

Chapter 6

Modelling Changes in Surface Water Quality for Watersheds Undergoing Urbanization

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6.1 Introduction

In this paper we describe a linked cascade of modelling procedures assembled specifically to assess changes created by urbanization in the quantity and quality of streamflow. This

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assessment is a key to successful integrated watershed management, a concept which has received widespread support in Ontario recently (PCAO, 1991; Queens Printer, 1991; Charlton and Tufgar, 1991).

Subwatershed studies are needed as part of integrated watershed management to determine the impact of development that exists or is anticipated, to evaluate the effectiveness of measures to prevent or remediate damage, and to assist decisions on acceptable levels of urbanization. Urbanization changes both the flow rates of water within various hydrological processes and the physical, chemical and biological attributes associated with these processes. Techniques used for assessment of the environmental impacts of urbanization must account for all these changes.

The modelling approach that is summarized here has been created as part of the Laurel Creek Watershed Study (Charlton and Tufgar, 1991). This study is being carried out primarily by Triton Engineering Services Ltd. of Kitchener and Ecological Services for Planning Ltd. of Guelph, for the Grand River Conservation Authority, the Regional Municipality of Waterloo and the cities of Kitchener and Waterloo in Ontario. The first three authors of this paper are subconsultants for this study.

The model components we assembled and used have been carefully selected to provide the assessments required to meet the objectives of the Laurel Creek Study. The objectives of the study are to establish acceptable levels of urbanization, and to recommend measures to protect, rehabilitate and enhance water quality, associated water resources, fisheries, wetlands and environmentally sensitive areas.

In the following sections of this chapter we describe component modelling procedures and the links among them that were used to assess changes in water quality from urbanization. Typical results from Laurel Creek illustrate the range of impacts that can be assessed. The chapter concludes with comments on the effectiveness and applicability of the methods.

6.1.1 Laurel Creek Watershed Study

Laurel Creek is a tributary of the Grand River located within Waterloo Region in southwestern Ontario. The watershed area of approximately 77 km² is currently half urban and half rural land use. There is both a strong demand for additional urban development in the rural area, and a desire expressed by citizens and planners in Waterloo Region to maintain natural features in the watershed. A study funded by the Cities of Waterloo and Kitchener, the Regional Municipality of Waterloo, and the Grand River Conservation Authority was initiated in 1991. The objectives of the study are to:

- establish acceptable levels of urbanization,
- protect and rehabilitate fisheries,
- protect wetlands and environmentally sensitive areas, and
- protect and enhance water quality including associated water resources.

The assessment technique had to meet these objectives, and account for the impact on water resources of land use changes, and preventative and remedial measures. The study is being carried out primarily by the Consulting team of Triton Engineering Services Ltd, Kitchener, Ontario and Ecological Services for Planning Ltd., Guelph, Ontario. Additional details of the study may be found in Charlton and Tufgar, 1991.

6.2 Modelling Framework

In the Laurel Creek Study results from modelling of surface water quality were needed to assess impacts on various uses. There were specific objectives for streamflow, baseflow, protection of groundwater, water quality, fish species and habitat, wildlife habitat, natural resource areas and recreation. Assessment of possible impacts of urbanization on fisheries and stream habitat is particularly challenging because of the multiplicity of factors

involved. This type of impact assessment is emphasized in the following discussion of modelling procedures. The main impacts and their associated evaluative approaches are:

1. **IMPACT:** Increased overland runoff, increased peak flows in channels, and reduced baseflow.

EVALUATION: A watershed model which accounts for
REQUIREMENT imperviousness and channel characteristics in rural and urban land uses.

APPROACH: The GAWSER model linked to a GIS indicates these effects.

2. **IMPACT:** Physical changes caused by changes in flow, including higher peak velocity in runoff events, reduced depth during low flows, and increased channel erosion due to increased velocity.

EVALUATION: Average channel velocity and depth as a
REQUIREMENT function of flow.

APPROACH: The GAWSER model calculates velocity-depth-flow relationships which are used to calculate stream power.

3. **IMPACT:** Reduced water quality due to runoff from urban and rural areas. The main contaminants of concern are sediment, nitrogen compounds, phosphorous, dissolved oxygen and temperature.

EVALUATION: Water quality contaminant levels to
REQUIREMENT compare with stream reach based targets for fisheries.

APPROACH: The DOMECOL Model package is used to calculate plant biomass and dissolved oxygen. Suspended solids concentrations are generated by the GAWSER model. Temperatures are calculated by an empirical approach based on observed conditions (with expected improvements in approach prior to project completion). The HSI suitability model is used to convert contaminant levels and physical factors to fish species suitability.

Figure 6.1 shows how the models interrelate. The details of the approaches are provided in succeeding sections.

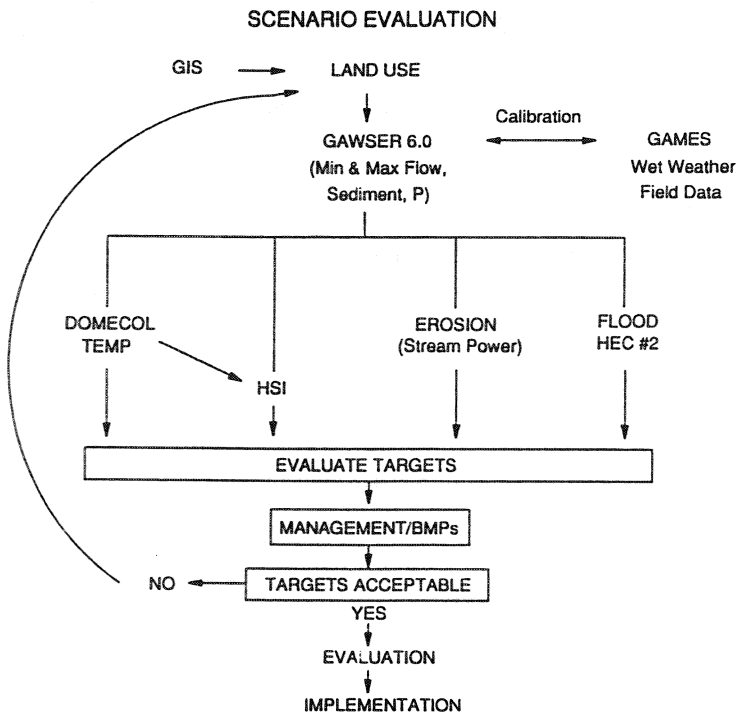


Figure 6.1: Interrelationship of models used in evaluation.

6.3 Watershed Hydrologic Model: GAWSER

An overall watershed model was employed to simulate the hydrological conditions and amounts of pollutant washoff, and to provide a framework from which to operate the DOMECOL model package.

The Guelph All-Weather Sequential-Events Runoff (GAWSER) model is a deterministic hydrologic model, based on the HYMO format (Ghate and Whiteley, 1982; OMNR, 1989), that is applied widely in Ontario for planning, design, real-time flood forecasting, and evaluating the effects of physical changes in the drainage basin (e.g. GRCA, 1988; Triton 1990; Schroeter et al., 1992). GAWSER is used to simulate the total streamflow resulting from precipitation inputs defined in terms of rainfall, snowmelt or a combination of both. For simulation, drainage basins can be divided into a series of linked elements representing watersheds, channels and reservoirs (see Figure 6.2). The physical effects of each element are simulated using efficient numerical algorithms representing tested hydrologic models that are described briefly below.

GAWSER was modified recently to operate in a continuous mode, and to predict pollutant accumulation, washoff and transport. These changes have resulted in version 6.0 of GAWSER.

6.3.1 Representation of Spatial Variation in Runoff Amounts

To account for the spatial variability in sequences of rainfall, snowfall, air temperature and wind speed, a watershed is divided into zones of uniform meteorology (ZUM) (see Schroeter et al., 1991). Each ZUM uses one set of meteorological measurements and covers one or more subwatersheds. Typically, a ZUM may be from 100 to 350 km² (Schroeter et al., 1991). Variations among spatially-distinct surfaces of infiltration, percolation rates within the soil, and overland runoff amounts are accounted for in each ZUM by separate calculations for one impervious and up to four pervious areas.

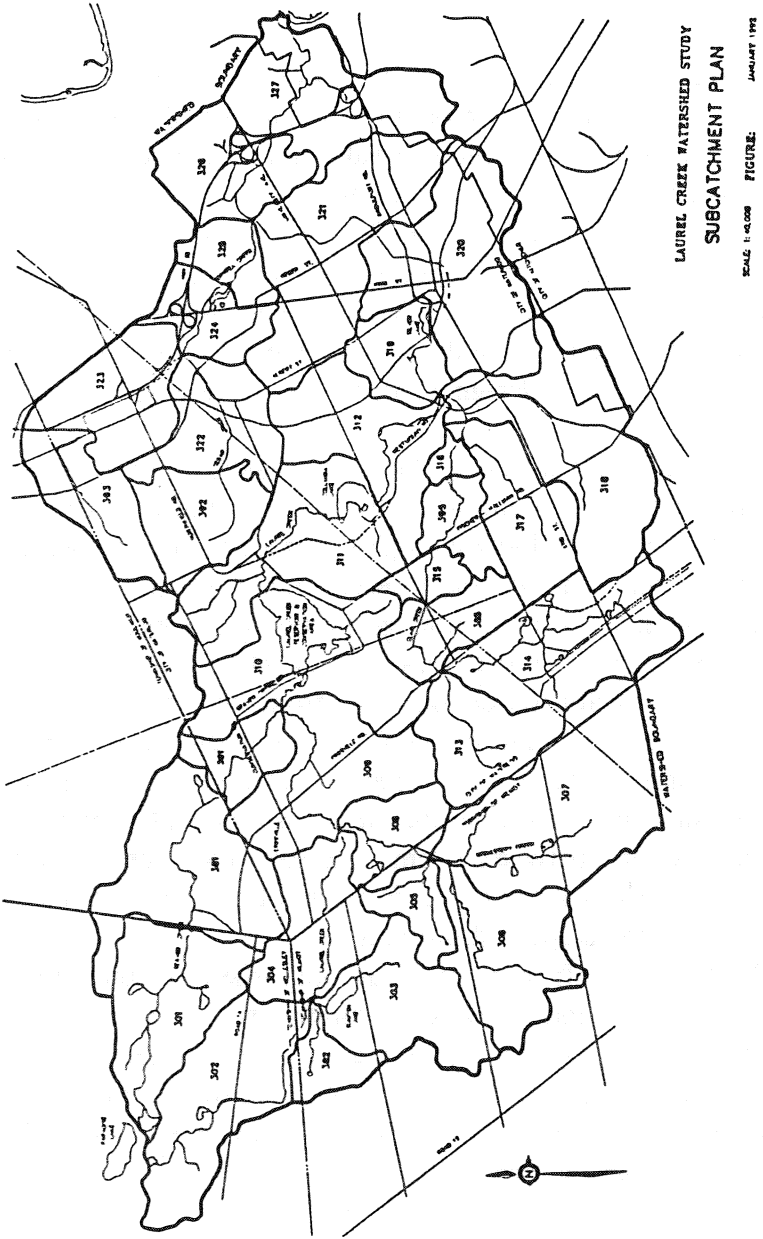


Figure 6.2: Subcatchment plan for Laurel Creek Watershed Study.

6.3.2 Model Inputs and Simulation of Hydrologic Processes

The model can operate at time steps as small as one minute or as long as 24 h, depending on the availability of meteorological inputs for the selected time interval. In most applications to date, GAWSER has been operated at a one hour time step to correspond with available rainfall rate inputs and streamflow comparison data. The program can access standard input data formats (e.g. Atmospheric Environment Service compressed hourly and daily files), and will compute the rainfall distribution for standard urban design storms directly (e.g. Chicago, SCS, Hydrotek).

GAWSER considers eight hydrological processes: snow accumulation and melt, infiltration, evapotranspiration, runoff estimates, overland flow routing, subsurface and baseflow routing, stream channel routing, and reservoir routing (with operations).

A flow chart for the runoff generation procedures is given in Figure 6.3. Each pervious area within a ZUM is modelled as two soil layers. Soil-water outflow from the second layer is distributed between subsurface flow and groundwater storage by a proportioning factor. The Green-Ampt equation is used in the infiltration calculations; the computations account for the recovery of infiltrability between events. Evaporation, or sublimation during periods of snow cover, is set at a fixed daily amount, and applied in time steps with no rain.

Overland runoff routing is accomplished by the area/time versus time method, in which computed rating curves based on cross-section measurements for main and off channels are used to define the computational parameters. Outflows from subsurface and groundwater storage (baseflow) are simulated using a single linear reservoir approach.

Channel routing is handled by the Muskingum-Cunge method (see Schroeter and Epp, 1988), and the reservoir routing is accomplished by Puls method in which controlled releases are allowed.

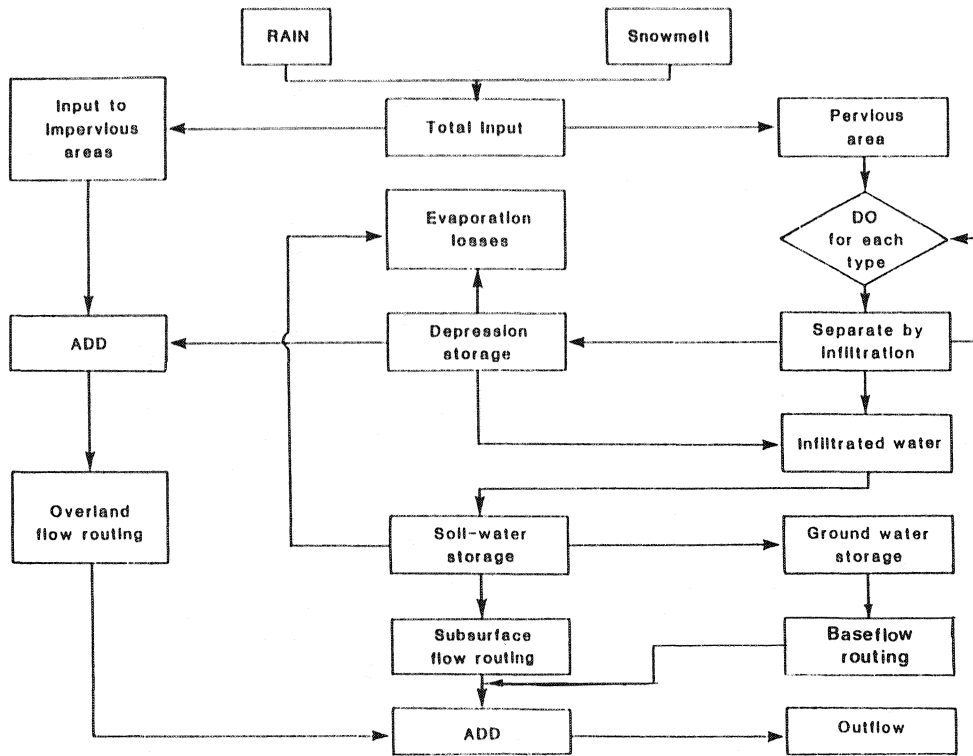


Figure 6.3: GAWSER model runoff generation procedure.

6.3.3 Pollutant Accumulation-Washoff and Transport

The approach for simulation of water quality selected for use in GAWSER V6.0 was based on sediment transport. It is generally recognized that many contaminants, especially organics, nutrients, toxics and heavy metals, are associated with sediment or solids transported by stormwater runoff (e.g. Dickinson and Green, 1988; Marsalek and Schroeter, 1989). The new water quality submodel in GAWSER is based on the Equivalent Solids Reservoir (ESR) algorithm developed and tested by Schroeter and Watt (1989) for use in the Queen's University Urban Runoff Model (Q'URM), but expanded to include a pollution accumulation feature for continuous simulation work.

The dry-weather accumulation of pollutants is modelled using the approach employed in STORM (U.S. Army Corps of Engineers, 1977). Here, dry-weather build-up between events is accounted for by specifying a daily rate of accumulation. The base daily rate is reduced by the number of dry-days since the last runoff event or street sweeping episode times a reduction constant.

The complex sediment transport process is represented by the mechanisms of translation and scour/deposition. First, the mass inflow of contaminants is lagged by the kinematic travel time of the water flow in each drainage element (for subwatershed elements - each impervious and pervious zone). Next, the deposition and resuspension (erosion/scour) processes are simulated using a fictitious equivalent solid reservoir located at the outlet of each drainage element. Required parameters and inputs are limited to two sediment characteristics (particle size and relative density), scour and deposition rate parameters, and initial sediment loadings. Sediment inputs from rainfall, surface and baseflow are considered by assigning fixed concentrations to these sources.

Up to four water quality parameters can be simulated in GAWSER. Where it is known that a given parameter is a function of another one already being simulated (e.g. total phosphorous as a function of suspended solids), the modelling is

made simpler by specifying a constant ratio between the two parameters for washoff calculations.

6.3.4 Continuous Operation Mode and Linkage to Other Models

To allow operation of GAWSER in a continuous simulation mode a configuration (or batch) file system was installed, whereby the user specifies a series of event files that follow sequentially in time, and hence, are run by the program one after another. While executing a particular event file for a given calculation period (e.g. Nov. 1 to 25), GAWSER creates a file on disk to initialize the next event file in sequence. This end file is read by the program during the next calculation period to initialize the same computation variables.

Seasonal changes in model parameters (e.g. effective hydraulic conductivity, or snowmelt/refreeze factor) are directly specified in the sequential event files. At present, each individual event file can simulate a 25 day period when the computation time step is set at one hour.

To help transfer hydrograph and "qualograph" output from GAWSER in a format for input to other programs (e.g. ECOL, DOMOD7, and hydrograph plotting software), a special program called GAWSTRAN was created. At present, GAWSTRAN will read hourly temperature and solar radiation data from AES files and create input directly for the ECOL model. It will also create daily flow and water quality load summary tables that are similar to those printed in Water Survey of Canada's annual Surface Water Data publication.

6.4 Plant Biomass Model: ECOL

6.4.1 Overview

Attached algae and macrophytes (rooted aquatic plants) are the

agents that predominantly determine dissolved oxygen levels in rivers of southern Ontario. Models must account for their effects.

The Grand River Simulation Model (GRSM) (Weatherbe, 1986) is a continuous simulation model that accounts for sewage treatment plant inputs, main channel inputs, tributaries, and urban runoff. Dissolved oxygen relationships include carbonaceous and nitrogenous oxygen demand, sediment oxygen demand, reaeration, and the impact of three species of aquatic plant and algae through oxygen production by photosynthesis and oxygen uptake by respiration. The plant growth relationships were incorporated into a subroutine called ECOL. A stand-alone version of the ecological subroutine was also programmed, called ECOL1. (Walker et al, 1982). A simple steady state version of the dissolved oxygen model was also prepared called DOMOD7. These three models were resident on mainframe computers at the Ontario Ministry of Government Services and the Grand River Conservation Authority. The two simpler models, ECOL1 and DOMOD7 were converted to run on IBM PC compatible computers for use in the Laurel Creek Study by Dr. Alan A. Smith, Burlington, Ont.

6.4.2 ECOL Model Descriptions

The ECOL model provides continuous simulation of the growth of aquatic plants and algae over a typical season, ie. April to November. Inputs of plant nutrients (phosphorous and nitrogen) along with sunlight are the main factors leading to growth. The predominant species observed in the Grand River Basin are accounted for.

Figure 6.4 shows the interrelationships in the model. The energy source for the plant growth is sunlight. The model accounts for sunlight variations in two-hour time-steps, and allows each species to grow with the amount of growth depending on its current biomass, available nutrients in the plant and water, available light, temperature, and species-specific growth coefficients. Available light is affected by incoming solar

incident sunlight, stream flow, concentrations of sediment and phosphorus) and result in changes in aquatic plant biomass. To determine if changed biomass level is of concern, the effect of the plant biomass on the dissolved oxygen (DO) regime, and particularly the minimum daily DO of the stream is required. This can be facilitated with the aid of the model, DOMOD7 (Dissolved Oxygen MODEL- Version 7) (MOE, 1987).

DOMOD7 simulates dissolved oxygen concentration in the stream during a 24 hour day accounting for principal sources and sinks. Once calibrated using field data, the model can specify minimum DO under "design" conditions of critical stream flow, temperature and biomass level.

6.5.2 DOMOD7 Model Description

DOMOD7 simulates stream conditions for a 24-hour period on a 2-hour time step basis. Six water quality parameters are simulated: dissolved oxygen (DO), ultimate biochemical oxygen demand (BOD_u), nitrogenous oxygen demand (NOD), nitrite plus nitrate (NITR), suspended solids (SS) and total phosphorus (TP).

For modelling purposes, the river system is divided into sequential sections termed "reaches". The junction points of these reaches are called "nodes". DOMOD7 can handle up to two tributary streams or outfall discharges in each reach. Flow and water quality from these point sources are input on a two-hourly interval basis.

The model incorporates the principle oxygen sources and "sinks" associated with a flowing stream. Sources are atmospheric re-aeration, photosynthetic oxygen production of plants; sinks are sediment oxygen demand (SOD), exertion of nitrogenous and carbonaceous biochemical oxygen demand and plant respiration.

Plant respiration and photosynthetic production are modelled by a subroutine which is essentially a reduced version of ECOL.

First-order kinetics apply to the exertion of BOD and NOD and to the reaeration process. BOD and NOD decay rates

generally have to be measured in the field. Re-aeration rates are more readily estimated by empirical formulae; for Laurel Creek, the rate was derived using the depth and velocity of the stream reach of interest. Velocity, travel time and depth were computed based on the stream flow rate of interest and the same channel hydraulic relationships used in the GAWSER model. Decay rates are not critical in Laurel Creek, since BOD and NOD are relatively low; therefore reasonable approximations to decay rates were made based on rates from other streams in the vicinity.

Sediment oxygen demand data have been measured in the study area and are converted from the measured areal rate to a volumetric rate by dividing by depth of flow.

Both the average daily temperature and daily range for the corresponding Julian Day are input into DOMOD7. The model applies a sinusoidal diurnal variation in water temperature, based on the mean temperature and temperature range input by the user, which allows for a temperature to be calculated at each time step. DO saturation concentrations are computed for each time step from the water temperature. All key rates in the model are adjusted for temperature.

Stream temperature was adjusted to simulate the effect of development according to a relationship suggested by Galli (1990). Typically, mean stream temperature increases of about 1.0° C. are seen with watershed imperviousness increases of 12%. Further development is required to fully integrate all major temperature effects into the models.

6.6 Sample Application of Modelling Approach

In this section, we give sample output from each of the models described above to demonstrate the capabilities of our modelling framework for surface water quality assessment. Our results are only preliminary as the final assessment procedures in the Laurel Creek study are still in progress and under review.

For modelling purposes, the watershed was divided into a

number of reaches, each draining the accumulative area from more than 25 subwatersheds as depicted in Figure 6.2. The watershed model included consideration of the Laurel Creek Dam, which controls outflows from a 39 km² area and is operated by the Grand River Conservation Authority (GRCA) for flood control and recreation.

6.6.1 The Typical Year Approach

Changes to the surface water resources within the watershed in response to anticipated development were assessed on the basis of a typical year approach. The typical year was selected using the historical streamflow records for the Laurel Creek gauge in downtown Waterloo. Here, a year was defined on a water year basis (Nov. to Oct.), because the long-term simulations had to begin during a period prior to the accumulation of snow.

Our typical year was defined as being a mean flow year that had a distribution of monthly flows that corresponded to the most frequent pattern observed in the historical records. The period Nov. 1, 1968 to Oct. 31, 1969 had eight months with close to long-term mean flows, the greatest number of any year in the record, and hence was selected as our typical year.

6.6.2 Sample GAWSER V6.0 Output

This section illustrates the types of output from GAWSER V6.0 that are used in water quality assessments. The results presented are for 1968-69 typical year input with data for the existing (1991) watershed conditions and a few of the future development scenarios.

The hydrologic model parameters throughout the year were established from previous experience in applying GAWSER in forecast mode for the whole Grand River basin over the last four years (Schroeter et al., 1992). Due to the lack of event specific data on water quality for Laurel Creek, published values for the

ESR model parameters (Schroeter and Watt, 1989) were used to provide the initial settings for the GAWSER water quality submodel. Because the sediment washoff routine had not been applied previously in rural watersheds, the computed annual sediment loads for the rural areas (e.g. Reach 309) were compared with the reported annual sediment loads for selected Ontario streams (Dickinson and Green, 1988). There was considerable agreement in the computed sediment loads.

Figure 6.5 shows the simulated daily discharge hydrographs for existing and ultimate development conditions at the Laurel Creek Weber Street gauge for the period May 15 to July 15 in the typical year. Notice the program's ability to model the baseflow recession between runoff events. For the period shown, the discharges during events are slightly higher for the ultimate over the existing case, whereas the baseflows are slightly lower in the ultimate case.

A plot of monthly total sediment load for Laurel Creek Reach 309, upstream of the reservoir, is presented in Figure 6.6 for two future development scenarios. Notice that the ultimate development case (Fut 4A) produces a significant increase in sediment load for the November period.

The sediment transport algorithm produces useful information for fish habitat assessments. Figure 6.7 gives a plot of net sediment deposition in a number reaches in the upper Laurel Creek watershed. Such a plot can be used to show how changes in stream channel conditions (e.g. channelization, or naturalization) will influence the amount of sediment that deposits in a stream segment. From this plot, Reach 309 is generally free of sediment deposits.

6.6.3 ECOL Model Applications and Results

The model was set up and applied for several reaches with input provided by the GAWSER output, augmented by water temperature and sunlight data. The predicted biomass of each species is shown in Figure 6.8 for one set of temperature and

Daily discharge - May 15-July 15, 1969
modelled for Laurel Creek at Weber St.

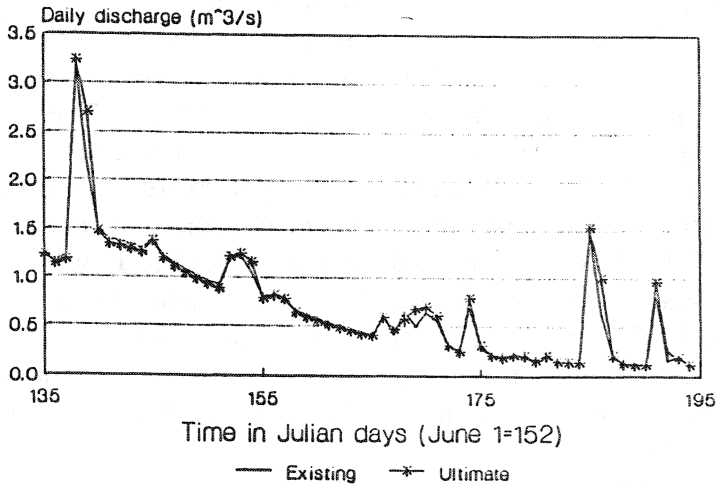


Figure 6.5: Sample GAWSER flow output.

Mean Monthly Sediment Loads
for Laurel Creek Reach 309

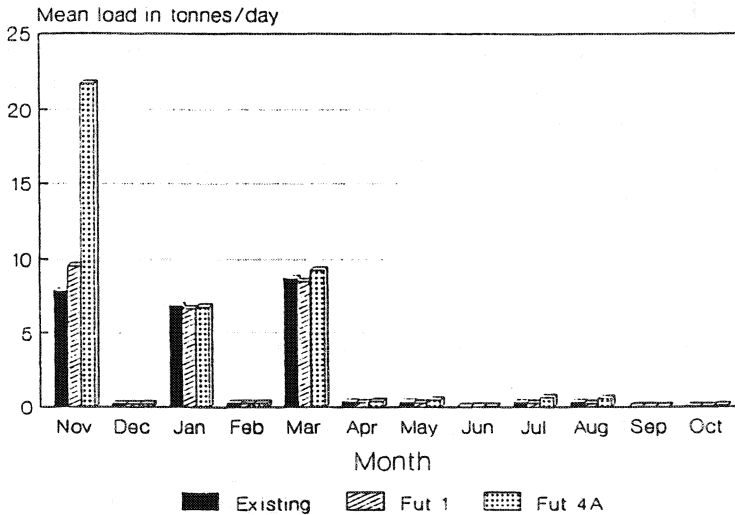


Figure 6.6: Sample GAWSER sediment load prediction.

SEDIMENT DEPOSITION UPPER LAUREL CREEK

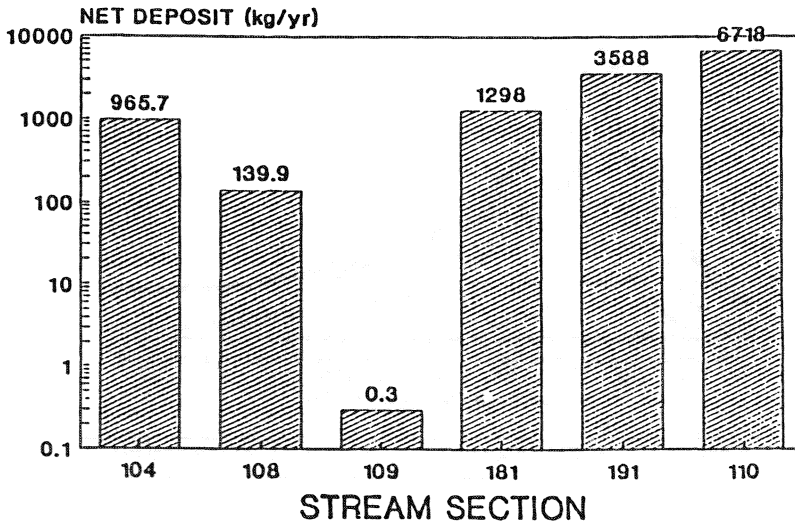


Figure 6.7: Sediment deposition predicted by GAWSER.

flow conditions, and total phosphorus concentrations generally below .01 mg/l. Note that the model defaults to a minimum biomass of 5gm/m² for each species. Note also that plant biomass consists primarily of epiphytes and cladophora. This is consistent with the observed species in the Laurel Creek. Total biomass peaks around the end of May (day 140) as temperatures start to increase and spring flows are receding.

The model was also used to test the sensitivity to phosphorous input variations. Figure 6.9 shows the total predicted biomass for the same reach later in the year at various constant phosphorous input levels. (Note that 109 and 309 refer to the same reach).

6.6.4 Sample DOMOD7 Output

In the Laurel Creek application of DOMOD7, model rates as described above were initially adjusted according to reach-specific characteristics. The model was calibrated using the model's subroutine light and plant inhibition factors. Calibration success

Laurel Creek ECOL Simulation
Reach 109 - Base Condition

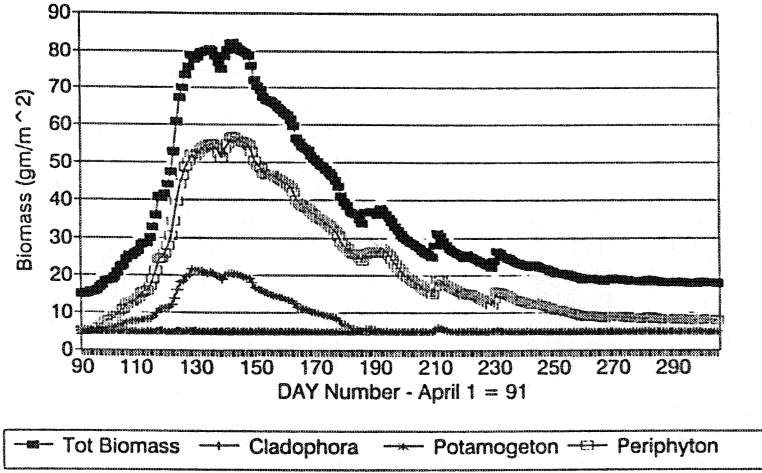


Figure 6.8: Sample ECOL output - predicted biomass for different species.

was based on matching the daily DO maximum and DO minimum with the survey data.

The calibrated model was then used for predicting DO under various conditions of stream flow, temperature and aquatic plant biomass as predicted by ECOL. To set up these runs, the ECOL output for a specific development scenario was examined to determine the peak biomass occurrence date and the stream flow and water temperature associated with this peak growth. DOMOD7 was run under these conditions. An example DO predicted with this high biomass condition is shown in Figure 6.10.

In our application of this model, plant respiration and photosynthetic DO production, and re-aeration were the key processes influencing the diurnal variation of dissolved oxygen.

Aquatic plant biomass as simulated by ECOL did not respond dramatically to development; consequently no major shifts in dissolved oxygen minimums simulated by DOMOD7 for specified reaches and design conditions were noted. The processes simulated by DOMOD7 are sensitive to temperature, however;

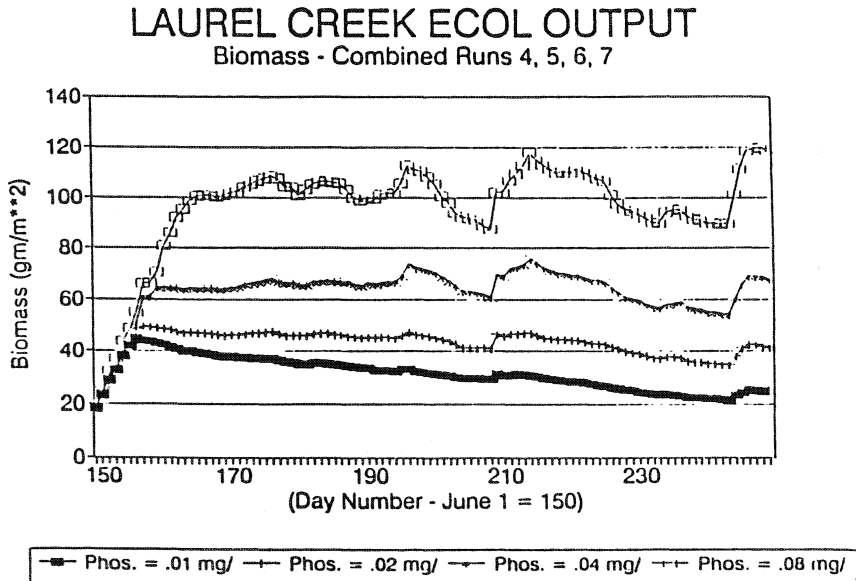


Figure 6.9: Total biomass predicted by ECOL at different phosphorous input concentrations.

hence increases in temperature related to urban development must be taken into account when using the DOMOD7 model in predictive mode.

Outputs of daily minimum DO from DOMOD7 runs are plotted in Figure 6.11, showing the effects of increased biomass and temperature for one stream reach. Model runs were done with existing, and increased biomass levels, and with design stream temperatures increased as a result of two levels of development. These model runs were "worst case" scenarios which combined peak seasonal biomass predicted by ECOL with least favourable stream flow. Even with no increase in biomass, temperature effects associated with development can be seen to result in minimum daily DO being lowered by nearly 0.5 mg/l. In terms of HSI targets, this is a significant departure from the HSI minimum desirable DO concentration of 6.0 mg/L for trout.

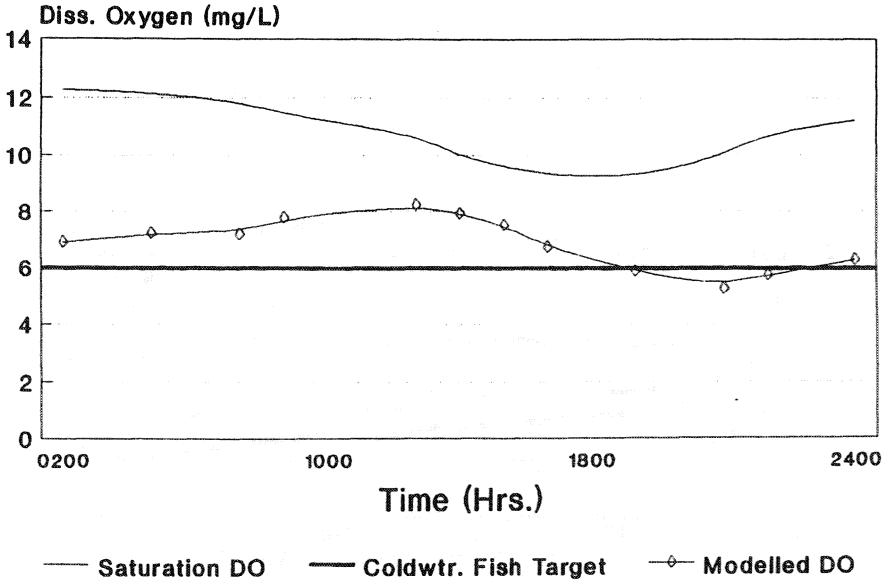


Figure 6.10: Dissolved oxygen predicted by DOMOD& during peak biomass conditions for reach 109.

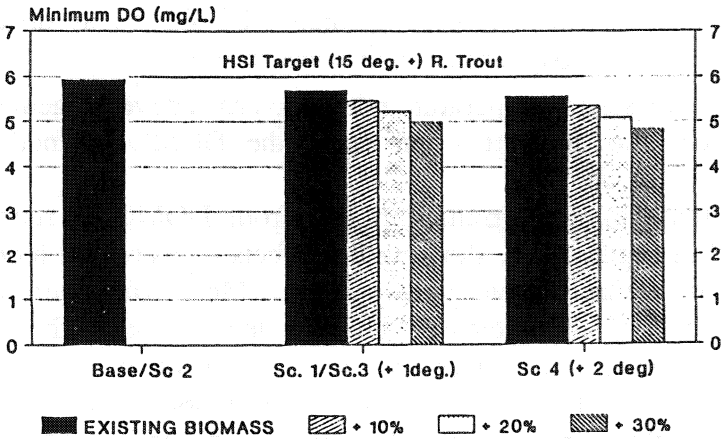


Figure 6.11: Dissolved oxygen levels predicted at various land use scenarios and temperature levels.

6.6.5 Application of Output for Fish Habitat Assessment

In this study a number of water quality and quantity parameters related to fish habitat and other water uses were selected as key for assessment of the watershed impacts of different development scenarios. These parameters, or related outputs can be generated by GAWSER, ECOL and DOMOD7 and compared between scenarios or with criteria of interest.

The selected outputs are in part derived from the Habitat Suitability Indices (HSI) developed for use by the U.S. Fish and Wildlife Service (Raleigh *et al*, 1984; Edwards *et al*, 1983). This approach uses an extensive number of parameters concerning physical, chemical and biological characteristics of streams to develop indices ranging from 0 to 1 for fish species of interest.

For the present study, two fish species were of interest: smallmouth bass and rainbow trout, which are considered "warm water" and "cold water" fish species, respectively. From the extensive list of HSI variables, several may be selected about which information may be gained using the models. An example list as selected from the smallmouth bass HSI is shown in Table 6.1, also indicating the model(s) used to generate the required data.

Table 6.1 Selected Habitat Suitability Indices - Smallmouth Bass.

Variable	Desireable Range	Model Source
Spawning period Temp.	11 - 27 deg. C.	Temperature Model
May - Oct Water Temp.	Adult: 11 - 29 deg. C.	Temperature Model
	Fry: 13 - 33 deg. C.	" "
	Juvenile: 10 - 31 deg. C	" "
Monthly ave. Turbidity	0 - 70 JTU	GAWSER
Minimum DO through year	4 mg/L (6 mg/L is optimum)	DOMOD7

Note that Suitability Indices (SI's) have been selected from the overall array of HSI variables only because of model ability to generate values for comparison; a comprehensive habitat assessment would include the full array of HSI variables related to physical, other chemical and biological factors.

6.7 Conclusions

The models presented in this paper are useful for predicting the impact of urbanization for the major impacts anticipated in the watershed under study. At the time of presentation of the paper (March, 1992), additional work was still to be completed, to be reported in future. This is identified here, both to indicate the additional applications, and to clarify some limitations of the procedure.

Future work includes:

1. completion of the evaluation of different land-use scenarios;
2. addition of a temperature modelling routine to the procedure;
3. evaluation of reservoir impacts. The option of removing reservoirs or bypassing base flow is being considered in the watershed;
4. the model packages could be improved with enhanced integration, to make them more efficient; and
5. the models would benefit from additional verification.

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