Catchment Modelling Of Non – Point Source Pollution Accretion For Rivers

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Abstract

Catchment process simulation models are designed to model the interaction of hydrological, geochemical and ecological processes and the effects of change.

TOMCAT, a catchment scale model was applied in modeling the transport of determinands from non-point (diffuse) sources to Mimram river, a tributary of the river Thames.

The magnitude and timing of the processes taking place is stochastic with the model representing as accurately as possible the systematic and random variability of various model inputs and their inter-relationships.

The results indicate that the BOD, NH_4N and Un-ionised NH_3 loads which enter the rivers from non-point sources increased by 0.55mg/l, 0.024mg/l and 0.001mg/l respectively. These values are relatively small. The Dissolved Oxygen concentration along the reach increased by 2.5 mg/l indicating substantial re-aeration along the reach. The accretion value for the conservative determinand Chloride was 3.75mg/l.

Non-point source pollutants accretion to the Mimram is influenced by agricultural and silvicultural practices in the catchment.

The results of the investigation indicate that the model could be adopted by environmental pollution control agencies as a management tool for intervention in the area of pollution abatement for catchments.

Keywords: Non-point source pollution, modelling, stochastic, catchment, accretion, riparian forest buffers

Introduction

Mathematical modelling is increasingly being used for studies related to environmental pollution and its control. Water quality models are being developed to facilitate the work of researchers, designers, managers and planners in their task of conceiving and solving problems associated with the physical, chemical and biological processes that are inherent in water pollution and its control.

In developing models for the investigation of river impact of non-point (diffuse) discharges, care has to be given to fitting the model to the specific problem without compromising on model simplicity, accuracy and flexibility. Data requirements and data availability should also be considered as controlling factors (Crockett, 1989).

Catchment process simulation models are designed with the inbuilt capability of modelling the hydrological, geochemical, and ecological processes and the effect of change. They are developed to model rainfall, evaporation, runoff, soil systems, geology, vegetation and river processes.

Non-point source pollution simulation models are “loading models” which represent the inputs and movement of materials from the point of origin to watercourses. They provide input concentrations and flow rates at interfaces with water quality models and simulate highly dynamic storm events, which result in high flows and flooding. The hydrologic components of non-point pollution models are sensitive to the magnitude of surface storage and soil permeability that determine surface runoff volume. Surface roughness affects the magnitude and time location of runoff peaks. Ground slope, soil moisture, soil erosion, adsorption characteristics and attenuation rates contribute immensely to the hydrologic component of models (Ekenta, 1990).

Theoretical and conceptual framework

Theoretical framework

A generalized catchment model TOMCAT - Temporal/Overall Model for Catchments (Brown, 1988) was developed by Thames Water for the investigation and review of the quality requirements of all discharges to rivers. The model combines a simulation based approach with the modular logic of the steady state catchment approach and has provisions for calibration and verification of simulated data with observed data.

It simulates the overall distribution of flow and concentrations of determinands by applying ‘Temporal Correlation’ concept, which takes account of seasonal and diurnal effects present in observed data. Time of travel effects are also modelled.

The model uses a comprehensive set of river catchment features termed ‘Catchment Events’ to represent a catchment. Interrelated catchment events of the model are linked to form a catchment unit by a combination of three basic processes:

- Data generation
- Self-purification and flow augmentation
- Flow mixing and mass balance

Data generation is carried out by sampling values from a known distribution. Self purification and flow augmentation are described by the empirical relationships

$Bt = (Bo – Bmin) \exp(-KBt) + Bmin$ . . . .(2.1)

$Qd = Qo + \phi\, dQo / Qo$ . . . .(2.2)

where Bo and Qo are the BOD concentration and flow at distance = 0 km
Bt and Qd are the BOD concentration and flow at distance = d km
Qo is the arithmetic mean flow at distance = 0 km
Bmin is the background BOD concentration at which the reach might be expected to stabilize in the absence of polluting discharges.
KB is a distance related first order exponential decay constant (Km^{-1})
ϕ is a distance related flow augmentation (accretion) constant.

Flow accretion is the overall non-point source input from overland flow spread over the catchment. It is a measure of the increase in long term average flow per unit distance due to storm runoff, sub-surface flow and base flow. Its effect on river quality is modelled by treating it as a point source located a distance d km with defined mean concentration.

The oxidation of Ammoniacal Nitrogen is described by the first order equation

$Nt = (No – Nmin) \exp(-KNt) + Nmin$ . . . . (2.3)

Where Nt = concentration of Ammoniacal Nitrogen at time t
No = concentration of Ammoniacal Nitrogen at time t=0
Nmin = concentration of Ammoniacal Nitrogen at stabilization point in absence of polluting discharges
KN = exponential decay constant whose value doubles for a 10 ^{o}C temperature rise.

The Oxygen Balance of the river is given by the Streeter – Phelps equation :

$dC/dt = kR(Csa\ t- Ct) - dB/dt - EdN/dt$ . . . . (2.4)

where
kR is the overall absorption coefficient
Ct is the dissolved oxygen concentration at time t
Csat is the dissolved oxygen saturation concentration and
E is the equivalent oxygen demand of ammoniacal nitrogen, assumed to be
4.57 (Gameson andWheatland, 1958).

TOMCAT uses an empirical expression for re-aeration of weirs (UK Department of Environment, 1973):

$r = 1 + 0.38abH(1 - 0.11H) (1 + 0.046T)$ . . . .(2.5)

where
r is the ratio of oxygen deficit above the weir to that below the weir

a is a parameter, the value of which depends on the degree of pollution of water flowing over the weir

b is a parameter, the value of which depends on the type of weir

H is the height of the weir above the water level downstream of it (m)

and T is the temperature of water flowing over the weir (^oC)

A decay constant similar to KN in the equation for Ammoniacal Nitrogen is applied in the simulation of Un-ionised Ammoniacal Nitrogen. Its formation is represented by the equilibrium equation

$NH_4^+ (aq) \Rightarrow \Leftarrow NH_3 (aq) + H^+ (aq)$ . . . . (2.6)

It is influenced by variations in pH and temperature.

Flow mixing and mass balance is followed by self purification and flow augmentation.

Conceptual Framework

Figure 2.1 shows the basic conceptual flow mechanism for a simple reach made up of flow along the principal water course and lateral flow from non-point sources.

By summing the flows for the reach the mass balance equations are obtained as follows:

$Ql = Qu + Qi - Qo$ . . . .(2.7)

$Ql.Cl = QuCu + QiCi - QoCo$ . . . . (2.8)

The mixing process is a mass balance, which utilizes a simulation approach for combining the distributions. Flow and quality data are generated for the start of the principal water course at the upper stream section. Self-purification and flow accretion are applied along the reach and across the reach respectively. Prior to mixing, quality data from non-point sources are input to simulate the flow accretion component. Flow and quality at the lower stream section is finally simulated.

This conceptual approach is further developed to include more complex components interacting with the principal water course -- tributaries, confluences, sewage effluent discharges, bifurcations and water supply abstractions (Bowden and Brown, 1983).

The quality interactions of the TOMCAT model is illustrated in Fig. 2.2 while Catchment Events are indicated in Table 2.1.

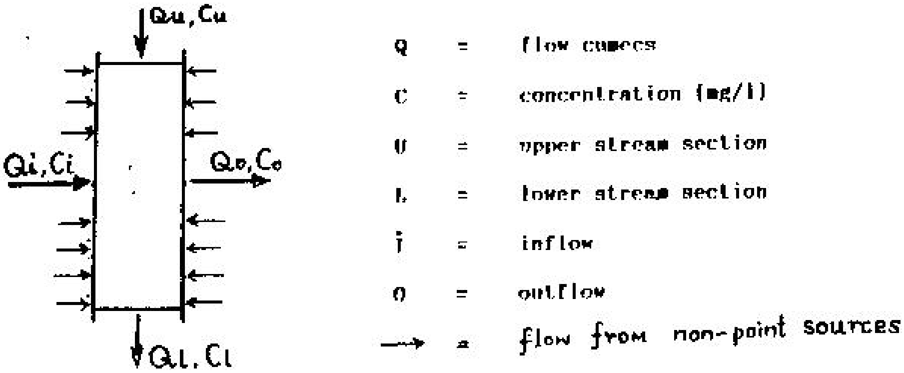

Fig 2.1: Conceptual Flow Mechanism for a Simple Reach

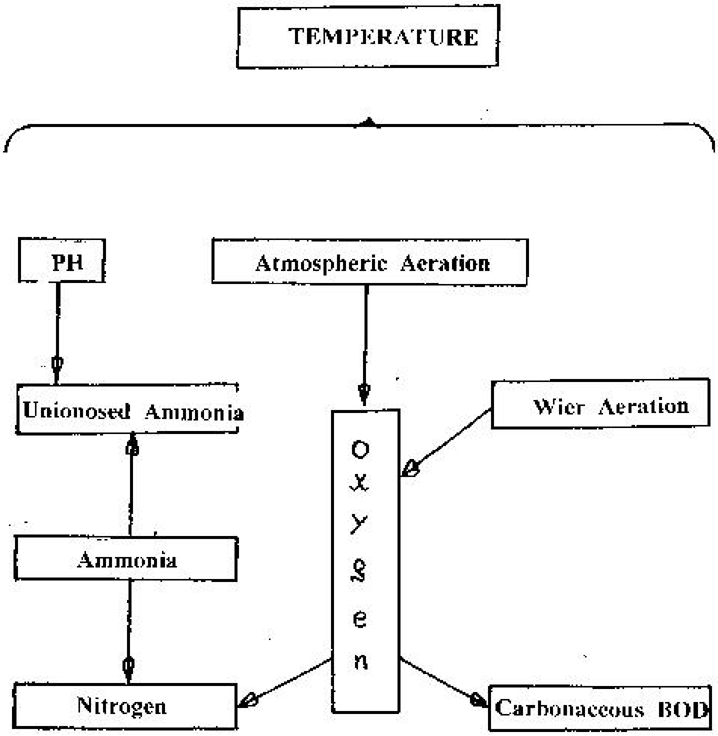

Fig 2.2: Quality Interactions of the TOMCAT Model

Table 2.1 : Catchment Events

Event No	Event Name	Subsidiary Options
1	Start of Principal Watercourse	
2	Start of Tributary of Current Watercourse	Independent or formed by bifurcation
3	Start of Reach	Compare simulation with observation
4	Hypothetical Interpolation Point	
5	Confluence of two Watercourses	
6	Sewage Effluent Discharge	Independent or abstraction linked
7	Weir	Free, stepped, cascade or slope
8	Bifurcation of a Watercourse	Open channel or weir/ spillway
9	Industrial or Water Supply Abstraction	Conditions of abstraction license
10	River Sampling Point	Compare simulation with observation
11	Catchment terminator	

Methodology

Introduction

A catchment scale model should as accurately as possible represent the systematic and random variability of various model inputs and their inter-relationships. The magnitude and timing of the processes taking place should be stochastic. TOMCAT introduces a temporal dimension in data analysis by carrying out random sampling from temporally – correlated non-parametric (TCNP) distributions. It takes into account the underlying seasonal and diurnal variations by extracting monthly and hourly means from observed data and finally deriving input data from the observed means and residuals.

Calibration and Verification

The calibration of a model involves the estimation and adjustment of various model parameters. The simulated model values are compared with field data by applying graphical and statistical techniques viz:

- Pictorial overlay of the two distributions
- Comparism of means and variances
- Mann-Whitney test for equality of the two medians
- Two sample Kolmogorov Smirnov test for equality of the two distribution functions

The method adopted was based on tests of statistical hypothesis. This procedure compares the goodness of fit of observed and simulated samples of the determinand.

The Mann-Withney (M-W) test was used as the limiting factor for the computation of non-point source accretion rates for the reaches. The M-W null hypothesis is that the medians of the two distributions are the same. The test estimates the probability P(X<Y) for two distributions viz:

$X_i, i = 1 , 2 , 3 , \ldots\ldots n$

$Y_j, j = 1 , 2 , 3 , \ldots\ldots m$

The test statistic U is the number of times observations in X is less than observations in Y. This implies that

$P(X<Y) = U/nm$

The hypothesis is rejected if the median of the simulated sample is not in the 100(1- $\propto$) percent confidence interval where $\propto$ is the probability of rejecting the hypothesis when it is true and is called the significance level of the test. For this investigation a significance level of 10 percent is applied.

An optimization process was carried out for each of the determinands with a view to locating the exact upper and lower limiting calculated probabilities in the given confidence interval. This involved the systematic adjustment of non-point source accretion rate of each determinand for several runs of the model. The accretion rates that indicate an acceptance of the null hypothesis at the highest and lowest calculated probability values were considered as constituting the non-point source determinand accretion rates for the reach.

The optimization process was aided by the observation of the closeness of fit of the observed and simulated distributions from a pictorial overlay displayed by a frequency plot program.

The Kolmogorov-Smirnov (K-S) test which compares the overall closeness of the observed and simulated distribution functions was also applied in assessing the measure of fit of the two distributions.

Calibration was carried out by fixing the rate constants at the default values and adjusting the concentration of non-point source determinands until good fits were obtained between observed and simulated values.

Verification is carried out by applying as many different sets of observed data as are available to the calibrated model.

Goodness Of Fit Tests

The goodness of fit tests indicated that all the determinands except Temperature passed the Mann-Whitney test. Two determinands, BOD and Chloride passed the Kolmogorov-Smirnoff test.

Appendix A shows a summary of calibration results obtained for the Mimram Model.

Analysis of non-point source determinamds inputs to rivers

Introduction

The Mimram river is a tributary of the Thames river, one of the largest rivers in England.

Fig. 4.1 shows the Thames river and its tributaries, the Mimram, Lee and Rib.

The Mimram reach for this investigation stretches from the village of Panshanger to the town of Hertingfordbury. It has a length of 3.43 km. The location of the reach is
shown in Figure 4.2.

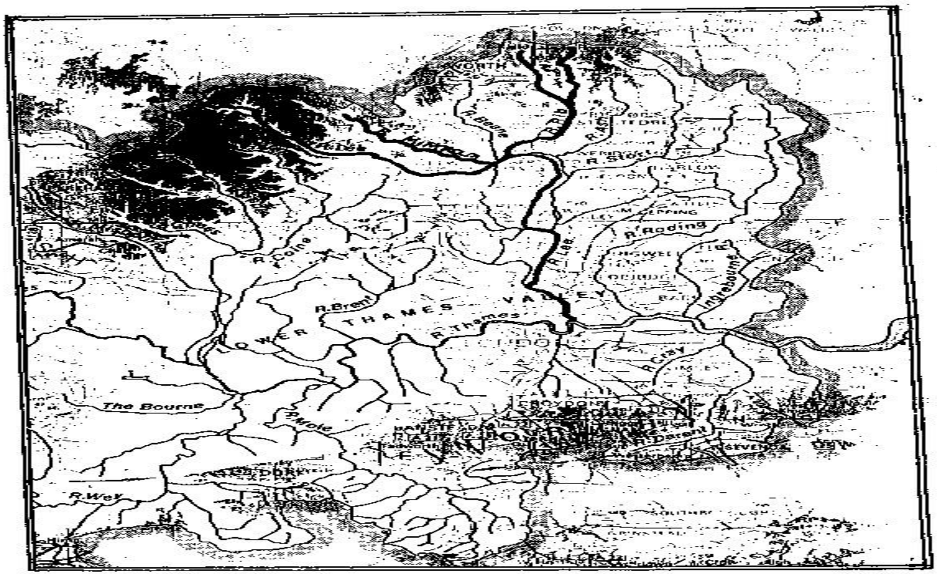

Fig 4.1: Thames river and its tributaries, the Mimram, Lee and Rib.

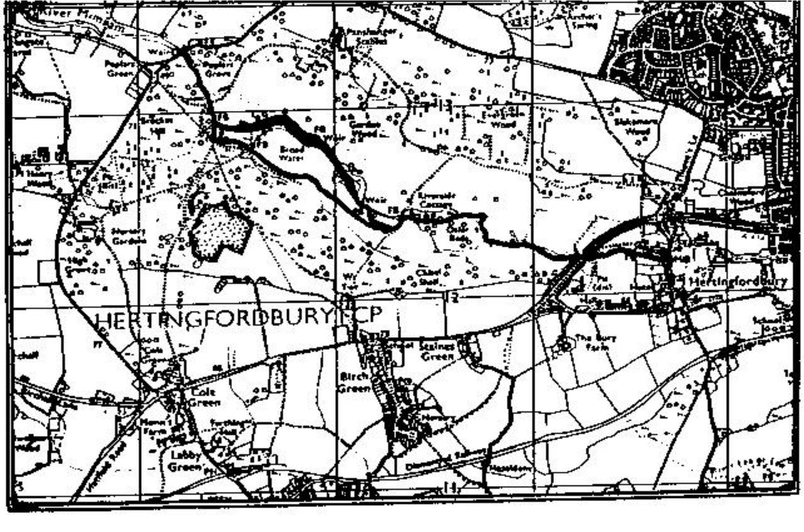

Fig 4.2: The Mimram Reach: Village of Panshanger to the town of Hertingfordbury.

The terrain is rolling and undulating. The land use pattern is predominantly made up of farmlands, open fields, pasture lands and pockets of natural forests preserved for conservation purposes. In the farmlands, wheat, vegetables, fruits and other crops are grown. Livestock including cattle and pigs are reared in feedlots. Riparian forests are observable along most of the right bank verges of the reach. For some stretches of the reach forest widths exceed 150 meters. The left bank has farmlands, grasslands and a few pockets of woodlands. The riverbed has a little weed growth and mud deposits and its water has low turbidity. Trees in the area include coniferous, non-coniferous and bracken.

Non-point source determinands transport to the reach is derived from overland flow, subsurface flow and base flow. The modeling of the Mimram reach was made slightly more complex by the splitting of the principal watercourse at a point 0.5 km downstream of Panshanger thereby introducing a bifurcation. Also located along the mainstream of the bifurcation are two weirs at distances of 1.1 km and1.35km from the start of the principal watercourse. The confluence of the principal watercourse and the tributary is located at a distance of 1.9 km from the start of the reach at Panshanger.

The properties of the watercourse at the start of the reach at Panshanger are indicated in Table 4.1.

Table 4.1: Mimram: Reach Properties

Reach length	3.3 km
Channel mean top width	12.0 meters
Channel bed width	8.0 meters
Channel mean depth	2.25 meters
Channel mean slope	0.0024 meters
Channel roughness co-efficient	0.04 (Manning)
Rate Constants for:	
Thermal Equilibrium	0.1/day
Carbonaceous Oxidation	0.1/day
Nitrification	0.43/day
Un-ionised Ammoniacal Nitrogen Decay	0.43/day
Oxygen Exchange (surface mass Transfer coefficient)	1.8 m/day
Background concentration:	
BOD	0.00mg/l
Total Ammoniacal Nitrogen	0.00mg/l
Un-ionised Ammoniacal Nitrogen	0.00mg/l
Flow accretion	2100.0 m^3/day/km
Concentration in non point sources:	
BOD	0.65mg/l
Total Ammoniacal Nitrogen	0.060mg/l
Un-ionised Ammoniacal Nitrogen	0.000mg/l
Dissolved Oxygen	4.500mg/l
Conservative Determinand	21.25mg/l

4.2 Data Preparation and Analysis

Five year (1980 – 1984) flow and quality data were analyzed for the upstream end of the reach at Panshanger. The outputs from the data preparation programs were used for the setting up of the Principal Input Data File in accordance with the format specified in the TOMCAT Users Manual. Similarly the Secondary Input File was set up for data obtained at the downstream end of the reach at Hertingfordbury.

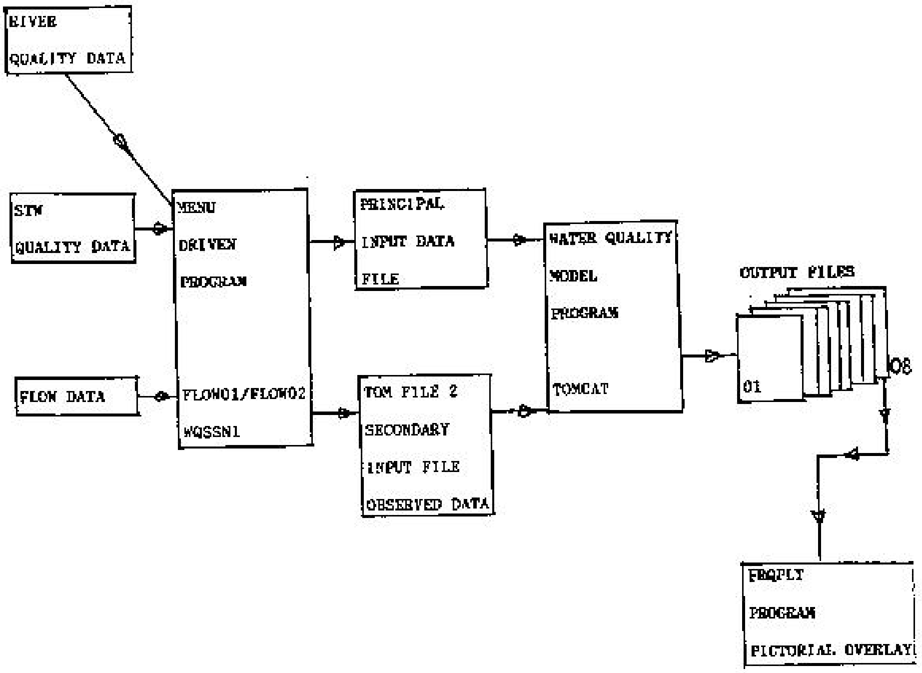

Fig 4.3: Interaction between data archives, data preparation programs, input/output files, frequency plot program and TOMCAT model

Pictorial Overlays

Best-fit distributions were determined from relative frequency histograms output and pictorial overlays for observed and simulated values at the downstream end of the reach.

The pictorial overlays for the model showed a close fit for observed and simulated BOD values with the greater part of the distribution located in the range 0.8 mg/l to 2.40 mg/l. NH_4-N showed a fair fit with the greater part of the distribution located in the range 0.0 mg/l and 0.2 mg/l. For Un-ionised NH_3 the range 0.001 mg/l to 0.003 mg/l showed that observed samples had significantly higher class percentages than simulated samples. Dissolved Oxygen had significant variations in the ranges 8.5 mg/l to 9.2 mg/l and 9.20 mg/l to 11.4 mg/l where higher class percentages are predominant for observed and simulated values respectively. Temperature with observed values exceeding simulated values for the greater part of the distribution did not show a good fit The conservative determinand Chloride with the greater part of the higher class percentages in the range 14.0 mg/l and 23 mg/l had the best fit of all the determinands.

Results

The investigation showed that about 90 percent of Mimram river catchment is agricultural. Non point source determinand inputs to the river is influenced by the agrarian environment of the area. The concentration of each input is controlled by agricultural and silvicultural practices in the area. Agricultural practices include – conservation tillage, contour farming, stream bank protection, stream channel stabilization and terracing while silvicultural activities concentrate on the development of riparian forest buffers.

Table 5.1 shows the results for non-point source accretion for the Mimram.

Table 5.1: Non-Point Source Determinand Accretion for Mimram

Determinand	Non Point Source Concentration (mg/l)		
	At Panshanger (start of reach)	At Hertingfordbury (end of reach)	Accretion
BOD	0.65	1.2	0.55
NH_4N	0.06	0.084	0.024
Un-ionised NH_3	0.00	0.001	0.001
DO	4.50	7.0	2.50
Chloride	21.25	25.0	3.75

The results indicate that the BOD, NH_4-N and Un-ionised NH_3 loads which enter the rivers from non-point sources are relatively small. The application of modern agricultural practices and the development of vegetative riparian forest buffers of adequate widths with effective filtering capacity (Phillips, 1989) contributed to the low accretion values obtained and the reduced level of pollution of the river.

The Dissolved Oxygen concentration along the reach increased by 2.5 mg/l indicating substantial re-aeration along the reach despite the continuous diffusion of pollutants from cross-flow and co-current sources.

The accretion values obtained for Dissolved Oxygen and the conservative determinand Chloride agree with average loading rates and relate to the environmental conditions of the area.

Conclusion

The investigation achieved the objective of determining magnitudes of non-point source (diffuse) determinand accretions into the river Mimram through the application of a stochastic water quality catchment model.

The accretion of determinands is a function of the land use pattern in the area. Agricultural practices and the existence of riparian forest buffers, which filter off pollutants contributed to the low levels of accretion, simulated (Rogers and Rosenthaal, 1988)

Organisations responsible for water quality management have applied various techniques in regulating pollution levels in rivers. Two approaches being enforced are Emission Standards (ES) and Environmental Quality Standards (EQS). A catchment scale model like TOMCAT can be applied as a management tool for the investigation of different catchment scenarios to facilitate decision making for intervention in water quality planning.

Terminology

Bifurcation	- Branching of a watercourse into two separate channels
Determinand	- Physical, chemical and biological characteristics of waters and wastewaters. Parameters that determine the quality of water sources.
Principal Watercourse	– Any hydrological network of which the upstream and downstream boundaries are located on the same watercourse.
Residuals	- Values that are left over after the subtraction of all seasonal and/or diurnal effects.
Simulations	-Subjecting a model to various changes in such a way as to explore the possible effects of these changes on real systems
Abatement	- Reduction in intensity of occurrence.
Stochastic	- A process that connotes the chance of occurrence of an event within space or time and containing elements of randomness.

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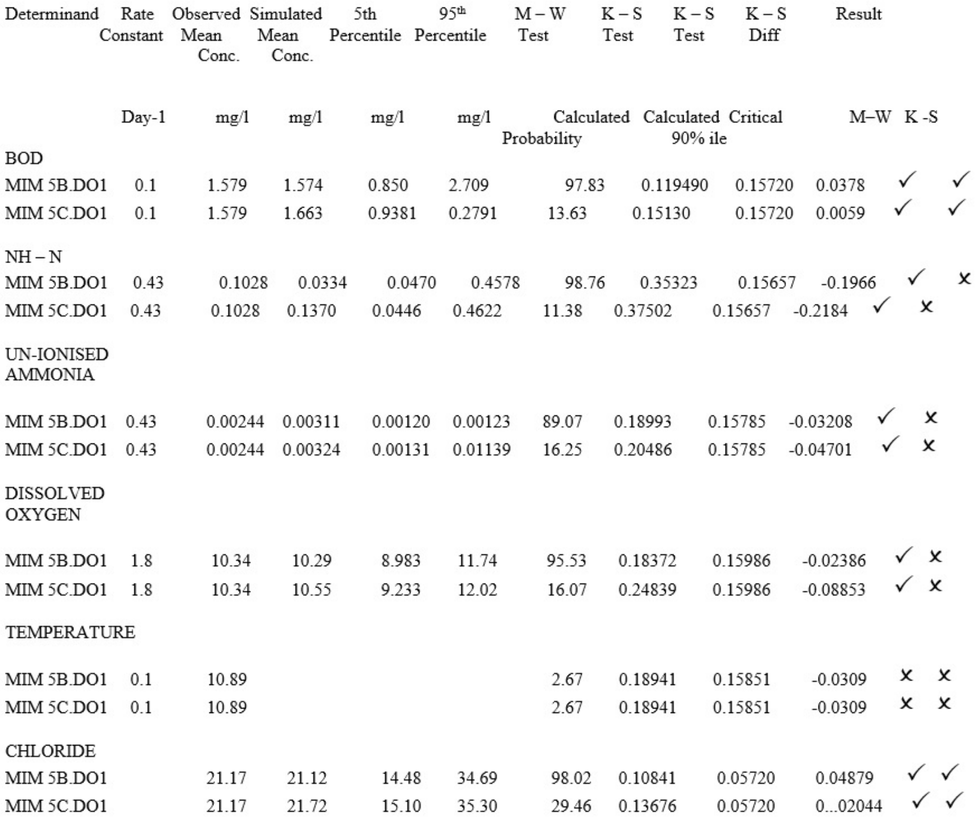
APPENDIX A: Summary of Calibration Results Obtained for the Mimram Model



Determinand	Rate Constant	Observed Mean Conc.	Simulated Mean Conc.	5th Percentile	95th Percentile	M – W Test	K – S Test	K – S Test	K – S Diff	Result	
	Day-1	mg/l	mg/l	mg/l	mg/l	Calculated Probability	Calculated 90% ile	Critical		M–W	K -S
BOD											
MIM 5B.DO1	0.1	1.579	1.574	0.850	2.709	97.83	0.119490	0.15720	0.0378	✓	✓
MIM 5C.DO1	0.1	1.579	1.663	0.9381	0.2791	13.63	0.15130	0.15720	0.0059	✓	✓
NH – N											
MIM 5B.DO1	0.43	0.1028	0.0334	0.0470	0.4578	98.76	0.35323	0.15657	-0.1966	✓	✗
MIM 5C.DO1	0.43	0.1028	0.1370	0.0446	0.4622	11.38	0.37502	0.15657	-0.2184	✓	✗
UN-IONISED AMMONIA											
MIM 5B.DO1	0.43	0.00244	0.00311	0.00120	0.00123	89.07	0.18993	0.15785	-0.03208	✓	✗
MIM 5C.DO1	0.43	0.00244	0.00324	0.00131	0.01139	16.25	0.20486	0.15785	-0.04701	✓	✗
DISSOLVED OXYGEN											
MIM 5B.DO1	1.8	10.34	10.29	8.983	11.74	95.53	0.18372	0.15986	-0.02386	✓	✗
MIM 5C.DO1	1.8	10.34	10.55	9.233	12.02	16.07	0.24839	0.15986	-0.08853	✓	✗
TEMPERATURE											
MIM 5B.DO1	0.1	10.89				2.67	0.18941	0.15851	-0.0309	✗	✗
MIM 5C.DO1	0.1	10.89				2.67	0.18941	0.15851	-0.0309	✗	✗
CHLORIDE											
MIM 5B.DO1		21.17	21.12	14.48	34.69	98.02	0.10841	0.05720	0.04879	✓	✓
MIM 5C.DO1		21.17	21.72	15.10	35.30	29.46	0.13676	0.05720	0...02044	✓	✓