text{Chloride}\right) \tag{8.12}$$

$$K_{2s} = K_{2f} \exp\left(0.007\ \text{Salinity}\right) \tag{8.13}$$

where

K_{2s} = reaeration coefficient of saline water, day^{-1}
K_{2f} = reaeration coefficient of fresh water, day^{-1}
Chlorinity = chlorinity of receiving water, g/L
Chloride = chloride concentration of receiving water, mg/L
Salinity = salinity of receiving water, ‰, or ppt, or parts per thousand

Glossary [31–35]

Ammonia nitrogen A common way to report ammonia concentration (expressed as ammonia-nitrogen).

Ammonification A process of formation of ammonia nitrogen from reduced organic nitrogen compounds.

Biological oxidation A process by which living organisms in the presence of oxygen convert organic matter into a more stable or a mineral form.

Carbonaceous Containing carbon and derived from organic substances such as coal, coconut shells, and organic waste.

Denitrification A biochemical process of conversion of nitrite nitrogen and nitrate nitrogen to molecular nitrogen, nitrogen dioxide, or a mixture of these two gases, under reducing conditions in the absence of free dissolved oxygen.

Deoxygenation It is a process for depletion of the dissolved oxygen in a liquid either under natural conditions associated with the biochemical oxidation of organic matter present or by addition of chemical reducing agents.

Deposit Material left in a new position by a transporting agent such as earth quake, gravity, human activity, ice, water current, or wind.

Dissolved gases The sum of gaseous components, such as oxygen, nitrogen, carbon dioxide, methane, hydrogen sulfide, etc. that are dissolved in water.

Dissolved oxygen (DO) The concentration of oxygen dissolved in water, which is often expressed in units of mg/L.

Dissolved oxygen deficit (D) The difference between the dissolved oxygen saturation concentration (C_s) and actual dissolved oxygen concentration at time t (Q) in a receiving water (such as river) at some downstream distance away from the point of waste discharge ($D = C_s - C$). See dissolved oxygen deficit and dissolved sag curve.

Dissolved oxygen sag curve (DO sage curve) A stream water quality curve that represents the profile of dissolved oxygen concentration along the course of a stream resulting from deoxygenation associated with biochemical oxidation of organic matter and reoxygenation through the absorption of atmospheric oxygen and biological photosynthesis. Also called oxygen sag curve.

Dissolved oxygen saturation concentration (C_s) The maximum concentration (mg/L) of dissolved oxygen in water under specific water temperature, pressure and salinity.

Dissolved solids The constituents in water that can pass through a 0.45-μm pore-diameter filter.

Initial dissolved oxygen deficit (D_0) The difference between the dissolved oxygen saturation concentration (C_s) and actual dissolved oxygen concentration (C) in a receiving water (river or lake) at the point of waste discharge ($D_0 = C_s - C$). See dissolved oxygen deficit.

NCKU (National Cheng Kung University) equations They are reaeration coefficient equations developed by National Cheng Kung University, Taiwan, showing the effect of salinity on receiving water's reaeration coefficient. The NCKU equations are modeled by $K_{2s} = K_{2f}$ exp (0.0127 Chlorinity); $K_{2s} = K_{2f}$ exp (0.0000127 Chloride); and $K_{2s} = K_{2f}$ exp (0.007 Salinity); in which K_{2s} = reaeration coefficient of saline water, day^{-1}; K_{2f} = reaeration coefficient of fresh water, day^{-1}; Chlorinity = chlorinity of receiving water, g/L; Chloride = chloride concentration of receiving water, mg/L; and Salinity = salinity of receiving water, ‰, or ppt, or parts per thousand.

Nitrate nitrogen A common way to report nitrate concentration (expressed as nitrogen).

Nitrification A process of formation of nitrate nitrogen from reduced inorganic nitrogen compounds, such as ammonia nitrogen. Nitrification in the natural environment is carried out primarily by autotrophic bacteria.

Nitrite nitrogen A common way to report nitrite concentration (expressed as nitrogen).

Non-tidal stream/river A stream/river which water level and flow direction will not fluctuate and will not be affected by the action of lunar and solar forces upon the rotating earth.

Oxygen-sag curve See dissolved oxygen sag curve.

Photosynthesis The conversion of light energy to chemical energy. At night, this process reverses: plants and algae suck oxygen out of the water.

Reaeration (a) The physical chemical reaction by which oxygen is absorbed back into water, (b) An aeration process by which oxygen in air is absorbed back into natural water, such as stream water and lake water, (c) A natural process of oxygen exchange between the atmosphere and a natural water body in contact with the atmosphere. Typically, the net transfer of oxygen is from the atmosphere and into the water, since dissolved oxygen levels in most natural waters are below saturation. When photosynthesis produces supersaturated dissolved oxygen levels, however, the net transfer is back into the atmosphere, (d) Reaeration process is modeled as the product of reaeration coefficient multiplied by the difference between dissolved oxygen saturation and the actual dissolved oxygen concentration, that is: $F_c = K_2\ (C_s - C) = (K_L/H)\ (C_s - C)$. Here F_c = rate or flux of dissolved oxygen across the water body. $M/L^3/T$; C = dissolved oxygen concentration, M/L^3, C_s = saturation dissolved oxygen concentration, M/L^3, K_2 = reaeration coefficient, $1/T$, H = water depth, L, K_L = surface transfer coefficient, L/T.

Reaeration coefficient A mass transfer coefficient (K_2) in reaeration process. See reaeration and mass transfer coefficient.

Reaeration rate (a) The rate at which oxygen is absorbed back into water. This is dependent, among other things, upon turbulence intensity, temperature, and the water depth, (b) The reaeration rate is defined as the rate of dissolved oxygen across the water body $F_c = K_2\ (C_s - C)$. Here F_c = rate or flux of dissolved oxygen across the water body, $M/L^3/T$; C = dissolved oxygen concentration, M/L^3; C_s = saturation dissolved oxygen concentration, M/L^3; K_2 = reaeration coefficient, $1/T$.

Reaeration rate coefficient See reaeration coefficient.

Receiving waters (a) A river, lake, ocean, stream, or other bodies of water into which wastewater or treated effluent is discharged; (b) A distinct water body that receives run off, or wastewater discharges, such as streams, rivers, lakes, estuaries and oceans.

Saline water intrusion The movement of saline groundwater into a formerly freshwater aquifer as a result of pumping in that aquifer usually near coastal areas where the source of saline water is the nearby ocean.

Sensitivity (a) In analytical testing, the lowest practical detection level; (b) In microbiological testing, the likelihood that the test result will be positive when the target organism is present, (c) In water resources engineering, the smallest changes of certain physical parameters that will affect hydraulic or hydrological model's solutions.

Sensitivity analysis (a) A mathematical analysis of the sensitivity of the dependent variable in a mathematical expression as a function of variations in the value of any independent variables or coefficients associated with the independent variables, (b) A mathematical analysis which determines how much the value of Y is affected by changes in the values of a and b.

Tidal Pertaining to periodic water level fluctuations due to the action of lunar (moon) and solar (sun) forces upon the rotating Earth.

Tidal current A water current brought about or caused by tidal forces.

Tidal stream/river A stream/river which is affected by tidal current and its water level and flow direction fluctuate due to the action of lunar and solar forces upon the rotating Earth.

Appendix 1: Water Quality Models

For Non-tidal Streams

1. Biochemical Oxygen Demand (L) Model

$$L = L_O[\exp(-K_1 t)] \tag{8.14}$$

2. Dissolved Oxygen Deficit (D) Model

$$\begin{aligned} D = {} & K_1 L_O (K_2 - K_1)^{-1}[\exp(-K_1 t) - \exp(-K_2 t)] \\ & + K_n N_O (K_2 - K_n)^{-1}[\exp(-K_n t) - \exp(-K_2 t)] \\ & + (B - \alpha)(K_2)^{-1}[1 - \exp(-K_2 t)] + D_O \exp(-K_2 t) \end{aligned} \tag{8.15}$$

For Tidal Streams

1. Biochemical Oxygen Demand (L) Model

$$L = L_O[\exp(J_1 X)] \tag{8.16}$$

2. Dissolved Oxygen Deficit (D) Model

$$D = K_1L_O(K_2 - K_1)^{-1}[\exp\ (J_1X) - \exp\ (J_2X)] \\ +K_nN_O(K_2 - K_n)^{-1}[\exp\ (J_nX) - \exp\ (J_2X)] \\ +(B - \alpha)\ K_2{}^{-1}[1 - \exp\ (J_2X)\ ] + D_o\exp\ (J_2X) \tag{8.17}$$

Appendix 2: Sensitivity Formulas for Non-tidal Streams

1. The sensitivity of L to K_1:

$$S_{L,\ K1} = -L_Ot[\exp(-K_1t)] \tag{8.18}$$

2. The sensitivity of D to K_1:

$$S_{D,\ K1} = K_2L_o(K_2 - K_1)^{-2}[\exp(-K_1t) - \exp(-K_2t)\ ] \\ - K_1L_Ot(K_2 - K_1)^{-1}\exp(-K_1t) \tag{8.19}$$

3. The sensitivity of D to K_n:

$$S_{D,\ Kn} = K_2N_O(K_2 - K_n)^{-2}[\exp(-K_nt)\ -\ \exp(-K_2t)] \\ - K_nN_Ot(K_2 - K_n)^{-1}\exp(-K_nt) \tag{8.20}$$

4. The sensitivities of D to α and B:

$$S_{D,\ B} = -S_{D,\alpha} = (K_2)^{-1}[1\ -\ \exp(-K_2t)] \tag{8.21}$$

5. The sensitivity of D to K_2:

$$\begin{aligned} S_{D,\ K2} = \ & - K_1L_O(K_2 -\ K_1)^{-2}\left[\exp\left(-K_1t\right)\ -\ \exp(-K_2t)\right] \\ & +\ K_1L_Ot(K_2 -\ K_1)^{-1}\exp(-K_2t) \\ & - K_nN_O(K_2 -\ K_n)^{-2}\left[\exp\left(-K_nt\right)\ -\ \exp(-K_2t)\right] \\ & +\ K_nN_Ot(K_2 -\ K_n)^{-1}\exp(-K_2t) \\ & +\ (\alpha -\ B)(K_2)^{-2}\left[1\ -\ e_X\,p\left(-K_2t\right)\right] \\ & -\ (\alpha/K_2 -\ B/K_2 +\ D_O)\ t\ \left[\exp\left(-K_2t\right)\right] \end{aligned} \tag{8.22}$$

6. The sensitivity of DO to K:

$$S_{C,\ K} = -S_{D,\ K} \tag{8.23}$$

Appendix 3: Sensitivity Formulas for Tidal Streams

1. The sensitivity of L to K_1:

$$S_{L,\ Kl,\ t} = -L_O m_1 X[\exp(J_1X)] \tag{8.24}$$

2. The sensitivity of D to K_1:

$$\begin{aligned} S_{D,\ Kl,\ t} = {} & K_2Lo(K_2 - K_1)^{-2}[\exp(J_1X) - \exp(J_2X)] \\ & - K_1m_1XL_O(K_2 - K_1)^{-1}\exp(J_1X) \end{aligned} \tag{8.25}$$

3. The sensitivity of D to K_n:

$$\begin{aligned} S_{D,\ Kn,\ t} = {} & K_2N_O(K_2 - K_1)^{-2}[\exp(J_nX) - \exp(J_2X)] \\ & - K_nN_Ot(K_2 - K_n)^{-1}\exp(-K_nt) \end{aligned} \tag{8.26}$$

4. The sensitivities of D to α and B:

$$S_{D,\ B,\ t} = -S_{D,\alpha,\ t} = (K_2)^{-1}[1 - \exp(J_2X)] \tag{8.27}$$

5. The sensitivity of D to E:

$$\begin{aligned} S_{D,\ E,\ t} = {} & K_1L_OX(K_2 - K_1)^{-1}[n_1\exp(J_1X) - n_2\exp(J_2X)] \\ & + K_nN_OX(K_2 - K_n)^{-1}[n_n\exp(J_nX) - n_2\exp(J_2X)] \\ & + (\alpha/K_2 - B/K_2 + D_O)n_2X[\exp(J_2X)] \end{aligned} \tag{8.28}$$

6. The sensitivity of D to K_2:

$$\begin{aligned} S_{D,\ K2,\ t} = {} & -K_1L_O(K_2 - K_1)^{-2}[\exp(J_1X) - \exp(J_2X)] \\ & - K_1L_OXm_2(K_2 - K_1)^{-1}\exp(J_2X) \\ & - K_nN_O(K_2 - K_1)^{-2}[\exp(J_nX) - \exp(J_2X)] \\ & - K_nN_OXm_2(K_2 - K_n)^{-1}\exp(J_2X) \\ & + (\alpha - B)(K_2)^{-2}[1 - \exp(J_2X)] \\ & - \left[(\alpha - B)(K_2)^{-1} + D_Om_2X\exp(J_2X)\right] \end{aligned} \tag{8.29}$$

7. The sensitivity of DO to K:

$$S_{C,\ K,\ t} = S_{D,\ K,\ t} \tag{8.30}$$

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