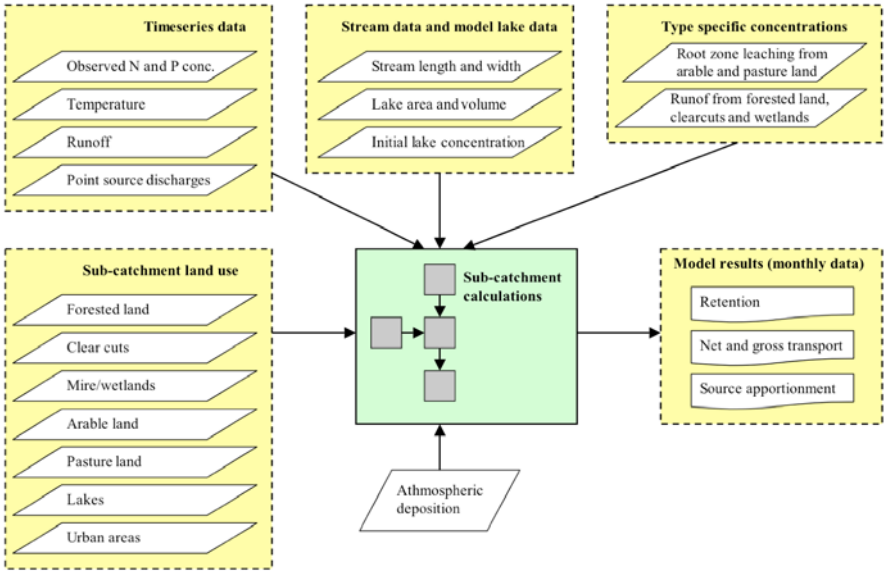
The FYRIS model Version 2.0

– A tool for catchment-scale modelling of source apportioned gross and net transport of nitrogen and phosphorus in rivers

Technical description



by

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2006 Report 2006:17

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ISSN 1403-977X

Contents

1 Model history

The dynamic Fyris model was originally developed by Hans Kvarnäs at the Dept. of Environmental Assessment at SLU[1] for calculating source apportioned nitrogen and phosphorus transport in the River Fyris catchment in central Sweden (Kvarnäs 1996). After this first model application the model has been further developed in applications for the Lake Vättern catchment (Kvarnäs 1997), the Lake Storsjön catchment (Johansson & Kvarnäs 1998), catchments of coastal areas in Lake Vänern (Wallin et al. 2000) and the River Göta catchment (Sonesten et al. 2004). During 2005-2006 the platform for the Fyris model has been changed from LabView (http://www.ni.com/labview) to Visual Studio and .Net Framework (http://msdn.microsoft.com/netframework). The users manual describes the new version of the model released in September 2006.

2 Input data from other models

Some of the data that the model requires is generated by other, external models. The dynamic SOILNDB model (Johnsson 2002) is used for calculating type-specific concentration of nitrogen in leaching from agricultural land. For calculating type-specific concentration of phosphorus in run off from agricultural land a regression model has been used until now (Ulén et al. 2001). This model will, however, in the future be replaced by the dynamic ICECREAM model (Larsson et al. 2003). For calculating the type-specific concentration of nitrogen and phosphorus in run off from forested areas a regression model is used (Löfgren & Westling 2002). For calculating run off and water discharge, the HBV model (Bergström 1995) or the Q model (Kvarnäs 2000) is used.

3 Model description

The dynamic Fyris Model calculates source apportioned gross and net transport of nitrogen and phosphorus in rivers. The main scope of the model is to assess the effects of different nutrient reduction measures on the catchment scale. The time step for the model is one month, and the area units of operation are sub-catchments. Retention, i.e. losses of nutrients in rivers and lakes through sedimentation, up-take by plants and de-nitrification, is calculated as a function of water temperature, nutrients load, water flow, lake surface area and stream surface area. By tuning of two parameters, the model output is calibrated to fit time series of measured nitrogen or phosphorus concentrations.

Data used for calibrating and running the model can be divided into time dependent data, e.g. time-series on observed nitrogen and phosphorus concentration, water temperature, run off and point source discharges, and time independent data, e.g. land-use information, lake area and stream length and width (Fig. 1).

[1] Swedish University of Agricultural Sciences

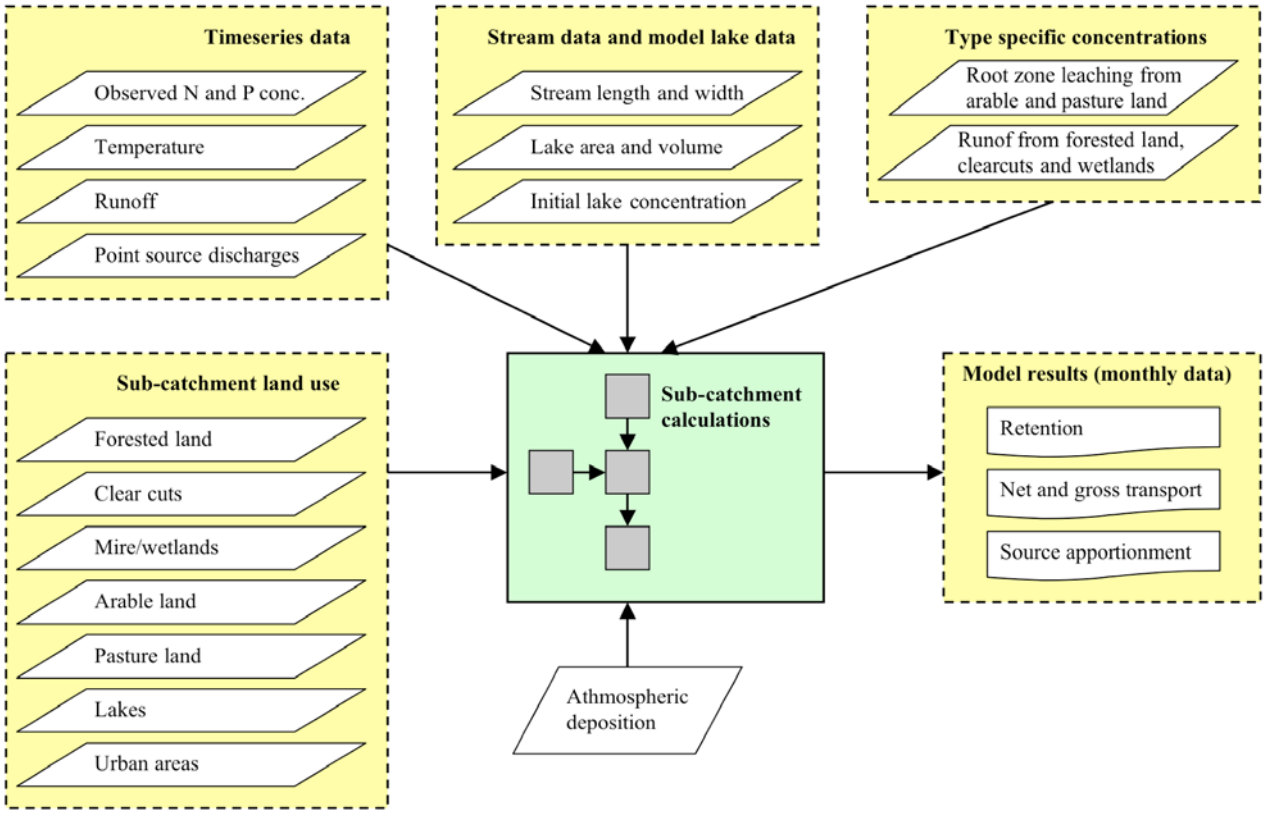

Figure 1. The structure and characteristics of inputs and outputs of the model.

4 Input data

The Fyris Model requires plenty of input data (Fig. 1). The characteristics of the data varies and includes e.g. data specific for a certain type of land use (like concentration of nitrogen in the root zone in an arable land), or data that is identical for the whole catchment area (such as the temperature time-series).

4.1 Time series data

The Fyris Model operates with a temporal resolution of one month. Consequently, the input data that has a different temporal resolution must either be averaged or interpolated in an appropriate way. The observed in-stream concentrations that are used for calibration do, however, not need to be given for every month.

Observed N and P concentrations
In-stream N and P concentrations are generally monitored at a few locations in the catchment area. This data is used for calibration and validation.

Temperature
Ideally, this should be the water temperature, but in practice the air temperature is often used as an approximation since it is more easily available. Given the relatively small size of most catchments, it is assumed that the temperature is the same throughout the catchment area. The temperature influences the nutrient retention calculations in the model.

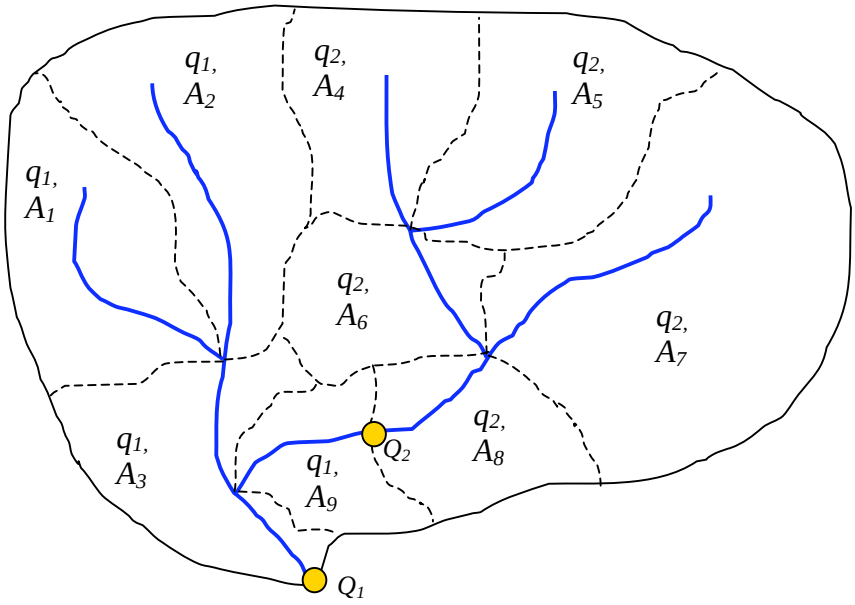

Figure 2. The areas (A), discharge measurement stations (Q), and area specific runoffs (q) within an example catchment.

Specific Runoff

The water flow determines the mobilization and transport of nutrients through the catchment. In the Fyris Model, the area specific runoff, $q(t)$ [LT^{-1}], is used to quantify these processes. In general, the water flow data is provided externally as discharge, $Q(t)$ [L^3T^{-1}], and must thus be converted to area specific runoff before usage in the Fyris Model. The external model typically calculates discharge for a spatial scale larger than the sub-catchment scale at which the Fyris Model operates. Similarly, when measured values of discharge are used rather than modelled values, these measurements are not generally available for every sub-catchment. This problem is solved by assuming that the area specific runoff is equal in every sub-catchment of the catchment, for which the discharge was computed or measured.

In order to facilitate the understanding of how the area specific runoff is computed from measured discharge, an example catchment area consisting of nine sub-catchments will be used (Fig 2). The catchment area contains two stations for discharge measurements, designated Q_1 and Q_2, whose locations are marked with filled circles. Starting with the upstream discharge measurements station, the sub-catchments whose runoff contributes to the measured discharge Q_2 are numbers 4, 5, 6, 7, and 8. Thus, the area specific runoff, q_2, is given by

$$q_2 = \frac{Q_2}{A_4 + A_5 + A_6 + A_7 + A_8},$$

where q_2 is applicable for sub-catchments 4, 5, 6, 7, and 8, and A_i is the area of sub-catchment i. Next, the discharge measured in station 1 (Q_1) includes the discharge passing station 2 in addition to the runoff from areas 1, 2, 3 and 9. Hence, the discharge measured in station 2 must be subtracted from the discharge measured in station 1 in order to correctly calculate the area specific runoff from areas 1, 2, 3, and 9, as given by

$$q_1 = \frac{Q_1 - Q_2}{A_1 + A_2 + A_3 + A_9}.$$

Storage
Lakes having a turnover time larger than about three months significantly affect the downstream transport of water and nutrients. The considerable turnover time in such lakes tends to dampen variations in both water and nutrient transport. In addition, the volume of the lakes (i.e. the storage) is not constant with time. If data is available about the volume changes of the lakes, this information can be included in the model. These changes in volume are referred to as changes in storage, ΔS, and are used in the model to dampen the water mass flow rate.

Major point sources
Point sources may have a considerable impact on the nutrient transport through a catchment. In the model, major point sources often include discharge from waste water treatment plants (WWTPs), both municipal and industrial facilities. For major point sources, the input data must be given with monthly resolution, in contrast to minor point sources which are considered constant in the model (see 4.5). The data obtained from WWTPs is often in the form of kg month^{-1} or similar, and can thus be incorporated directly into the model.

4.2 Sub-catchment land use data

Each land-use type, i, is associated with a type specific input concentration, c_i. To obtain the nutrient input mass flow rate $S_i(t)$ from land-use type i, c_i is multiplied with the discharge generated within the area A_i of this land use type.

Sources with constant input concentration
The concentrations in the root zone of agricultural and pastural lands are modelled as being constant in time. However, since the concentrations are multiplied with the discharge, i.e.

$$S_i(t) = A_i \cdot q(t) \cdot c_i ,$$

the contribution from these land types will have a temporal variation.

Sources with a seasonal variation in the input concentration
For some land use types, the type specific solute concentration c_i varies with season (or month). For instance, the type specific concentration is always the same in January every year, but may differ from the concentration in June. The load exerted by these land types for a given sub-catchment is calculated using

$$S_i(t) = A_i \cdot q(t) \cdot c_i(month).$$

The land types modelled in this way are mountains, forests, clearcuts, mires, built environments, cities and a type called open which among other things contains bare rock faces. The type concentrations of built environments and cities are the same as for the “open” type. In addition, the nitrogen concentration in the leachates from the clearcuts is assumed to increase by a constant factor 0.95 mg/l when the nitrogen deposition exceeds 800 kg month^{-1} km^{-2} (Löfgren & Westling 2002).

4.3 Stream data

This is the length and width of streams within every sub-catchment. The stream area is used in the retention calculations, and for determining the atmospheric nitrogen deposition on surface water. Typically, this data is generated from a GIS tool.

4.4 Atmospheric deposition

The total deposition of nitrogen on water surfaces, S_d [MT^{-1}], in every sub-catchment is modelled using a constant area specific deposition, F_d [$MT^{-1}L^{-2}$], multiplied with the sum of stream and lake surface areas [L^2] in the sub-catchment as defined by

$$S_d = (A_{lakes} + A_{stream}) \cdot F_d .$$

4.5 Minor point sources

Minor point sources [MT^{-1}] include e.g. effluents from rural houses, milk rooms, and manure pits. The minor point sources are considered constant in time. Even though they are referred to as minor in the model, these sources may be very significant in some sub-catchments. The minor point sources are given as monthly loads.

5 Modelling retention

The nutrients found in a stream as it crosses the boundary of a certain sub-catchments stem from the sub-catchment itself and, if such exist, upstream sub-catchments. Parts of the nutrients are, however, retained due to processes such as sedimentation, uptake by plants, and de-nitrification.

The relative removal is given by the retention coefficient, R [-], defined as

$$R = \frac{T_a \cdot kvs}{q_s + kvs}$$

where kvs [LT^{-1}] is an empirical coefficient. T_a [-] is a temperature adjustment factor given by

$$T_a = \begin{cases} 0, & T < 0 \\ c_0 + \dfrac{T(1 - c_0)}{20}, & 0 \le T \le 20 \\ 1, & T > 20 \end{cases}$$

where T [K] is the water temperature, and c_0 [-] is an empirical calibration parameter. The parameter c_0 determines how strongly the retention is reduced by temperatures below 20 °C (Fig. 3). Furthermore, the hydraulic load, q_s [LT^{-1}], is given by

$$q_s = \frac{Q}{A_{lake} - A_{LM} + A_{stream}}$$

where A_{lake} is the total surface area of all lakes in the given sub-catchment, A_{LM} is the area of the lake treated in the separate lake module (if one such exists in the sub-catchment), and A_{stream} is the surface area of all streams in the sub-catchment.

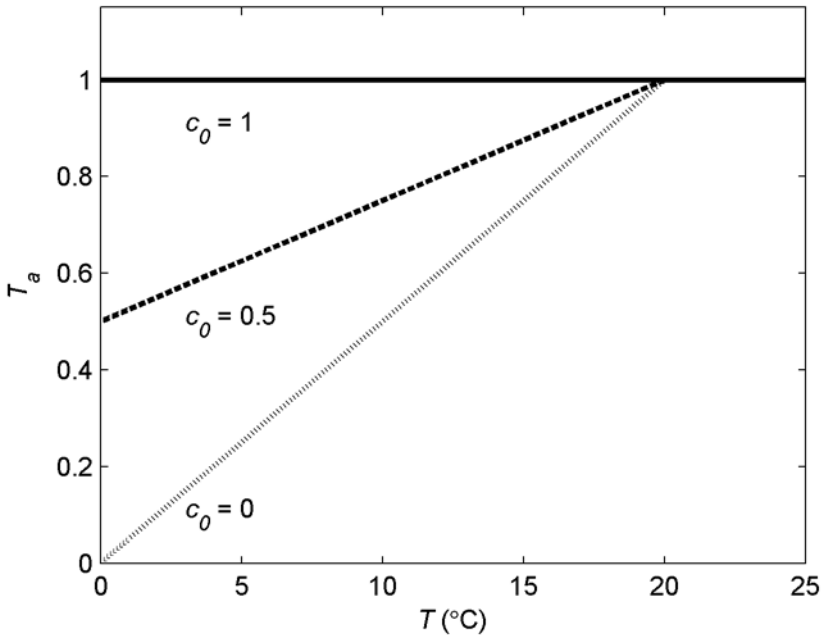

Figure 3. The influence of c_0 on the temperature dependence of T_a.

The retention coefficient varies with time, and does in practice take on unique values for each sub-catchment as the areas involved in the hydraulic load equation differs between sub-catchments.

6 Modelling river system discharge

The area specific runoff is used in the model to calculate the contribution of nutrients from every sub-catchment. However, when dealing with the transport of nutrients within the entire catchment, from one sub-catchment to another, the discharge (the mass flow rate of water) from every sub-catchment is needed. The discharge generated within a given sub-catchment *k*, for which $q_k(t)$ has been provided, is conveniently computed using

$$Q(t) = q_k(t) \cdot A_k .$$

However, many sub-catchments receive an external input of water from upstream, neighbouring sub-catchments in addition to the internally generated runoff. Hence, adding the external, incoming mass flow rate of water, as well as storage when such exists, yields the total discharge from sub-catchment *k*

$$Q_k(t) = \sum_{j=1}^{m} \left[Q_j(t) \right]_n + q_k(t) \cdot A_k - \Delta S_k(t)$$

where $Q_j(t)$ is the inflow of water from upstream, neighbour sub-catchment *j*, and $\Delta S_k(t)$ [L^3T^{-1}] is the storage in large lake *k* (referred to as "model lakes" in this report). This equation thus needs to be solved for every sub-catchment, and every time step.

7 Modelling nutrient transport

The mass transport, $Q_k(t) \cdot c_k(t)$ [MT^{-1}], of nutrients from sub-catchment *k* is given by

$$Q_k(t) \cdot c_k(t) = [1 - R_k(t)] \cdot \left\{ \sum_{j=1}^{m} [Q_j(t) \cdot c_j(t)]_n + load_k(t) \right\}$$

where c_k [ML^3] is the nutrient concentration in the outgoing water, *j* indices refer to upstream, neighbouring sub-catchments, and $load_k$ [MT^{-1}] is the sum of all nutrient sources within the given sub-catchment.

8 Modelling "Model Lakes"

In contrast to the modelling of sub-catchment areas without specific model lakes, the model lakes are affected by previous time steps, i.e. they have a memory and tend to dampen the response with regards to nutrient concentrations downstream. If storage change is included, the water mass flow rate variability will also be attenuated. The change of nutrient mass in a given model lake located by the outlet of catchment *k* is described by the following ordinary differential equation, derived by assuming mass conservation,

$$\frac{d[c(t) \cdot V(t)]}{dt} = [1 - R_L(t)] \cdot [Q_k(t) \cdot c_k(t) + atmospheric\ deposition] - Q_{out}(t) \cdot c(t)$$

where *c* [ML^{-3}] is the lake concentration, *V* [L^3] is the volume of the lake, and *t* is time [T]. The retention coefficient R_L for a model lake is given by

$$R_L = \frac{T_a \cdot kvs}{\frac{Q_k}{A_{LM}} + kvs},$$

and thus differs slightly from the other retention coefficient as a result of different hydraulic load in the "model lake" compared to the rivers and smaller lakes. If no storage data is given for the model lake, the outflow mass flow rate Q_{out} [L^3T^{-1}] equals the inflow mass flow rate Q_k. Notice that the model lake receives the nutrient mass flow defined in paragraph 7 as input. Hence, sub-catchments must be organized such that their outlets coincide with the model lake outlet if a model lake is to be simulated. I.e., the model lakes do in a sense operate between sub-catchments.

9 Statistics

In order to evaluate the fit of simulated to measured values, two statistical measures are used in the Fyris Model: the model efficiency, *E*, and the correlation coefficient, *r*. The definition of model efficiency (Nash and Sutcliffe, 1970) is

$$E = 1 - \frac{\sum_{i=1}^{n} (\theta_{obs,i} - \theta_{sim,i})^2}{\sum_{i=1}^{n} (\theta_{obs,i} - \bar{\theta}_{obs})^2}$$

where n is the number of observations, and $\bar{\theta}_{obs}$ is the mean value of all observations. The θ symbolizes whatever time-series are compared. In the Fyris Model, θ_{obs} and θ_{sim} are the observed and modelled concentrations respectively. $E = 1$ implies that the measured and modelled series are identical, and $E = 0$ indicates that the simulation is no better than a straight line representing the average value of the observations.

10 Calibration and parameter sensitivity/uncertainty

The model provides the user with two different methods for calibration and/or evaluation of sensitivity to individual parameter values.

1. The manual calibration allows the user to manually change both parameter values (c_0 and *kvs*), after which the model performs one simulation over the entire time period, using all measurement stations to calculate the model efficiency and the correlation coefficient. The user can inspect the simulation by looking at time-series plots, or plots of simulated versus observed concentrations for every sub-catchment having at least on measured concentration.

2. In the Monte Carlo simulation, the user specifies a uniform distribution of values for both parameters, and the number of individual simulations to carry out. As was the case for the manual calibration, the simulation covers the entire time period, and all measured in-stream concentrations are used to calculate model efficiency and correlation coefficient. The outcome may be analyzed graphically in the model by means of scatter plots.

11 Computer model

The computer code generated to solve the problem described in the preceding paragraphs was written in Visual Basic 2005, utilizing the .NET-framework.

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