Dynamo water quality modelling for the Hsintien River, Taiwan

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Abstract

Considering mass balance in a river and using the principles of systems dynamics, a water quality model was formulated for the DO and BOD distributions in the Hsintien River in Taiwan. The simulated results were found to be acceptable regardless of simplified conditions on input data. A sensitivity analysis was also carried out and it revealed that flow rate, reoxygenation and deoxygenation coefficients had considerable influences on these distributions.

Notation

The following symbols are used in this paper.

A: river cross section area
ABDRB: auxiliary of BDRB
AODRB: auxiliary of ODRB
AODRF: auxiliary of ODRF
AOIR: auxiliary of OIR
AOIRD: auxiliary of OIRD
AOIRF: auxiliary of IORF
AOIRN: auxiliary of OIRN
ARWT: auxiliary of RWT
BDR: BOD decreasing rate
BDRB: BOD decreasing rate due to bacterial decomposition
BDRD: BOD decreasing rate due to dispersion
BDRF: BOD decreasing rate due to advective flow
BDRS: BOD decreasing rate due to settling out of BOD
BIR: BOD increasing rate
BIRC: BOD increasing rate by scouring
BIRD: BOD increasing rate by dispersion
BIRF: BOD increasing rate by advective flow
BIRR: BOD increasing rate by local runoff
BIRW: BOD increasing rate by waste discharge
BOD: Biochemical Oxygen Demand
BODN: initial condition of BOD
CD: coefficient of deoxygenation, i.e., K1
CD20: value of CD at 20 °C
CR: coefficient of reaeration, i.e., K2
CR20: value of CR at 20 °C
CS: DO saturation concentration
CSET: coefficient of settling out of BOD, i.e., K3
DIS: distance (length) of the river section
DO: Dissolved Oxygen
DOO: DO concentration at the headwater
DOL: Dissolved Oxygen Level of the section
DON: initial condition of DO
DOW: DO concentration of wastewater
E: dispersion coefficient
K1: coefficient of deoxygenation (i.e., CD)
K2: coefficient of reoxygenation (i.e., CR)
K3 coefficient of settling out of BOD (i.e., CSET)
K4 coefficient of areal demand of DO of bottom deposit
MAX: DYNAMO MAX function
ODR: oxygen decreasing rate
ODRB: oxygen decreasing rate due to carbonaceous bacterial oxidation
ODRD: oxygen decreasing rate due to dispersion
ODRE: oxygen decreasing rate due to bottom deposit
ODRF: oxygen decreasing rate due to advective flow
ODRN: oxygen decreasing rate due to nitrification
ODRR: oxygen decreasing rate due to respiration of plants
ODRW: oxygen decreasing rate by the input of waste loading
OIR: oxygen increasing rate
OIRD: oxygen increasing rate due to dispersion
OIRF: oxygen increasing rate due to advective flow
OIRN: oxygen increasing rate due to natural atmospheric reaeration
OIRP: oxygen increasing rate due to photosynthesis
Q: quantity of design flow of the river system
RBOD: BOD level in river
RBODO: river BOD concentration at the head water
RWT: river water temperature
STEP: DYNAMO STEP function
SWITCH: DYNAMO SWITCH function
T: step time of the wastewater discharge to the river
TM: time of water travelling
V: river flow velocity
VOL: volume of river water section
W: waste loadings
WQ: wastewater quantity

Introduction

There is an increasing recognition that the health and well-being of man are becoming more dependent on the successful management of quality of the environment especially during the time of rapid growth of industrialization and urbanization. In order to manage this complex phenomenon, a system analysis approach to water quality management is needed to provide rational bases for making decisions on alternative courses of action. The optimum allocation of limited resources among competing activities by proper enforcement, and by reasoned analysis of the situation can significantly improve the water quality.

As defined by Gordon (1978), system simulation is a technique of solving problems by the observation of the performance over time, of a dynamic model of the system and the principal concern of a system dynamic study is to understand the forces

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operating on a system so as to determine their influence on the stability or growth of that system. Forrester (1968) pointed out that the system simulation model can rapidly and inexpensively give information about dynamic aspects, i.e. time varying, behaviour of the real system that the model represents, and thus it is desirable that the system dynamic approach be used in water quality modelling. Along with this approach, a special programming language called DYNAMO (for DYNAmic MOdels) has been designed to execute models that follow the structure and equation conversions used in system analysis. Moreover, the DYNAMO compiler is a computer program which accepts the equations of a model of dynamic feedback system and which can translate and run continuous models (models described by a set of differential equations). It was developed by the industrial dynamic group at the Massachusetts Institute of Technology for simulating dynamic feedback systems and can produce the requested simulation results in the form of graphical plots and numerical tables.

Forrester (1968) indicated that the DYNAMO compiler can also perform several duties such as (1) checking the equations for logical errors and print defects; (2) programming the model; and (3) reorganizing the model in accordance with the structural concepts of a dynamic system grouping level and rate equations, and arranging the auxiliary equations. DYNAMO makes available, easy-to-use computing facilities so that the user can focus his attention on building a useful model undistracted by complex computer requirements.

The most recent version of DYNAMO, DYNAMO III, offers a full array to simplify the duplication of disaggregated sectors as shown by Pugh III (1976). In addition, both DYNAMO III and the earlier DYNAMO II (Pugh III, 1973) offer the user two new facilities: translation of any algebraic statement, and user-defined macros (subroutines). They retain the extensive error checking of DYNAMO but significantly extend the recovery facilities and a model can frequently be run despite a number of errors.

In the present water quality modelling, the above system dynamic concept and DYNAMO language are used in the computer DYNAMO simulation model. An attempt is made to formulate the river water quality system in the scope of systems dynamics and to show its application to the Hsintien River in Taiwan.

Model Development

Oxygen Balance Models

During the assessment of multiple water uses, consideration of water quality requirements and deterioration in quality for each use, the response of the stream to various quality inputs and the behaviour of stream in its natural state, are all essential. This implies the need for a comprehensive river basin or estuary model that can simulate the quality characteristics of the stream and adjacent uses. Because of this need, several models for the oxygen balance in rivers and/or estuaries were developed and they are capable of predicting with a reasonable degree of accuracy, the consequences of results over time and space of the discharge of wastes. Most of the oxygen balance models, including dissolved oxygen (DO) and biochemical oxygen demand (BOD) balance, widely applied in the past were mainly based upon the equations proposed by Streeter and Phelps (1925). O'Connor (1960, 1967) considered the effects of dispersion in estuaries and demonstrated the temporal and spatial distribution of DO in streams. Camp (1963) considered the complicated situation in many rivers influenced by the settling out of BOD to the bottom deposits, the addition of BOD to the overlying water from the bottom deposits, and the production of oxygen by photosynthesis. Further important developments were made by Dobbins (1964), Harleman *et al.* (1967), O'Connor and Ditoro (1970), Thomann (1974), Loucks *et al.* (1981), etc. None of them can be readily applicable in the context of systems dynamics except the technique used by Thomann (1974). In this study, the concept employed by Thomann was adopted, but the formulation of the problem and the solution method were completely changed to suit to the DYNAMO language.

Mass Balance Consideration in Model Development

In order to simplify the problems of multi-dimensional reactions of substances in the river, most researchers follow a one-dimensional approach. Furthermore, if the water body is divided into a finite number of segments, each of which is assumed to be homogeneous as shown in Fig. 1, the principle of mass balance can then be applied to each segment as follows:

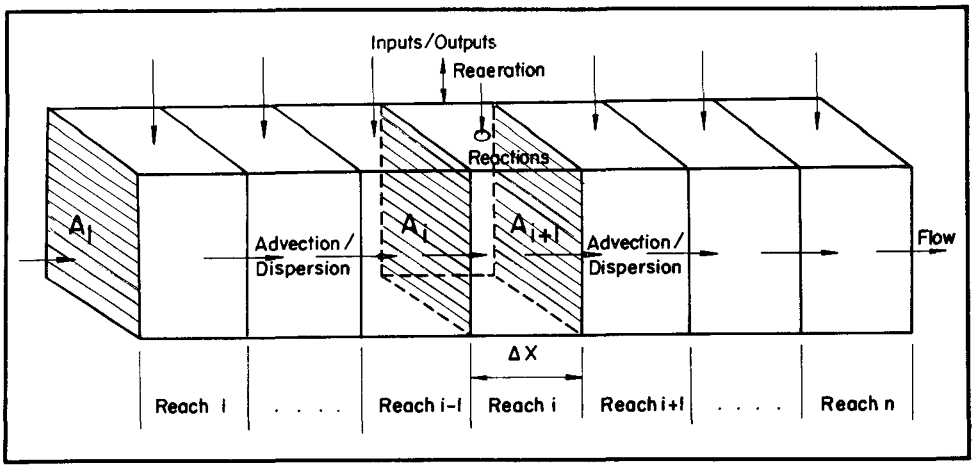


Figure 1
Schematic Diagam for DO/BOD Mass Balance

A. For the DO Balance in Reach i:

Sources which increase the DO level in reach i are:

(a) Rate of DO supply from reach i-1 by advection and from reach i-1 and/or i + 1 by dispersion.
(b) Rate of addition of DO from atmospheric reaeration.
(c) Rate of addition of DO from photosynthesis action of plankton (algae) and fixed plants, or other inputs, e.g., tributary flow or large waste discharges.

Sinks which decrease the DO level in reach i are:

(a) Rate of DO output to reach i + 1 by advection and to reach i – 1 and/or i + 1 by dispersion.
(b) Rate of DO consumption by carbonaceous oxidation, nitrification, bottom deposits, plant respiration and other inputs/removal by immediate oxygen demand or salinity.

Thus, the DO balance of reach i can be expressed as:

Rate of accumulation = Rate of Input – Rate of output

It can be expressed by the following equation:

$$d(DO)/dt = \{OIRF(i) + OIRD(i) + OIRN(i) + OIRP(i)\} - \{OIRF(i+1) + ODRD(i) + ODRB(i) + ODRN(i) + ODRE(i) + ODRR(i) + ODRW(i)\}$$

in which,

OIRF(i): Rate of increase of oxygen level of reach i by advective flow.
OIRD(i): Rate of increase of oxygen level of reach i by dispersion.
OIRN(i): Rate of increase of oxygen level of reach i by natural atmospheric reaeration.
OIRP(i): Rate of increase of oxygen level of reach i by photosynthesis.
OIRF(i + 1): Rate of increase of oxygen level of reach i + 1, i.e., decreasing rate to segment i, by advective flow.
ODRD(i): Rate of decrease of oxygen level of reach i by dispersion.
ODRB(i): Rate of decrease of oxygen level at reach i due to carbonaceous bacterial oxidation.
ODRN(i): Rate of decrease of oxygen level at reach i due to nitrification.
ODRE(i): Rate of decrease of oxygen level at reach i due to bottom deposit.
ODRR(i): Rate of decrease of oxygen level at reach i due to respiration of plants.
ODRW(i): Rate of decrease of oxygen level at reach i by waste loading.

B. For the BOD Balance in Reach i:

Sources which increase the BOD level in reach i are:

(a) Rate of BOD input by advection and dispersion.
(b) Rate of BOD input by the scour of bottom deposit.
(c) Rate of addition of BOD by waste discharges and/or local runoff.

Sinks which decrease the BOD level in reach i are:

(a) Rate of BOD output by advection and dispersion.
(b) Rate of BOD degradation by bacterial decomposition and settling out of BOD to bottom deposits.

Therefore, the rate of change of BOD mass in reach i can be expressed as:

$$d(BOD)/dt = \{BIRF(i) + BIRD(i) + BIRC(i) + BIRW(i) + BIRR(i)\} - \{BIRF(i+1) + BDRD(i) + BDRB(i) + BDRS(i)\}$$

in which,

BIRF(i): Rate of BOD increase at reach i by advective flow.
BIRD(i): Rate of BOD increase at reach i by dispersion.
BIRC(i): Rate of BOD increase at reach i by scouring.
BIRW(i): Rate of BOD increase at reach i by waste discharge.
BIRR(i): Rate of BOD increase at reach i by local runoff.
BIRF(i + 1): Rate of BOD increase at reach i + 1, i.e., decreasing rate to reach i, due to advective flow.
BDRD(i): Rate of BOD decrease at reach i due to dispersion.
BDRB(i): Rate of BOD decrease at reach i due to bacterial decomposition.
BDRS(i): Rate of BOD decrease at reach i due to settling out of BOD.

Theoretical Aspects of System Dynamics

In a broad sense, a 'System' is any reasonably well-defined entity which is acted upon by certain external forces or influences and as a result produces a specific effect. Rivers, which contain microorganisms, DO, BOD, and physical characteristics such as river flow, river section area, bed slope and/or tidal effects, which have interactions among each other, and are subject to waste load and have the variations in space and time, are systems. In the river system, all the subsystems of bacteria, DO and BOD are influenced by their own past behaviour. For example, bacteria multiply to produce more bacteria which increase the rate at which new bacteria are generated. Thus, a river system may be classified as a 'feedback' system having many components of which each component can itself be a feedback system in terms of some subordinate purpose. The basic structure of a feedback loop is shown in Fig. 2.

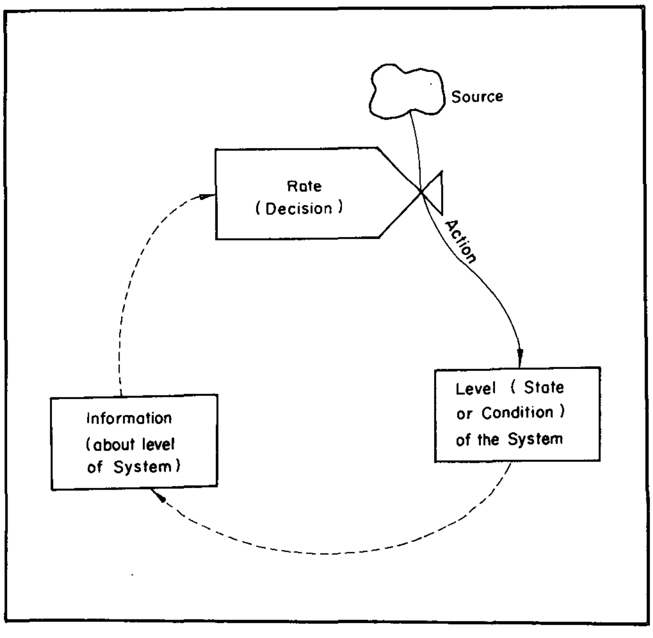


Figure 2
Feedback Loop

For developing the system dynamic model, the two variables of time and space of the river system must be considered. For the space variable, the river can be separated into many sections, where each section represents the individual level of DO and BOD at a different distance. The length of each section could be chosen arbitrarily e.g. 0,1 km; 1 km; 2 km; according to the river's characteristics and the modelling accuracy wanted.

System Structure of DO and BOD

From the mass balance analysis, the basic system structure of DO and BOD may be expressed in the form of a causal loop diagram as shown in Fig. 3, whereas the system feedback loops are shown in Fig. 4. It may be noted that oxygen is supplied by reaeration from the atmosphere and by other sources even if the DO concentration is zero in the river. In this instance, the rate of oxygen supply is at a maximum because the oxygen deficit is equal to the saturation concentration. Therefore, the rate of deoxygenation in the reach of zero DO is limited by the oxygen available rather than by BOD. Thus, it is necessary to use some function to control the rate of deoxygenation. The modified flow diagram is shown in Fig. 5. A step function for waste loading is used to represent it at different spaces and time although some other types of waste inputs may also be used.

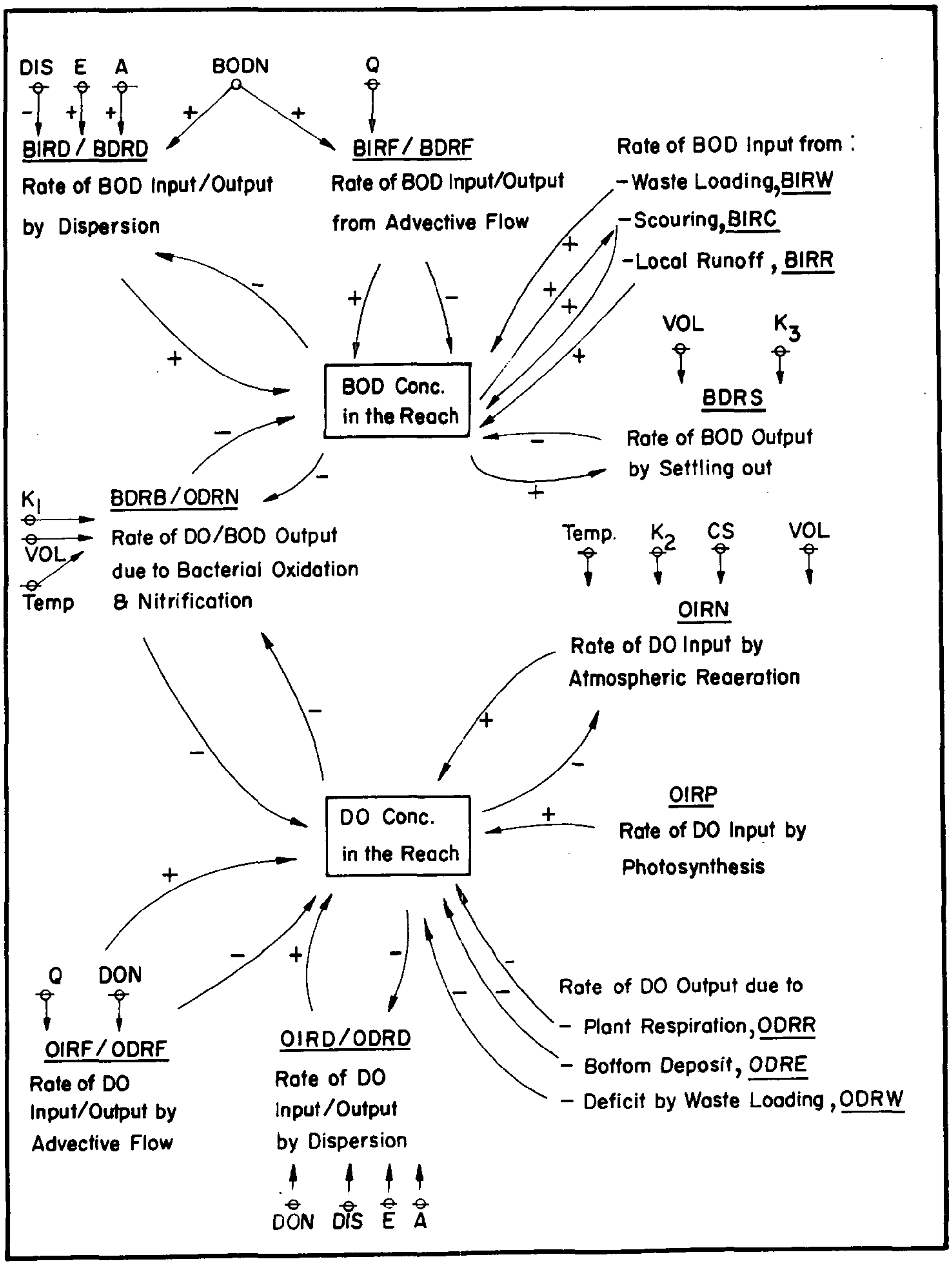


Figure 3
Causal Loop Diagram of DO/BOD in a River Reach

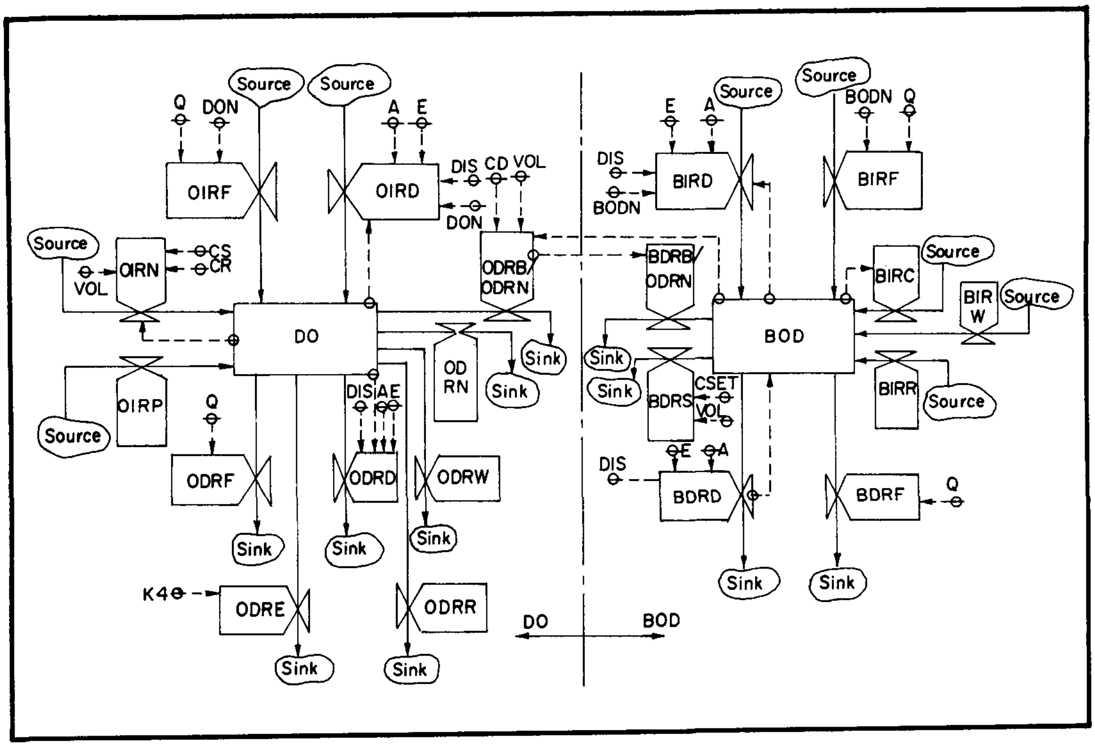


Figure 4
Basic System Flow Diagram of DO/BOD

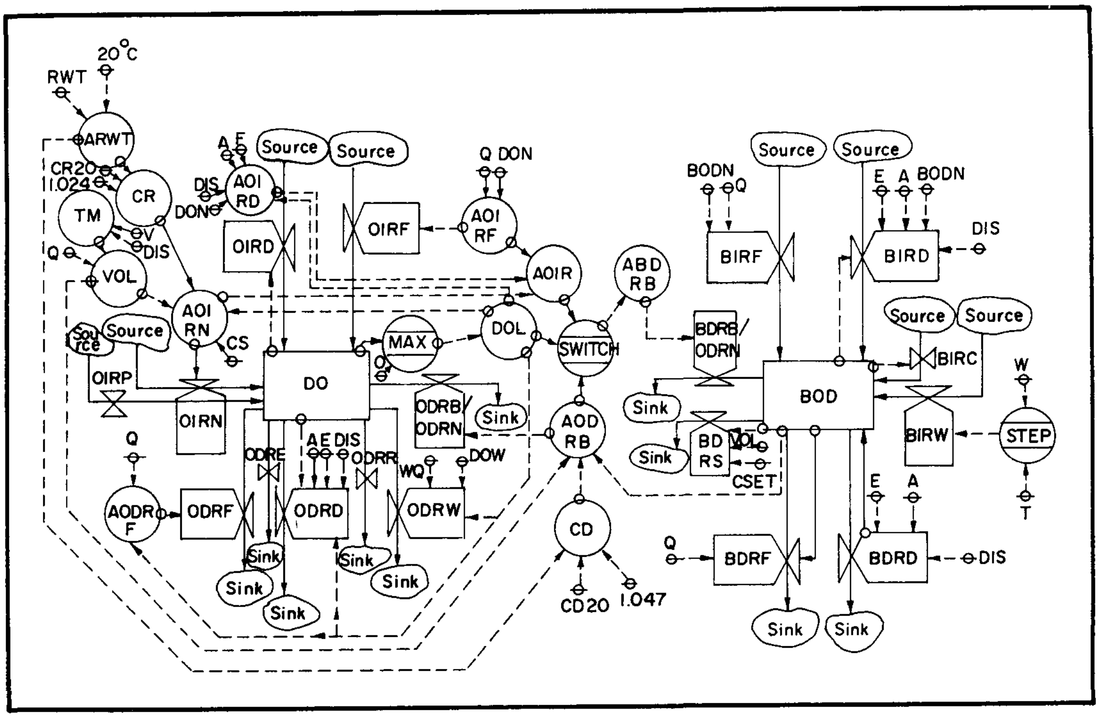


Figure 5
System Flow Diagram of DO/BOD

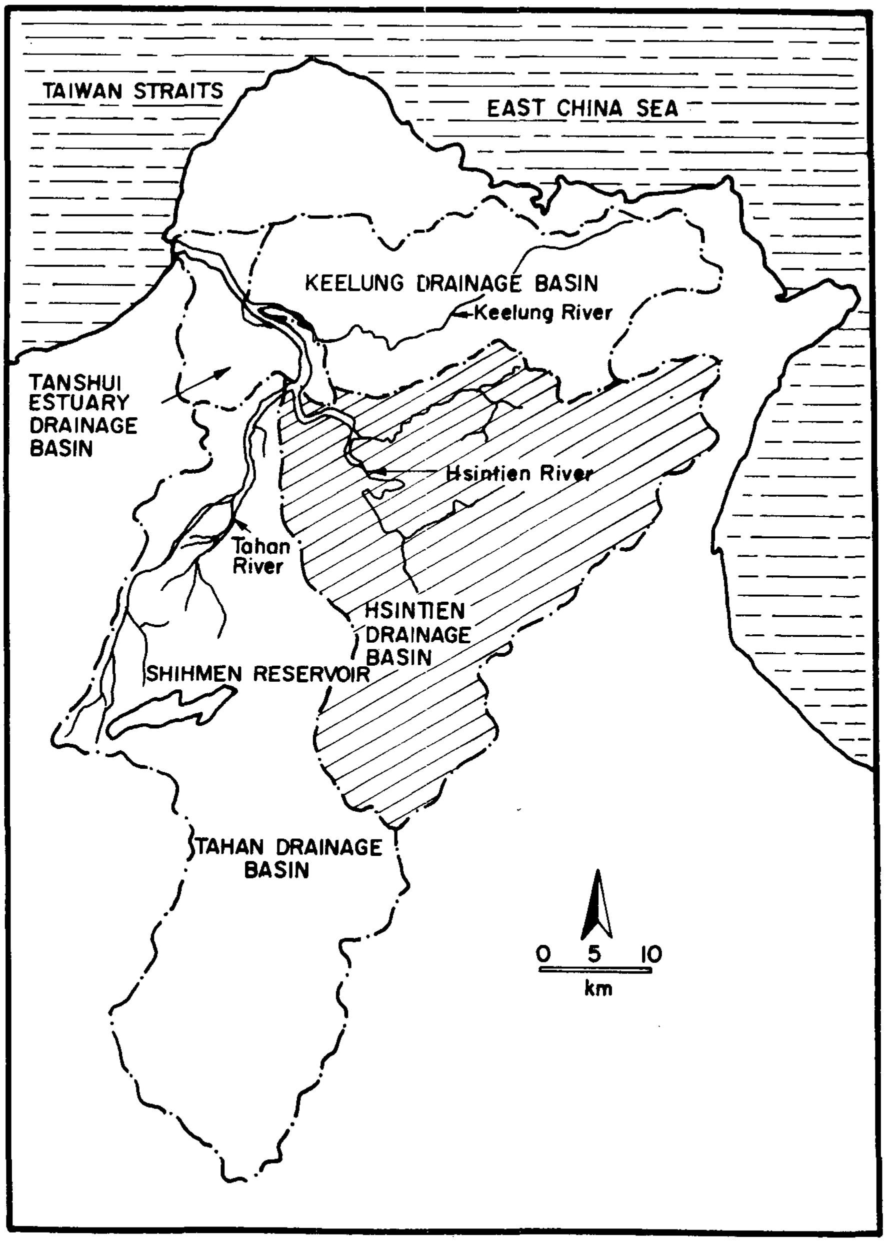


Figure 6
Hsintien River Drainage

Application

General Descriptions

The Hsintien River – The Hsintien Drainage Basin shown in Fig. 6, which is located in the northern part of Taiwan, has an area of approximately 916 km². The Hsintien River converges with the Tahan Stream to form the Tamsui River. The Hsintien River is the major source of water supply for the city of Taipei and its suburban area with a population of 4 million.

Potable water supply, fishing, recreation, irrigation, industrial and wastes disposal are the important uses of the Hsintien River. In order to handle different water uses efficiently, an understanding of water quality is very important and hence modelling of the river system can help to develop an optimum strategy and predict reliable future conditions to maintain desirable stream standards.

Data Used

Stream Flow and Characteristics Analysis – Due to the fact that the Hsintien River is surrounded by steep hills and is subject to intensive rainfall during the period of typhoons, from June to November, the range between maximum and minimum flow is quite large. Thus it is inappropriate to assume the feasible minimum flow with high percentile of flow. Also, a too high percentile of flow selected as the design flow may require more waste treatement than necessary in the pollution control in the future. Therefore, it was decided to take 80 percentile as the design flow to suit the local conditions. By frequency analysis of the available flow record as shown in Fig. 7, a feasible minimum flow for August (equal to 11,6 m^3/s), which is the minimum design flow for the whole year, is used as the ***overall design flow*** in the modelling. The river characteristics data at different reaches in the Hsintien River used in the study are shown in Table 1.

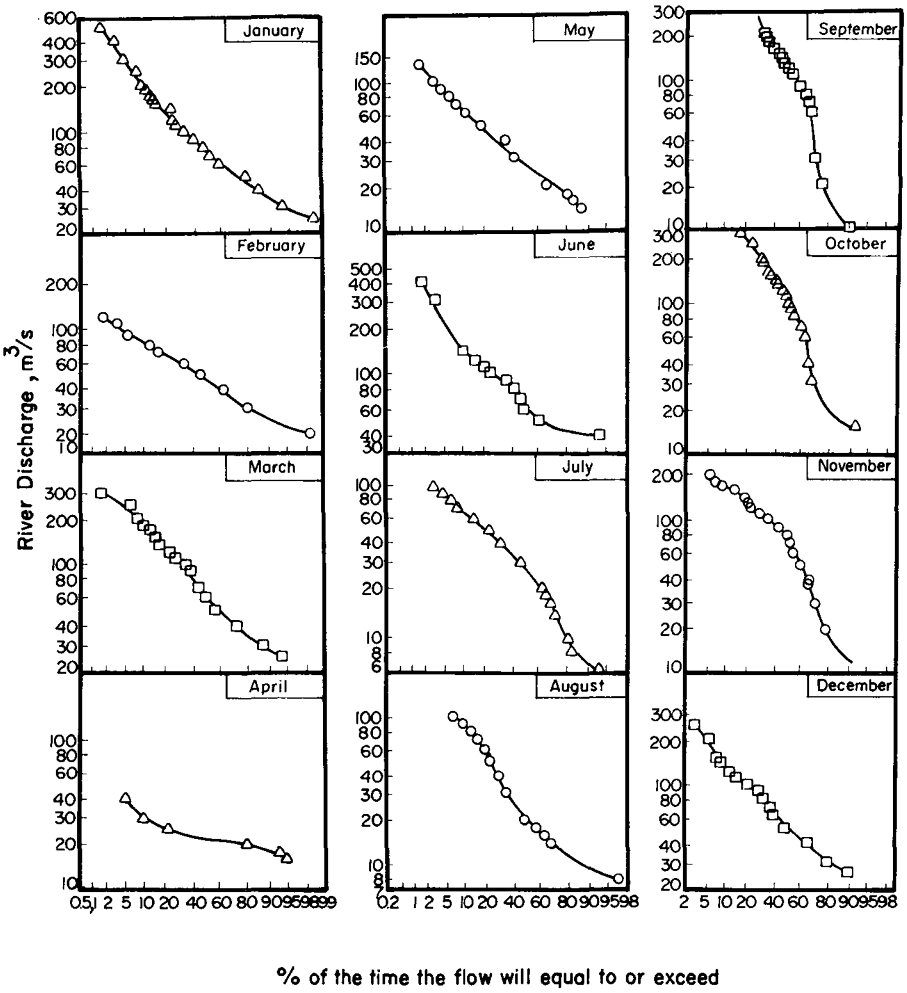


Figure 7
Probability Curves of River Flows

TABLE 1
DATA FOR REACHES IN THE HSINTIEN RIVER

Reach No.	River Distance (km)	Sampling Station	River Depth (m)	K1 (ℓ/d)	K2 (ℓ/d)	K3 (ℓ/d)
1	0,0- 1,5	H01	4,05	0,398	0,046	0,230
2	1,5- 3,0		-	0,268*	0,030*	0,230*
3	3,0- 4,5	H02	12,0	0,138	0,014	0,230
4	4,5- 6,0		-	0,139*	0,266*	0,230*
5	6,0- 7,5		-	0,140*	0,518*	0,230*
6	7,5- 9,0		-	0,141*	0,760*	0,230*
7	9,0-10,5	H03	1,445	0,143	1,002	0,230
8	10,5-12,0		-	0,113*	0,799*	0,230*
9	12,0-13,5		-	0,053*	0,391*	0,230*
10	13,5-15,0	H04	2,13	0,023	0,187	0,230
11	15,0-16,5		-	0,138*	1,397*	0,230*
12	16,5-18,0	H05	1,17	0,253	2,607	0,230
13	18,0-19,5	H06	2,35	0,120	0,180	0,345
14	19,5-21,0		-	0,187*	0,110*	0,403*
15	21,0-22,5	H07	4,74	0,253	0,039	0,461
16	22,5-24,0		-	0,253*	0,058*	0,461*
17	24,0-25,5	H08	3,72	0,253	0,076	0,461
18	25,5-27,0	H09	2,71	0,253	0,223	0,461
19	27,0-28,5	H10	2,71	0,253	0,223	0,461

Notes: (-) not available
(*) values at reaches between sampling stations are obtained by interpolation

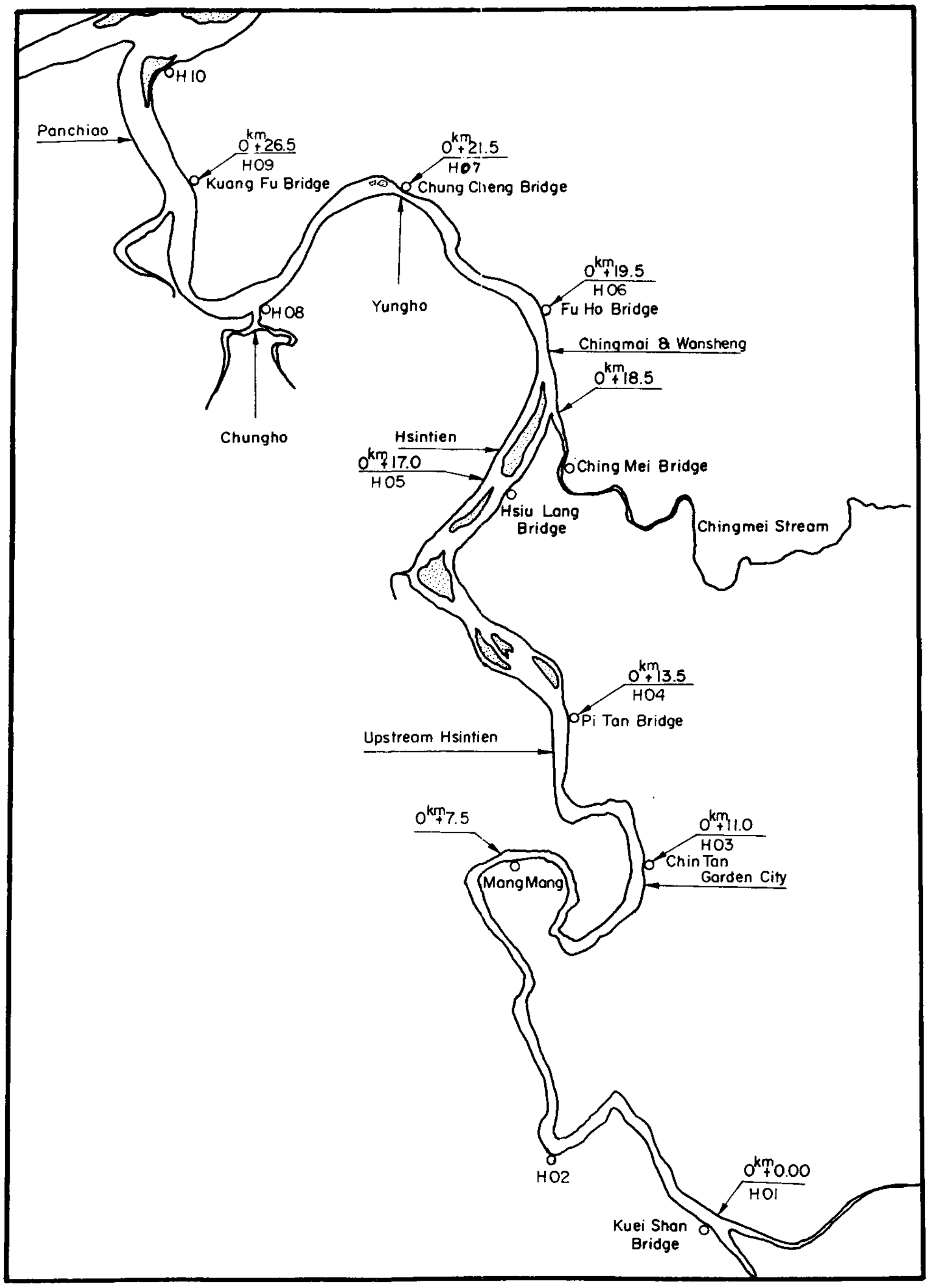
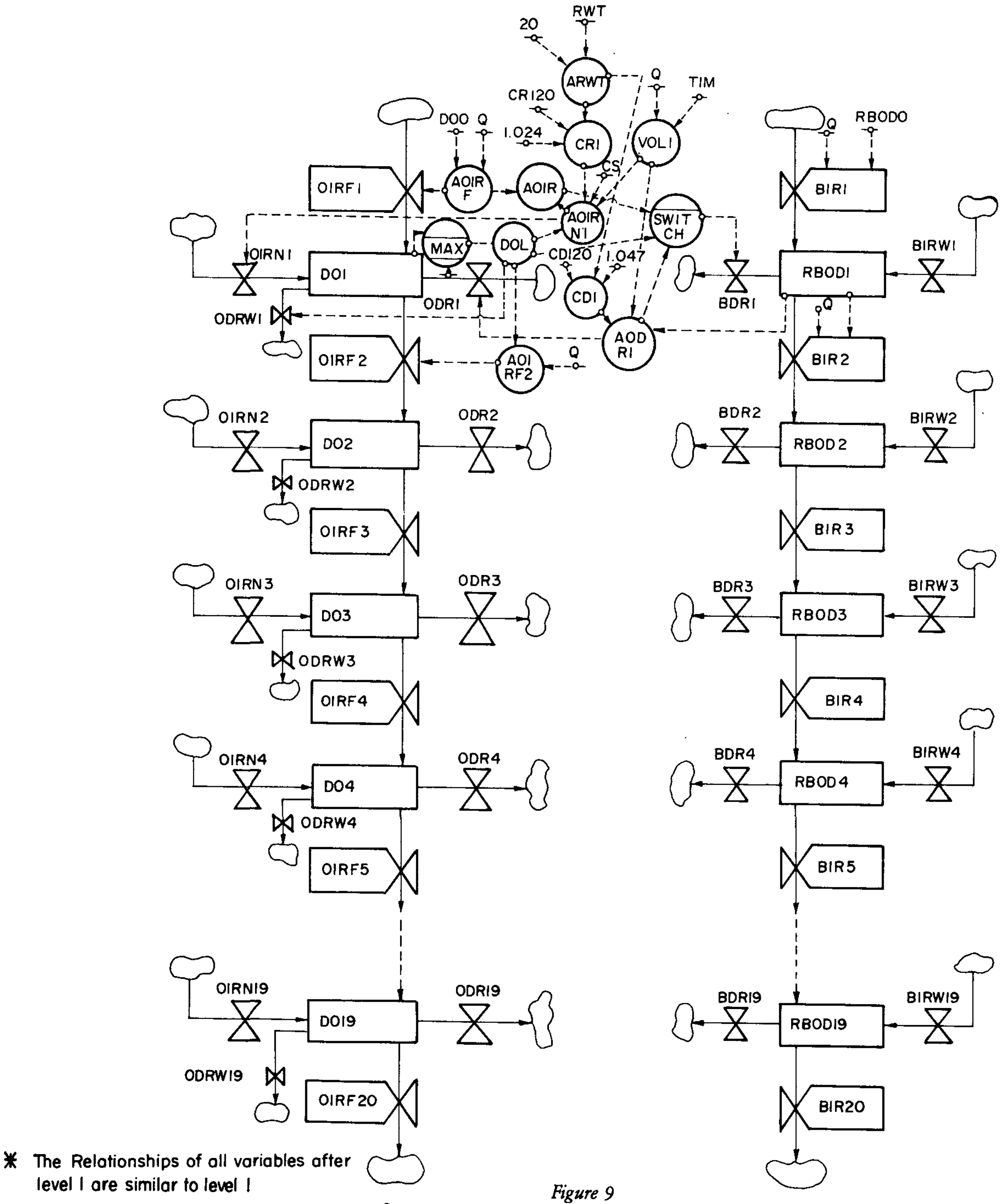


Figure 8
Waste Loadings along Hsintien River

Waste Loading Data – The entire drainage area of the Hsintien River, except for the steep hills, is inhabited. The upstream reach of the stream receives domestic discharges, coal mine and agricultural drainage, containing nightsoil resideus, insecticides and industrial wastes. The waste-water quantity and quality data including domestic and industrial wastes were collected/selected from the files of the Taipei Area Sewerage Engineering Department (1971), from Camp, Dresser and McKee International Inc. (1970), and from the Working Group (1974) of the Taipei Environmental Sanitation Department. From these studies, it was decided to take 40 g BOD_5/day/capita and 180 ℓ/day/capita as estimates for domestic wastes. The total amounts of waste loading are then obtained and shown in Table 2. Further detail may be found in Chen (1975). The locations of waste loadings along the river are shown in Fig. 8.

TABLE 2
ESTIMATED WASTEWATER LOADING IN THE HSINTIEN RIVER

No	Location	Strength of Wastewater, kg/d	Volume of Wastewater, m^3/d
1	Garden City	200	900
2	Upstream Hsintien	4 100	18 450
3	Hsintien	5 370	26 600
4	Chingmai and Wansheng	3 460	22 880
5	Yungho	4 670	22 000
6	Chungho	5 500	32 800
7	Panchiao	11 500	56 200



✱ The Relationships of all variables after level I are similar to level I

Figure 9
System Dynamic Flow Diagram of the Hsintien River

According to the pollution survey done by Camp, Dresser and McKee International Inc., (1970), and the Water Resources Planning Commission (1979) and considering the situation of the main source of wastes distribution, the waste loadings to the river are point additions rather than evenly distributed additions along the river. Meanwhile, the Hsintien River was divided into nineteen sections of 1,5 km each. The relationships of DO and BOD in the system flow diagram are shown in Fig. 9.

The deoxygenation and reoxygenation coefficients of K1 and K2 are taken from river sampling analysis with several methods of estimation and the feasible ones are adopted as shown by Chen (1975, 1981). The feasible minimum design flow is selected as discussed before while the coefficient K3 of settling out of BOD and river water temperature are taken from the survey of the Water Resources Planning Commission (1979). In this study, due to lack of data on other factors, the distributions of both DO and BOD were considered to be dependent on the coefficients K1, K2 and K3, the temperature, flow rate, and waste loading. Among these factors, the waste loading depends on the local condition and no intervention can be made in the analysis. Moreover, the effect of temperature on these distributions has been incorporated in the values of K1 and K2 while the coefficient K3 is not important for the Hsintien River which has a relative high flow velocity; consequently, in the sensitivity analysis carried out in this study, only the effects of K1, K2 and flow rate were considered. Typical results are shown in Fig. 10 for section 12. These revealed that the flow rate, deoxygenation (K1) and reoxygenation (K2) coefficients had considerable influences on the distributions of DO and BOD.

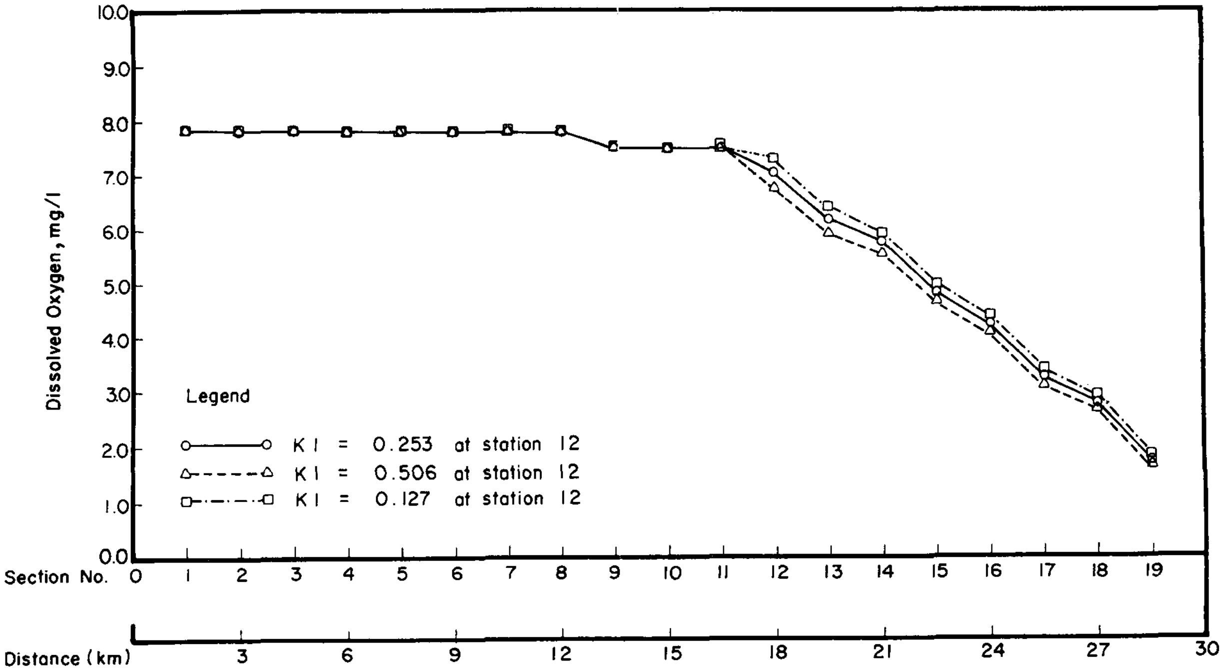


Figure 10.a
DO Distribution for Different K1 Values at Section 12

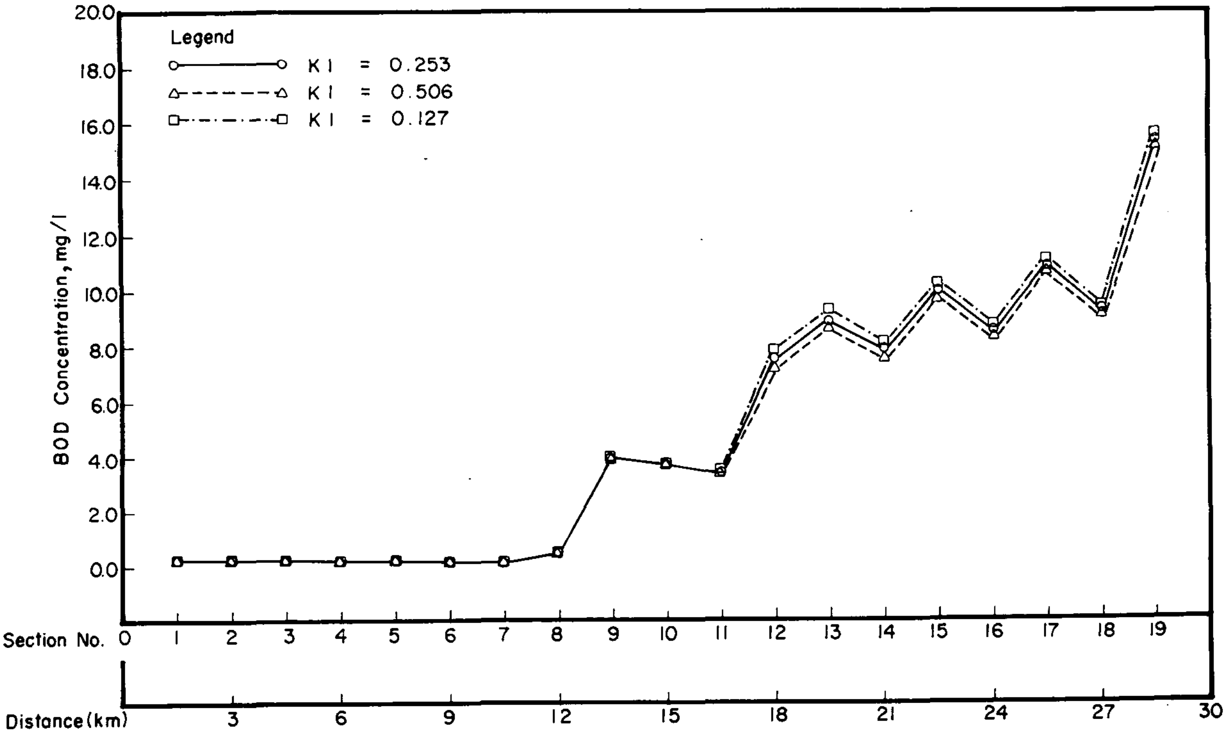


Figure 10.b
BOD Distribution for Different K1 Values at Section 12

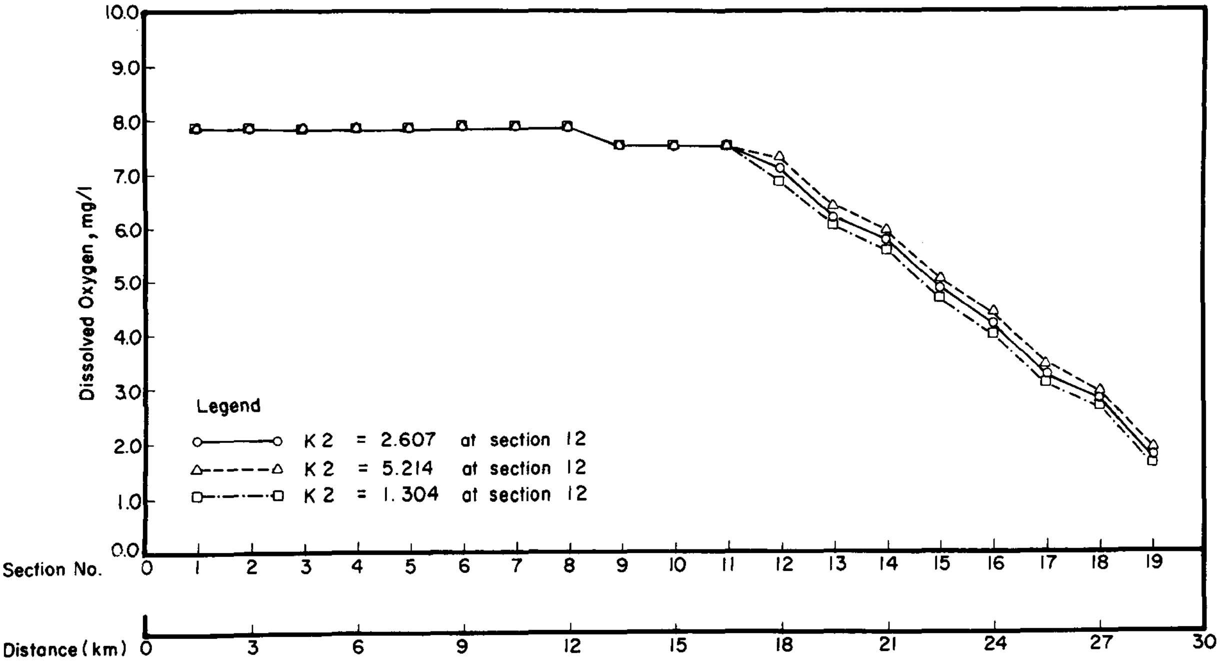


Figure 10.c
DO Distribution for Different K2 Values at Section 12

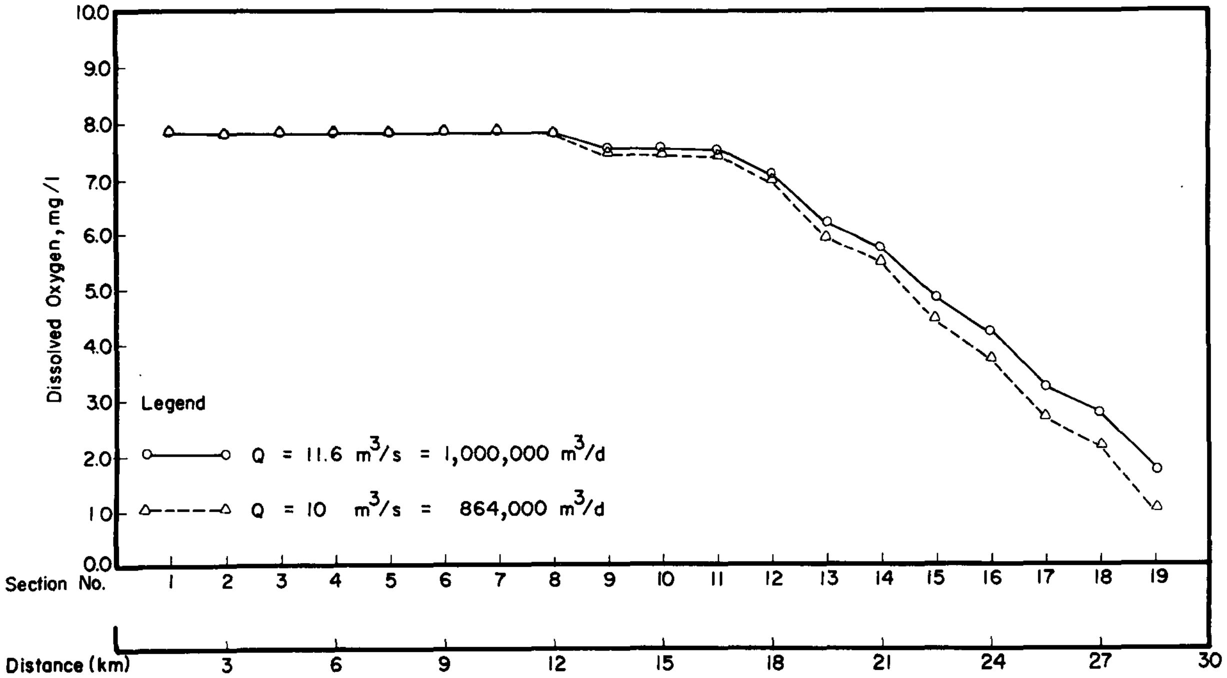


Figure 10.d
DO Distribution at Different River Discharges

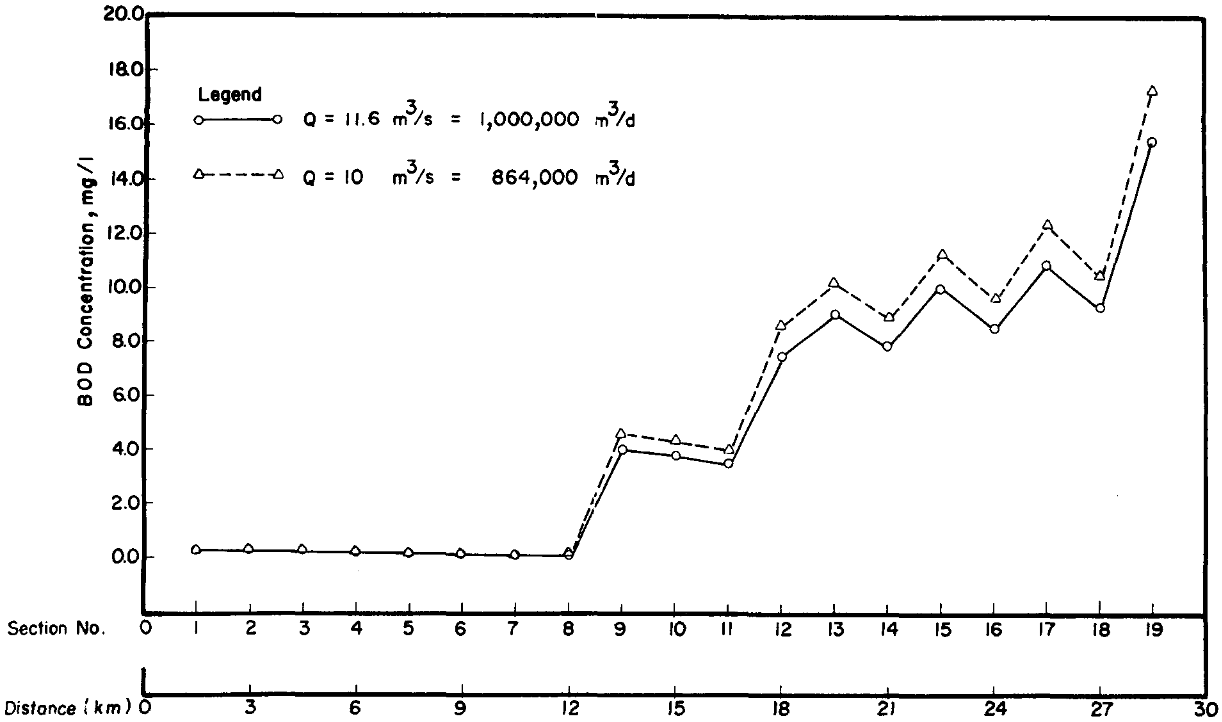


Figure 10.e
BOD Distribution at Different River Discharges

Results and Discussions

Using the available data obtained from several agencies in Taiwan as mentioned before, the system dynamic simulation model formulated earlier was applied to the Hsintien River using DYNAMO III/370 facilities at the Regional Computer Center of the Asian Institute of Technology (AIT). due to the lack of time-varying input data, a steady state input to the river water quality system was adopted. This obviously leads to the output which corresponds to the steady state conditions as well.

The feedback loops of reoxygenation rate to the DO level, deoxygenation rate and rate of settling out of BOD to the BOD level were taken into account in each reach. The simulated results are plotted in Fig. 11 along with sampled data for the distributions of DO and BOD. The simulated and computed values almost coincided at four stations and three stations for the DO and BOD distributions, respectively. The discrepancies obtained may be due to the following reasons:

- Apart from the fact that steady state input was used as previously mentioned, the sample data may not be representative. This is due to the fact that water samples were collected infrequently on different days at the differing stations, and of course they are time-varying. Consequently, they can represent neither the real situation at any time for all stations, nor the steady state. The comparison given here was intended to give some feeling about how the system dynamic modelling works rather than to show the reproduction of observed data.
- Industrial waste data were estimated very roughly. There is a significant difference between the data provided by the Working Group (1974) and those provided by the Taipei Area Sewerage Engineering Department (1971). It seems that both these data sets are unreliable, even though those from the latter were judged to be more appropriate, and they were used in this study.

Based upon its systems dynamic formulation, the simulation results would reveal the percentages of the time the DO or BOD will be below, or above any given concentration level, the relationships between DO and BOD, etc. However, more accurate data are certainly needed and attempts are being made to obtain these.

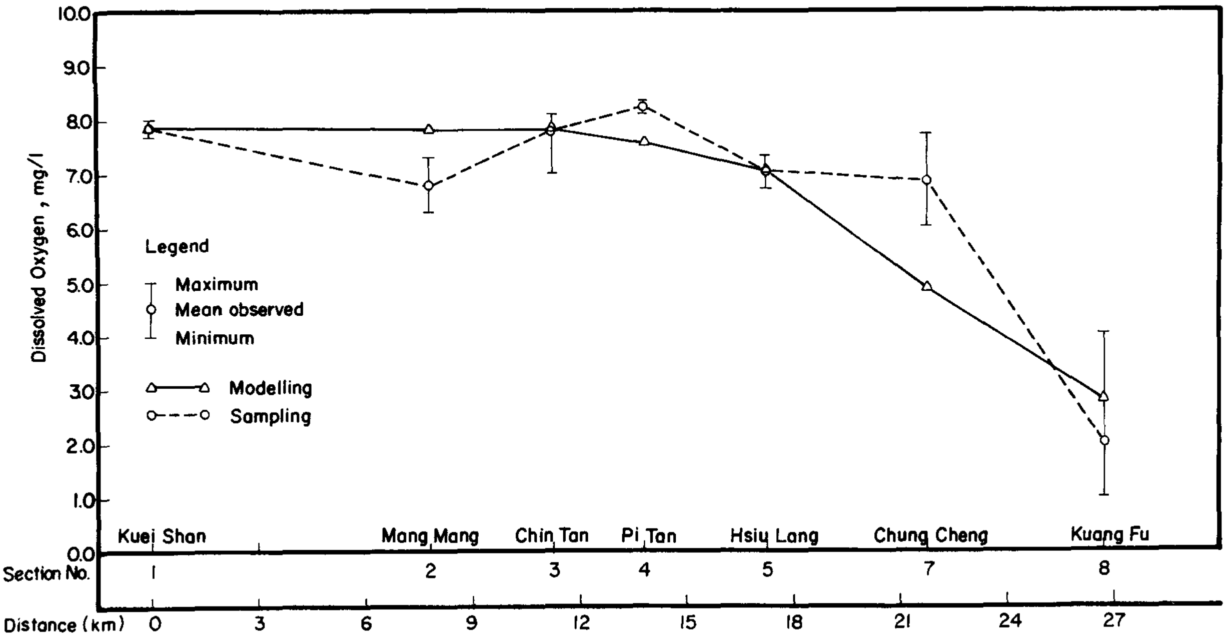


Figure 11.a
DO Distribution in the Hsintien River

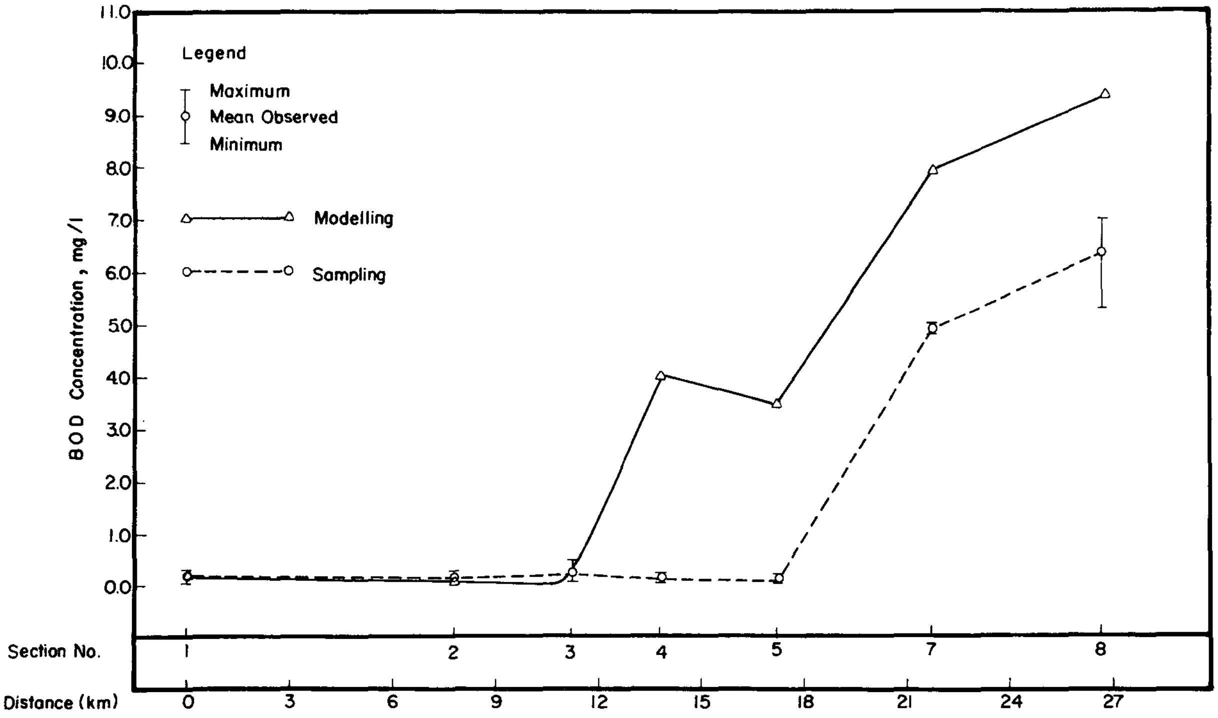


Figure 11.b
BOD Distribution in the Hsintien River

Conclusion

It is expected that with the approach formulated in this study, it is possible to predict the future conditions of the rivers in this basin. The information required includes: future population and industrialization, wastewater BOD estimation within the basin and the effect on river flow of a new project in the upstream of the Hsintien River (the Fei-Tsui Reservoir Construction Project) etc.

Further extension of the present study in the Hsintien River has been undertaken, using both the DYNAMO and CSMP (Continuous System Modelling Program) facilities. Moreover, the effect of the operation of the Fei-Tsui Reservoir in the upstream of the Hsintien River is under investigation and the results obtained will soon be reported.

Acknowledgements

The authors wish to express their sincere thanks to a referee for his valuable comments, and to the Asian Institute of Technology (AIT) for use of its computer facilities.

References

CAMP, T.R. (1963) *Water and Its Impurities,* Reinhold publishing Co.

CAMP, DRESSER and McKEE INTERNATIONAL INC. (1970) Sewerage Planning in the Great Taipei Area, Master Plan Report, Taipei, Taiwan.

CHEN, L.G. (1975) Water Quality Modelling of the Hsintien River, Taiwan. Master Thesis No. 822, AIT.

CHEN, L.G. (1981) DYNAMO Modelling for Water Quality Management: A Case Study of Tanshui River Basin, Taiwan. Special Study, AIT.

DOBBINS, W.E. (1964) BOD and Oxygen relationships in streams, *J. San. Eng. Div. ASCE* **90** (SA3) 53-78.

FORRESTER, J.W. (1968) *Principles of Systems,* Wright-Allen Press Inc. Massachusetts.

GORDON, G. (1978) *System Simulation,* Second Edition, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

HARLEMAN, D.R.F., LEE, C. and HALL, L.C. (1967) Numerical solution of the unsteady, estuary dispersion equation, National Symposium on Estuarine Pollution, Standford University.

LOUCKS. D.P., STEDINGER J.R., and HAITH, D.A. (1981) *Water Resource System Planning and Analysis,* Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

O'CONNOR, D.J. (1960) Oxygen balance of an estuary, *J. San. Eng. Div. ASCE,* **86** (SA3) 35-55.

O'CONNOR, D.J. (1967) The temporal and spatial distribution of Dissolved Oxygen in stream, *Water Resources Research* 3 (2) 65-79.

O'CONNOR, D.J., and DITORO, D.M. (1970). Photosynthesis and oxygen balance in stream, *J. San. Eng. Div. ASCE* **96** (SA2) 547-571.

PUGH III, A.L. (1973) *DYNAMO II User's Manual,* MIT Press, Cambridge, Massachusetts.

PUGH III, A.L. (1976) *DYNAMO User's Manual,* Fifth Edition, the MIT Press, Cambridge, Massachusetts.

STREETER, H.W., and PHELPS, E.B. (1925) A Study of Pollution and Natural Purification of the Ohio River, Public Health Bulletin 146, U.S. Public Health Service, Washington, D.C.

TAIPEI AREA SEWERAGE ENGINEERING DEPARTMENT (1971) Industrial Wastes Survey, Sewerage Planning in the Greater Taipei Area.

THOMANN, R.V. (1974) *Systems Analysis and Water Quality Management,* McGraw-Hill Book Co., New York, N.Y.

WATER RESOURCES PLANNING COMMISSION (1979) Planning Report, Water Pollution Control for the Tanshui River Basin, Taiwan, R.O.C.

WORKING GROUP (1974) Hsintien River Classification and Water Quality Standards, Research Report, prepared for the Chinese Institute of Civil and Hydraulic Engineering (published by this Institute in August 1975, in Chinese).