

A Model of hydrological and
biological interactions in a
Water Course

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Abstract

The model described in this report is meant to show how some of the practical problems of combining hydrological and biological processes can be addressed, how models can be used to examine specific questions, and along what lines the present model ought to be developed to eventually arrive at a useful policy tool.

Introduction

A model is best thought of as a map. As different maps serve different purposes, so do different models serve different programs. And just as a tourist would be ill-advised to use an industrial zoning map, so should a model not be used for purposes other than the ones it was designed for.

Ours is a model to demonstrate the feasibility of addressing the needs outlined in the Abstract through a formal system dynamics simulation model. The basic assumptions derive from that.

Assumption

First, we assume that the continuous river system can be broken down into discrete reaches. The desired resolution can be achieved by making the reaches smaller and smaller, thereby using more and more of them to cover a given section of the river.

Second, we assume that the biological processes that take place in the river part and the lake part of a watercourse are the same. What differs is the speed with which material is moved and the strata where the processes take place. We model this by using basically the same structure for all interactions in the water but vary the parameters from river to lake.

Third, we assume that the degree of diversity does not change over the course of our investigation.

Fourth, we assume that it is sufficient to keep track of biological energy, matter and nutrients, and of how hydrological conditions affect these three.

Fifth, we assume that the value of our model will be greater if the parameters chosen reflect to some extent a real river system. Therefore, we chose to model the outflow from a eutrophic lake, a mesotrophic river part and an oligotrophic lake. This situation exists in reality in the Halden watercourse from the outflow from Bjoerkelangen to Roednesjoen.

Overview

As a first approximation to reality we can view the biology and the hydrology of a watercourse as two planes at angles to each other.

The biological plane represents in this visualization a potential of (biological) production. The interaction with the hydrological plane determines then how much of the potential will be realized. Passing through a waterfall, for example, none of the potential will be realized on account of the fast flowing water; in a lake, on the other hand, most if not all will be realized.

We have further assumed that the interaction of both planes takes place along the line AB in Figure 1. The line corresponds in the formal model to the set of state variables (i.e. the variables that accumulate all differences in the rates of change). Each state variable has, in addition to in- and outflow rates determined by biological causes, in- and outflow rates determined entirely by hydrology.

In this first model we omit all interactions of the type CD. An example of that would be the relationship between flow and turbidity and mixing of nutrients. The strength and significance of these types of causal relations will be explored in later versions of the model.

Conceptually, therefore, our model looks like Figure 2, n reaches, linked by hydrology, are identical in structure, but different in parameter. Each reach contains as many organisms, currently grouped into trophic levels, as desired and keeps track of as many nutrients as necessary. Each trophic level in turn is split into compartments, initially only mass and energy. The model is, in short, a matrix with the following elements: reaches (2), trophic levels or species (3), living matter compartments (2), and nutrients (2). (The numbers in brackets refer to the current level of resolutions.) Repeated solution of the difference equations, currently once every eight hours of simulated time, moves all matrix elements through time.

The assumption of uniformity within a reach allows us to treat both biological and hydrological processes in a simplified manner. The biological reality is reduced to an interaction between matter and energy and a cycling of nutrients. Energy controls the growth, decay and consumption of matter, whereas matter is the medium of transporting

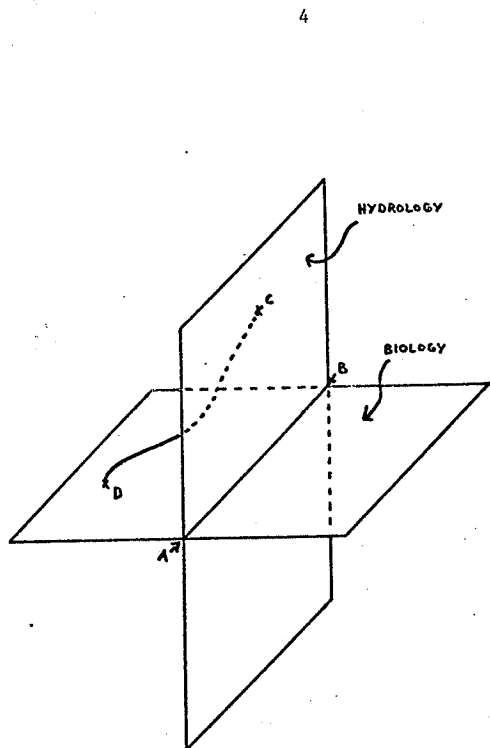


Figure 1 : Biological and hydrological planes.

The entire watercourse is then divided into reaches. The criterion to separate one reach from another derives from the assumption of uniformity within each reach. Whenever the conditions in the river change significantly, a new reach should be started. In the present model we chose the crudest interpretation of "significant" and merely differentiate between the river part and the lake part of the watercourse.

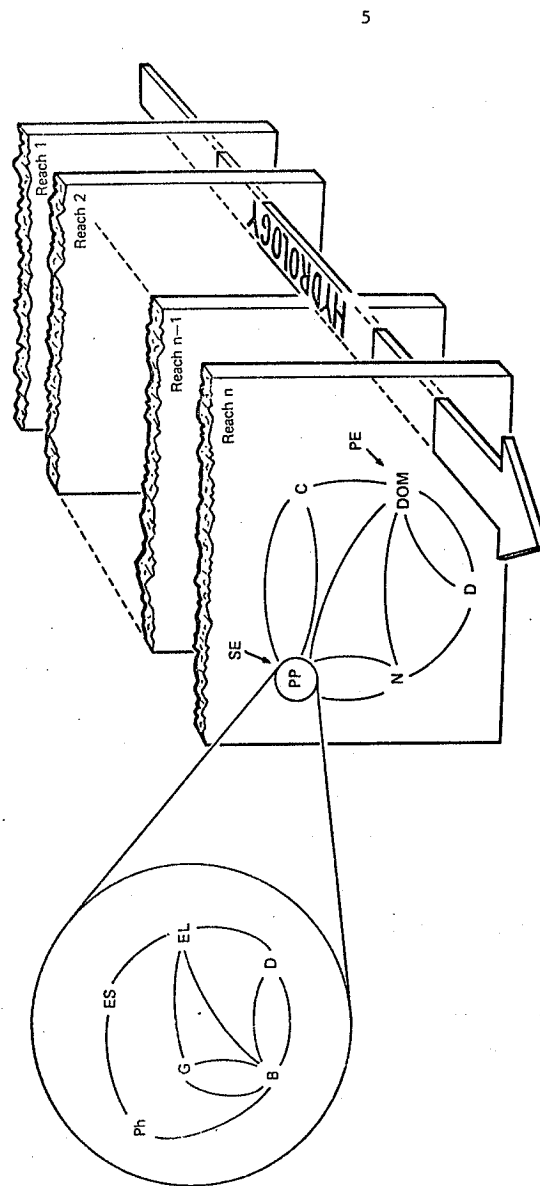


Figure 2 : Stacked Reaches connected by Hydrology

energy through the biological system. Once again we have in this demonstration model chosen the simplest of worlds: matter is divided into three trophic levels and dead organic matter. Of all possible nutrients we only keep track of nitrogen and phosphorous, which are judged to be the only limiting ones in Norwegian rivers.

Trophic Levels

In each trophic level we keep track of various attributes. Currently, only mass and energy are included, but in the future, stored nutrients, energy compartments and the like may be added.

We felt it necessary to include matter and energy even in this demonstration model, because we believe the usual linear relationship between the two to be wrong in a small, but crucial area, namely in the phase relationship between them.

Energy is fixed, through photosynthesis for primary producers, and through consumption and energy transfer for the other levels, stored and then released. The bulk of it is used for maintenance: respiration and maintaining the structural and biochemical integrity of the organism. Some is used for growth. Other uses, notably community energy expenditure and energy expenditure for defensive strategies are not yet accounted for. In any case, however, it is the availability of energy that determines an organism's maintenance, growth, and consumption strategies. Matter is intractably connected to the energy balance, for it provides the mechanisms to fix more energy while at the same time maintaining it constitutes the most significant energy drain. Time lags between growth of mass, fixing of energy, utilization of energy

and further changes in mass seemed to us important enough to trace the relationships in detail.

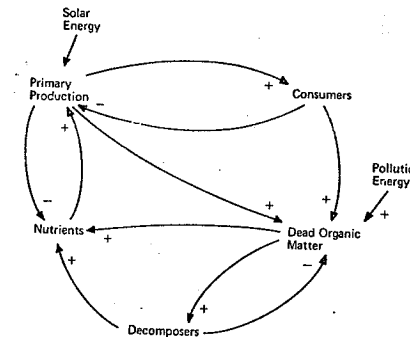


Figure 3 : General Trophic Level Structure

Figure 3 gives a general impression of the relationships included in each trophic level. Mass increases exponentially in the absence of death at a certain rate (i.e. doubling time) reflecting environmental conditions such as temperature, nutrient availability etc. Growth, in the long run, i.e. during a season, is balanced by deaths, either through grazing or simply through natural death. Phase shifts between growth and death lead to the usual abundance in the summer and the near absence of mass in the winter.

The level, or amount, of mass causes a certain amount of energy to be fixed, although the increase of energy is also related to the amount stored, relative to the needs. In other words, if an organism has starved for some time, it will use more of its remaining energy to secure more food (Calow: 30-36), thus raising its energy fixed per unit mass. Energy will be decreased primarily through maintenance expenditure. In the model we assume that if energy is limited other uses will be curtailed to allow the maintenance of existing organisms. This is achieved by manipulating the amount allocated to each of the tasks. The residual of energy is available for growth. Death of matter reduces both the mass and the amount of energy stored.

Nutrients

The role of nutrients in the demonstration model is limited. We keep track of nitrogen and phosphorous in their soluble form. We make allowances for the seasonal turnover in lakes that move nutrients from the bottom where they tend to be released up to the epilimnion where they tend to be used by primary producers. We link concentration to growth by Michaelis-Menton type relationships but loose track of nutrients once they are taken up in biomass.

At a later stage we believe it to be very fruitful to track nutrients even in the biomass which will then allow for a more realistic representation of the relationships between concentration and uptake, nutrients-in-biomass concentration and growth, and the luxury consumption relationships.

Hydrology

Since hydrological models are rather far advanced we have tried to avoid the mistake of reinventing the wheel. Instead, we have concentrated on the question of linking hydrology and biology and have provided only a very rough hydrology section. Principally, we generate average flows in each reach and keep track of the volume. By knowing the mass of organisms, grouped into trophic levels, we know the amounts entering and leaving a reach. At present, all water enters reach 1, flows through the system, and leaves reach 2. We have not yet allowed for evaporation, diversion, runoff and the like.

Model Extensions

Work on extending the model must be preceded by a thorough analysis of the purpose of the extension. Assuming for the time being that a more accurate policy tool is the purpose, the following guidelines may be of help.

Biology

It is easy to include more and more detail, but whether this will automatically lead to a better model is not clear. As maps can become confusingly complex, so can simulation models. The suggestion below should, therefore, be read with these reservations in mind.

Nutrients

One obvious extension is the inclusion of more, or different, nutrients. A prime candidate is oxygen. Care should be taken not to include all nutrients, but only those that make, or are expected to make, a significant contribution to a change in the behavior of the system.

Energy

Currently, energy is biological energy on the population level, even though the concept of maintenance and growth are mapped over directly from the organism level. A useful question to explore is the significance of other uses of energy at the population level: growth through division vs. growth through reproduction; defensive strategies; maintenance of structural and biochemical integrity; changes in energy uses over the life of the population; and the like. Equally interesting is the problem of mapping biological energy over to the ecosystem level to allow direct comparison between kinetic, chemical, heat, and biological energy.

Aggregation

The grouping of organisms into mutually exclusive trophic levels was made without much reflection simply because standard text books split up the world that way. Some thought should, therefore, go into the question of the best suited mechanisms of aggregation.

Compartments

Two attributes, mass and energy, are presently kept track of. It may well be advisable to describe living matter through more attributes. A first one that comes to mind for the primary producers is nutrients. This would allow the decoupling of external concentration from growth, a decoupling that is known to exist in reality through, for example, the phenomenon of luxury consumption.

Hydrology

The most useful extension in hydrology would be a thorough survey of existing hydrological model. Depending on the type of model

available, it may be possible to adapt one, or, at the very least, knowledge of other hydrological models will greatly reduce the development cost of a realistic hydrology sector. We feel that such a sector should allow for precipitation and temperature being transformed into monthly (or weekly) runoff, for ground- and river water exchanges if that is significant, and for evaporation from lakes. It should also be easy to simulate withdrawal of water in any given reach, introduction in other reaches, and regulation of flow.

Geography

Theoretically it is possible to cut the river system up into smaller and smaller reaches, so that the assumption of uniform conditions within the reach becomes more and more true. In practice, however, two problems arise. First, the solution interval must be not larger than 1/5 or so of the smallest time constant in the model to ensure reasonable computational accuracy. If reaches become tiny, retention time becomes extremely short and a model run of 5 to 10 years requires many millions of computations. Computers can handle this but the cost per run may be judged to be too high.

Second, the assumption of uniformity extends to exogenous inputs to the reach. It may be difficult, if not impossible, to get the input resolution to match the fine reach resolution. Taking larger input units and dividing them by the number of reaches over which they are spread defeats the whole idea of small reaches.

Data

Much of the data needed for a model of the kind described in this report is difficult to get. One model extension is, therefore, to

begin a dialogue with professional data gatherers to work towards a better match between data needed and data offered. Modern data gathering has developed to the point of being virtually automatic and continuous. The promise of a model like ours, which is to provide a theoretically solid and consistent framework for the analysis of these floods of data should make it easier to open such a dialogue.

Conclusion

Models are means. The end is to better understand the working of an entire river system to make more intelligent decisions about a limited resource. Model extensions should always be designed with that end in mind and not be allowed to become ends in themselves.

Acknowledgements

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