Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

ESTIMATION OF DISSOLVED POLLUTANT TRANSPORT TO RIVERS FROM URBAN AREAS: A MODELLING APPROACH

A.H. SCHUMANN, L. KONCSOS & G.A. SCHULTZ
Institute of Hydrology, Water Resources and Environmental Techniques,
Ruhr University Bochum, 4630 Bochum, Germany

ABSTRACT With the improvement of waste water treatment facilities, point sources of pollutants have become less important than non-point sources for the water quality of many rivers. One important source of pollutants is urban areas. Routine water quality monitoring usually is insufficient to describe the dynamics of short-term variations in the water quality of rivers, which are affected by the transport of pollutants from urban areas during storms. To improve the understanding of the processes controlling the transport and transformation of pollutants, it is proposed that runoff components generated in urban areas be identified using a hydrologic model. By estimating the storm runoff from urban areas and the corresponding chemical loads, the river pollution can be estimated. This analysis is useful for demonstrating the influence of urban areas on water quality conditions and for developing strategies for improving water quality of rivers.

INTRODUCTION

Short-term variations in the water quality of rivers, originating from non-point sources of pollution, has become important to understand since point sources have been reduced by effective management technology. Effluents from non-point sources are, in many cases, limiting factors for the stability of aquatic ecosystems. One of the most important non-point sources is storm runoff from urban areas. During storm events, a most waste spills directly from the sewage system into the river. Usually, water quality data are insufficient to document the rapid changes associated with this process. Hydrological models may provide a means to enhance our understanding of the transport process by analyzing the different components of discharge in a river. Knowing these water amounts, and their origin, i.e. pollutant history, it may be possible assess the impact of chemical loads spilled into the river from different sources. The purpose of this paper is to present assessments of pollutant impacts on a river using a simple pollution model. The model was developed to compute the COD loads that are transported into the river from urban areas. There are two different types of loads originating from storm events: untreated loads which are discharged directly from the sewer into the river (flush flow) and treated loads which are discharged into the river from a sewage treatment facility. It is difficult determine the relative contribution of these components without measurements which typically are unavailable. The model presented in this paper may be useful for evaluating various processes associated with wastewater transport from urban sewage systems. The main elements of the model and an example of its practical application are presented in this paper.

MODELLING APPROACH

Rainfall-runoff model for urban areas

In contrast to hydraulic models (e.g. the well-known Stormwater Management Model), a hydrologic model describes the rainfall-runoff processes in urban areas in a more generalized form which has a lower spatial resolution. The model, derived herein, computes two runoff components: (1) untreated discharge, which flows directly from the sewer into the river, and (2) treated discharge, which will be conveyed through the sewer to the wastewater treatment facility and into the river after treatment. Each of these components has been observed to contribute flow to rivers during storms.

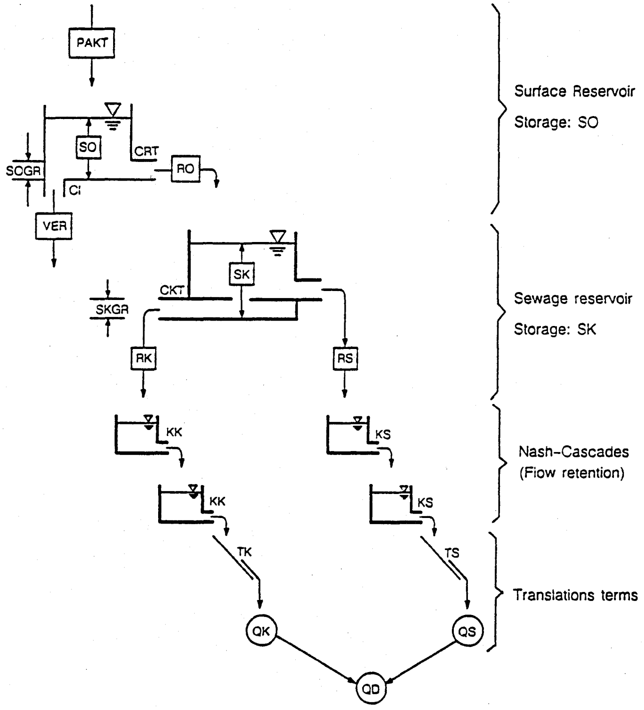


FIG. 1 Structure of the hydrological model for urban areas.

Two important effects of urbanization are incorporated in the model: (1) the impervious land surface, and (2) the drainage density, which is significantly increased by the sewage network. A schematic representation of the model is shown in Fig. 1 (Schumann, 1991). The model is divided into two reservoirs (Fig. 2), one for the land surface and the other for the sewage system.

Water transport from impervious areas, VER, is assumed to be proportional to the actual storage SO in the surface reservoir:

$$VER = CI \times SO \qquad \text{(CI: coefficient)}$$

VER quantifies the surface runoff from impervious to permeable areas and also the initial losses. The outflow of the surface reservoir into the sewer system, RO, is assumed to be proportional to the actual storage of the surface reservoir, if this storage does not exceed a limit (SOGR in Fig. 2). Otherwise, RO is assumed to be proportional to the square root of the actual storage:

$$RO = CRT \times SO \qquad \text{if } SO \leq SOGR$$

or

$$RO = CRT \times (SOGR \times SO)^{0.5} \qquad \text{if } SO > SOGR$$

This nonlinear assumption was chosen as an analogy to a hydraulic law, for which runoff in partly filled pipes is directly proportional to the water depth in the pipe, while the runoff in completely filled pipes (under pressure) is proportional to the square root of the pressure head. The same assumption with different parameters was used to describe the runoff that enters the sewage network, RK. If the actual storage of the sewage reservoir, SK, does not exceed the runoff capacity of the sewage system, SKGR, the sewage outflow into the treatment plant, RK, is directly proportional to the actual storage of the sewage reservoir:

$$RK = CKT \times SK \qquad \text{if } SK \leq SKGR$$

and the direct outflow to the river by storm drains, RS, is zero:

$$RS = 0 \qquad \text{if } SK < SKGR.$$

If SK exceeds the runoff capacity SKGR, RK is proportional to the square root of SK:

$$RK = CKT \times (SKGR \times SK)^{0.5} \qquad \text{if } SK > SKGR.$$

and the direct outflow, RS, is computed as the difference between SK and SKGR

$$RS = SK - SKGR \qquad \text{if } RK \leq SKGR$$

or the difference between the sewage storage, SK, and the outflow to the treatment plant:

$$RS = SK - RK \qquad \text{if } RK > SKGR.$$

Thus, the second reservoir, the sewage reservoir, divides the runoff into two components. These two components provide inflow to two cascades which are linear reservoirs (NASH-cascades,) and are used to describe the runoff concentration in the urban area. The impulse response function of each NASH-cascade contains two parameters (N and K). To reduce the number of model parameters to one, each cascade is assigned only two reservoirs (N = 2). Tests were conducted to determine the optimum number of reservoirs by comparing computed impulse response function with the observed unit hydrograph; the best fit was for N=2.

Pollution model

During storms, pollutants are transported into the sewage system. The average concentration of COD in the surface runoff is in the order of magnitude of 50 - 70 mg l^{-1} (Pressel, 1990). In sewers where storm runoff and waste water are mixed, previously deposited sediment/sewage is remobilized during storms. The loads transported by this process are difficult to estimate. The amount depends several factors including hydraulic parameters of the network, water quality parameters of the sewage runoff in non-storm periods, and the length of the antecedent dry periods. Pressel (1990) gives normalized curves of the COD concentration for storm events of 3.5 and 4 hours duration. Very high COD concentrations (between 300 and 400 mg l^{-1}) were observed in the first hour of the event and, following this maximum, concentrations decreased exponentially (Pressel, 1990). Based on these measurements, the concentrations of COD for the runoff components RS and RK were as follows:

(1) 300 mg l^{-1} COD in the first hour,
(2) 150 mg l^{-1} COD in the second hour,
(3) 75 mg l^{-1} COD in the third hour, and
(4) 50 mg l^{-1} COD in the fourth and following hours of the storm.

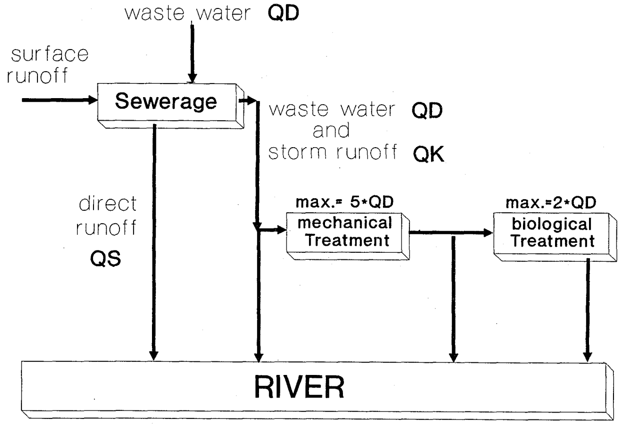


FIG.2 Structure of the pollution model.

Discharge was taken into account when selecting these concentrations. Sediment remobilization is controlled by the velocity of the runoff. In the hydrologic model, runoff for each time step is routed through the system using the impulse response function. Also, the pollutant loads have to be routed. Because COD concentrations vary with time, pollutant loads can be routed using the same response function used for runoff. Thus, for each runoff component (RS and RK), the corresponding amounts of dissolved loads can be estimated. Direct discharge from the sewage system into the river (QS) transports pollutants directly into the river. The sewage storm runoff, QK,i.e. the runoff sent to the treatment plant, will be mixed with waste water. The amount of waste water, QD, i.e. dry weather runoff in the sewage system, was estimated as a function of the number of inhabitants and their water demand. The inflow to the sewage treatment plant is the sum of QK and QD. Generally. treatment plants are designed for a limited inflow. In Germany, mechanical waste water treatment plants usually are able to process no more than 5 times the dry weather inflow. Biological treatment facilities are limited to 2 times the dry weather inflow (ATV, 1983). Accordingly, the pollution model (Fig. 3) considers three outlets of the treatment plant:

(1) the outlet at the inflow point of the treatment plan limits the inflow to the mechanical treatment plant to 5 times QD and inflows exceeding this limit are routed directly into the river without any treatment;
(2) the outlet after mechanical treatment limits the inflow to the biological section of the

treatment plant to 2 times QD; and
(3) the outflow of the biological section of the treatment plant.
The efficiency of waste water treatment, computed as the pollutant load ratio of outflow to inflow of the sewage treatment plant, depends on the water quantity (QK + QD).

Model testing

A 532 km^2 catchment in Germany, for which 15 percent of the area is urbanized, was chosen to test the model. The most urbanized area is a city with 300000 inhabitants and an urbanized area of 65 km^2, located in the center of the catchment.

The impact of this city on water quantity and quality of the river flowing through the city is significant. The impervious part of the urban area is 46%. The network of gaging stations was not designed to measure the effects of urbanization on the river. Consequently, runoff from the urban area was not measured directly, because gages above and below the city are lacking. A stream gage at the outlet of the catchment has been in operation for more than 30 years. During this time 153 floods were recorded. Two types of floods were identified from an evaluation of data from three rain gages in the catchment: those that were generated predominantly in the city and those generated from the whole catchment. Storms restricted to the city were rather seldom. Such a heterogenous spatial rainfall distribution was limited to convective rainfall events of short duration. The floods that were generated from rainfall on the city were used for the urban runoff model development and calibration. The remaining floods were used to verify the model. In either case, the water quality data were insufficient. No more than a few analyses were available for either the river or effluents from the waste water treatment plant. Therefore, the pollution model was not calibrated of verified using these data.

Verification and calibration of the runoff model

The hydrologic model was calibrated using 15 rainfall-runoff events. Because only one raingage is located in the southern part of the town, the rainfall data for the convective rain events were uncertain. Nevertheless, these data were used to estimate model parameters. An iterative optimization procedure based on Fibonacci-algorithm was used for calibration. The calibration was based on minimizing the differences between observed and predicted values of total runoff volumes and peak discharges. The criterion of the sum of mean square deviation between observed and computed hydrographs produced unsatisfactory results. This criterion depends primarily on high temporal accuracy of the rainfall measurements. Very important, however, was the answer to the following question: Is the model able to compute the runoff generated in the town as part of the total runoff from the catchment? In order to answer this question 35 rainfall-runoff events were simulated by a combination of the urban runoff model and a runoff model similar to the well known Stanford Watershed Model. The parameters of the urban model were not changed in these runs. The measured and predicted flow for one flood is shown in Fig. 3. The urban runoff component predicted by the model is similar to the observed catchment runoff. With this reasonably successful result, the urban model was then used to identify the specific runoff components generated in towns, which represents a fraction of total catchment response to rainfall as a basis for the analysis of the effects of urban runoff on water quality.

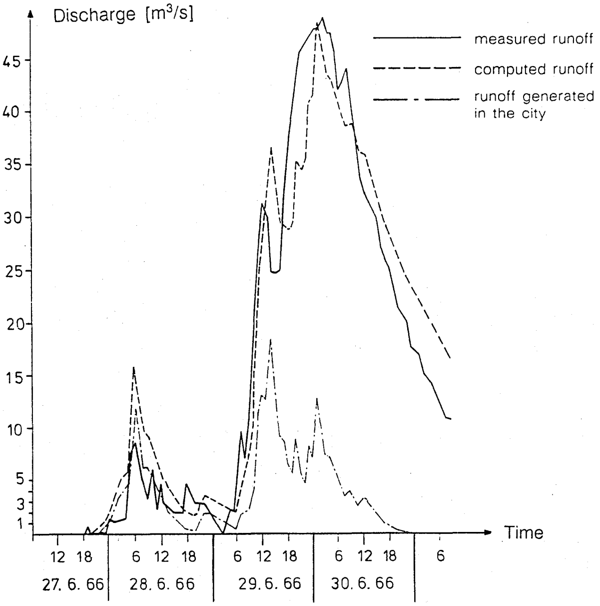


FIG. 3 Measured and computed hydrograph of a storm event with uniformly distributed rainfall (Chemnitz river, Streamgauge Göritzhain, Catchment Area 533 km², Germany).

Coupling the urban runoff model with the pollution model

Both models described above were combined to estimate the urban runoff and the COD load which is spilled into the river during storm events. As mentioned above the waste water flow had to be estimated. By comparison of the urban water supply and the outflow of the sewage treatment plant the waste water quantity during dry periods, OD, was estimated to be 1.3 m^3 s^{-1}. The concentration of COD before treatment was estimated at 400 mg l^{-1} (ATV, 1983). The impact of rainfall intensity on urban runoff and on the discharge of waste water into the river were evaluated using two rainfall scenarios: (1) a 10-mm rainfall that fell in 1 h, and (2) a 10-mm rainfall that fell in 7 h (Fig. 4). The rainfall was distributed uniformly over the area for each scenario.

The two runoff components QS and QK (direct runoff from the sewage system into the river and storm runoff into the treatment plant) varied between scenarios. For scenario (1), 55% of the total runoff was direct runoff, but, for the low intensity rainfall in scenario (2), only 12% of the total runoff was direct (Fig. 4). The hydrographs of direct runoff and outflow of the treatment plant (QD + QK) are shown in Fig. 6 and Fig. 7. The river loads of COD are computed consisted of:

(1) wastes transported by direct runoff and
(2) wastes transported by three outlets of the treatment plant.

COD concentrations of (1) were assumed to be equal to those for runoff from the sewer system which flows directly into the river.

COD concentrations of (2) were much less than those for (1) because this water was affected by the treatment plant. The COD concentration of inflow into the sewage treatment plant was computed from the concentrations of waste water QD and the storm runoff component QK as follows:

$$C_{in} = \frac{(QD \cdot C_D) + (QK \cdot C_K)}{Q_D + Q_K}$$

C_D: COD — concentration of QD,
C_K: COD — concentration of QK,
C_{in}: COD — concentration of the inflow to the treatment plant. The efficien-

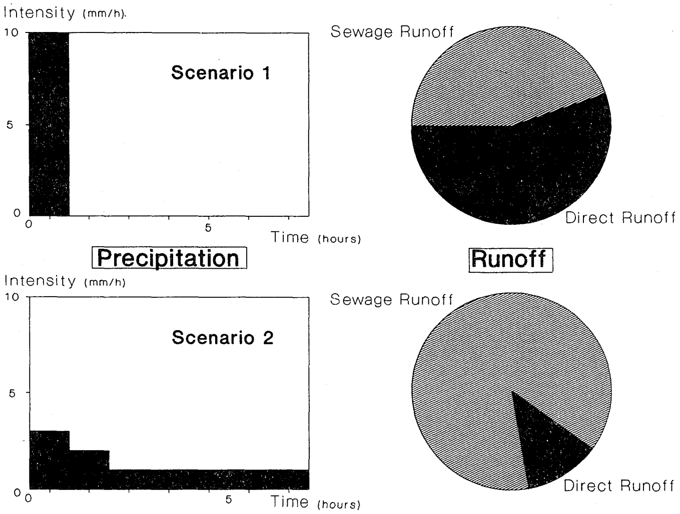


FIG. 4 Rainfall scenarios and urban runoff components.

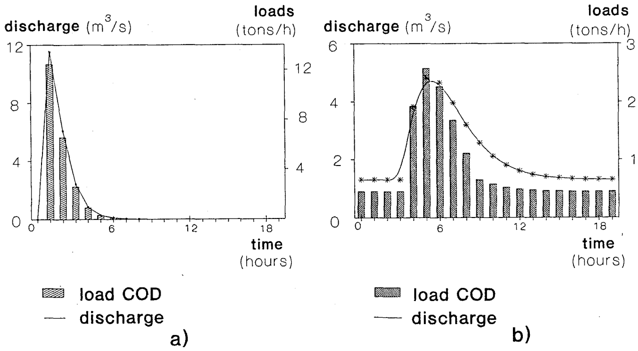


FIG. 5 Computed components of discharge and load of COD for rainfall scenario 1, a) direct runoff b) outflow of the sewage treatment plant.

cy of the sewage treatment plant is affected by flow passing through the plant. For the mechanical section of the plant, the efficiency was assumed to be 0.20, i.e. only 20% of a given load is removed. For the biological section of the plant, the efficiency was assumed to be 0.70. Consequently, the total efficiency of the treatment plant was 0.76.

As mentioned above, the capacity of the treatment plant is limited. If the inflow is more than 5 times the dry weather runoff, the outflow load is computed as:

$(QK - 4QD) \cdot C_{in}$	fraction of inflow load which cannot be handled
$3QD \cdot 0.8C_{in}$	20% of the load which is transported by a discharge of not more than 5 times QD can be reduced by mechanical treatment
$2QD \cdot 0.24\,C_{in}$	not more than twice the amount of QD can be treated mechanically and biologically.

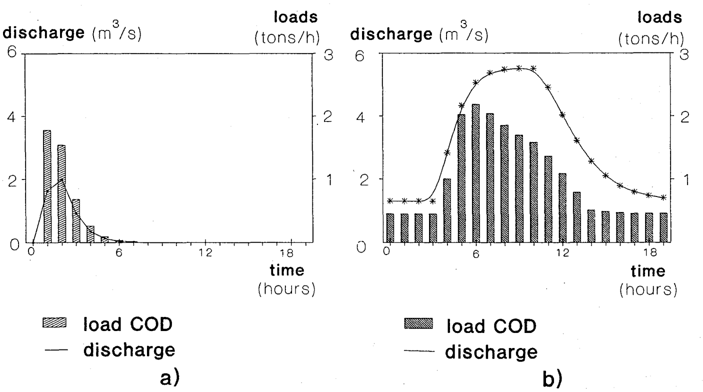
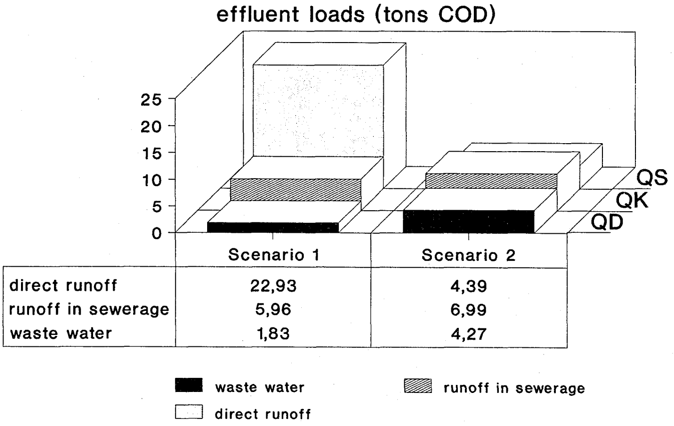


FIG. 6 Computed components of discharge and load of COD for rainfall scenario 2, a) direct runoff, b) outflow from the sewage treatment plant.



	Scenario 1	Scenario 2
direct runoff	22,93	4,39
runoff in sewerage	5,96	6,99
waste water	1,83	4,27

FIG. 7 Effluent loads of different runoff components into the river.

The outflow load of the treatment plant also can be divided into the load which originates from storm runoff and the load which originates from waste water. The computed loads of direct runoff and outflow from the treatment plant for the two scenarios are shown in Fig. 6 and Fig. 7. The total load of the various components for the two scenarios are shown in Fig. 8.

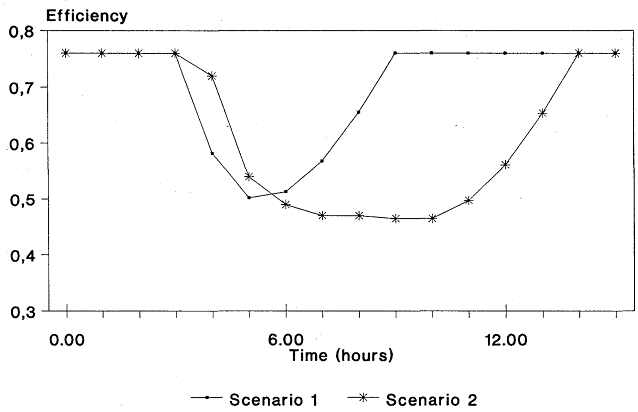


FIG. 8 Time variability of the total efficiency of the treatment plant.

Resulting from the influence of the fast or direct runoff from the sewage system into the river, Wastes derived from direct runoff from the sewage system were much more important than the other load components for high intensity rainstorms (scenario 1). The treatment plant efficiency, the load ratio of outflow waste to inflow waste (Fig. 9), was decreased more by low -intensity, long-duration rainstorms than by high-intensity, short-duration rainstorms.

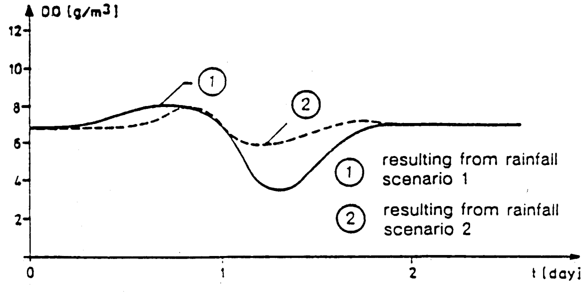


FIG. 9 Dissolved oxygen concentration during flood waves 30 km downstream of the city in the Chemnitz river.

The quantity of the untreated waste water is increased as shown in Fig. 7. The effects of the limited plant capacity is evident for loads which are not reduced by the treatment plant during storm events. If the city's waste water markedly affects river water quality, then treatment plant efficiency during storms should be investigated further.

Application of a river water quality model

A water quality model was applied to the Chemnitz River to demonstrate the impact of urban storm runoff on river water quality. Not only is the river water quality affected by increasing waste loads from urban areas but the river water quality is affected by the dynamic change of the reaeration capacity of the river. To estimate the effects of both factors, the Qual-II model (EPA, 1985) was coupled to a one-dimensional hydrodynamic model and the resulting model was applied to a series of river segments. Dissolved oxygen concentrations for a site on Chemnitz River were generated by this model for rainstorm scenarios 1 and 2 (Fig. 9). Results for scenario 2 indicate that low-intensity rainstorms do not cause a significant degradation in river water quality. However, the dissolved oxygen concentration decreased by more than 50% in for the high-intensity rain of scenario 1.

The reaeration capacity of a river increases with discharge and decreases with water depth. Rather, the reaeration intensity is a function of the discharge and water depth. At the beginning of the flood waves this phenomenon produces an improvement in the dissolved oxygen conditions: the higher oxygen level can sometimes (as it is the case in scenario 2) balance the increased biochemical oxygen demand.

CONCLUSIONS

a) The combination of a hydrological and a pollution model can be used to assess the effects of pollutants derived from an urban sewage system on river water quality.
b) The load estimates are uncertain because water quality data typically are unavailable to calibrate the concentration of pollutants in the different runoff components of the pollution model.
c) To calibrate the pollution model, a better knowledge of the behavior of the sewage treatment plant under different inflow conditions is required.
d) Model output is an inadequate substitute for data, but models can be useful for identifying which measurements are necessary and how these measurements could be used.

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