INTERNATIONAL COMMISSION FOR THE PROTECTION
OF THE MOSELLE AND SARRE RIVERS AGAINST POLLUTION
(ICPMS)

Oxygen budget and biological processes
in the regulated rivers Moselle and Sarre

PHASE 3

MODELLING OF THE RIVER ECOSYSTEM

Simulations with the 'ULG-FUNDPN' Meuse-Moselle Model

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September 1997

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1. Structure & conception of the 'ULG-FUNDPN' Meuse-Moselle Model

1.1 Scope of the Model

The model developed is a unidimensional, non-stationary model, capable of simulating annual cycles from the source to the mouth of the river. The results can be expressed either temporally (for example annual simulations) on a given location, or longitudinally for a given date. The time step used for calculation is of an order of magnitude of an hour, which enables us to simulate daily cycles (like oxygen for example), and to describe very important non-stationary phenomenons (a rainy day following a sunny period for example).

The model is structured as a series of three consecutive sub-models, and its functions are the following :

- the hydrodynamic sub-model takes into account the morphometry of the river, calculates discharge and the other hydrodynamic parameters (water velocity, depth, ...) in different reaches, on the basis of the morphometric characteristics of the river (slope, width, presence of dams, ...) as well as the daily values of discharge measured on any point;

- the thermic sub-model calculates water temperature in the different reaches on the basis of the temperature measured at any point, and of the various inputs of warm water;

- the biological sub-model calculates
  - on the basis of light (surface irradiance) as the main supplementary entry data, the development of planktonic biomass (phyto-, zoo- and bacterioplankton);
  - the degradation of organic matter, as well as the production of autochtonous organic matter (primary production of phytoplankton), the heterotrophic activity being also fed by domestic, industrial and agricultural organic waste inputs, nutrient input and transformation in the ecosystem are taken into account so that concentrations of various forms of N and P are also calculated;
  - the oxygen budget of the water column on the basis of the metabolic activities of planktonic biomasses (primary production, degradation of organic matter, respirations), taking into account surface reaeration.

Note : The carbon, phosphorus and nitrogen variables are uncoupled following :
. their physical properties (prone to sedimentation or not)
. their chemical properties (ammonia, phosphates, ...)
. their biological properties (quickly, slowly or non biodegradable)

1.2 Geographical field covered

The geographical field covered here is the entire River Moselle, from the source to, presently, the German frontier. Depending on the availabilty of input data and on proper modifications of the program, the simulations can easily encompass the whole Moselle/Sarre river network.

1.3 The way the (upstream) limit and initial conditions are taken into account

1.3.1 Limit conditions

Limit conditions can be given in two ways :

1. The model is able to compute from the source of the river to the German frontier. Limit conditions can thus be given at the source of the river, as a "non-point input".
2. There is also the possibility to put limit conditions at any point of the river with measured datas and (time) interpolation between measurements.

The first solution is preferred, because the solution is then very weakly influenced by the upper limit condition.

1.3.2 Initial conditions

Initial conditions are given from concentrations data at a given day along the river. In practice, we are doing simulation over one year (from 1st January to 31st December) : initial conditions are given on 1st January and have very little influence on the results.

1.4 Outputs of the model

Outputs of the model are then

- for given days (presently up to nine, but it could be easily more) :
  longitudinal changes (length scale ~ 1 km) of all concentrations and fluxes computed by the model (daily mean values);

- for given points (presently up to nine, but it could be easily more) :
  temporal changes (day by day) of all concentrations and fluxes computed by the model (daily mean values).

2. The constraints

2.1 Hydrology and Morphology

2.1.1 Description of the morphological characteristics of the river system

The model (see file 'moseco02.hyd' in **annex 1** for numerical values) needs as morphometric data (with a length scale of a few kilometres) :

- slope of the river, computed from altitudes of the river;
- width of the river;
- presence and characteristics (height) of dams.

2.1.2 Description of the hypotheses made for water transport calculations

2.1.2.1 Water discharge

The development of a complete model rain/interception/streaming/percolation/ discharge is not done, due to the difficulties of implementation, to the number of data needed and to the relative precision of the results of hydrological models for large catchments.

Water discharges are computed on a daily basis at any point of the river from measurements at one or several points. From measured water discharges, we compute the " natural water discharge " at the point of measurement (excluding influence of channels, ...) then, taking into account the surfaces and the characteristics of the river basin, we compute the "natural water discharge" at any point of the river, and finally, reincorporating the influence of channels and of water abstraction measures, we compute water discharges used by the model.

2.1.2.2 Transport modelling

Hydrodynamic variables (velocities, water depths, ...) are computed on a daily basis, as a succession of quasi-stationary states. Where the river can be considered as free-flowing or " natural " (no dams), water depths are computed in a classical way using Chézy coefficients (which can vary from reach to reach). Where dams are present, a complete computing of the water level is done.

2.2 Meteorological constraints

2.2.1 Water temperature

The water temperature is computed in three steps :

- ***natural temperature*** : the changes of natural temperature is chiefly the consequence of the exchanges taking place at the water/atmosphere interface (radiation, convection, evaporation, condensation); these processes are not explicitly described; in the model, the natural temperature is represented by a sub-model, where the entry data is a general reference temperature (daily values), the temperature in the different reaches being then calculated as a function of their altitude;

- ***warming*** : compared to natural temperature, warming is calculated on the basis of entry data such as the values of thermal wastewater inputs, the river gradually losing thermal energy downstream of the input (through radiation, convection, evaporation); this refreshment is represented by a linear exchange coefficient (value : 30 W m^{-2} s^{-1});

- ***water temperature*** : it is then calculated at any point from natural temperature, including increase from thermal inputs when necessary; this variable influences the kinetics of all the biological processes described below.

2.2.2 Light energy

Light energy is computed from solar radiation (hourly or half-hourly) which give light energy at the top of the water column. Light in the water column is then computed by the use of the Beer-Lambert law, i.e. energy decreasing with depth in an exponential fashion, depending on water transparency (characterised by a vertical extinction coefficient).

The value of the extinction coefficient (m^{-1}) is calculated as the sum of the contributions of three categories of suspended matter : suspended solids, particulate organic matter, and phytoplankton; the contribution of mineral suspended matter may vary with location. The contribution of particulate organic matter and the phytoplankton vary linearly with concentrations.

We have thus :

$$\eta = \eta_1(x) + A_1 \cdot PHY + A_2 \cdot CTOTP$$

where

where	η	is the extinction coefficient (m^{-1})
	η_1	is depending on the location in the river (see the file moseco02.hyd)
	PHY	is the phytoplankton concentration (gC m^{-3})
	$CTOTP$	is the particulate organic matter concentration (gCm^{-3})
	A_1	= 0.5 m^2 gC^{-1}
	A_2	= 0.2 m^2 gC^{-1}

2.3 Inputs from the watershed

(see **annex 2** for details)

The inputs of organic matter and nutrients in the river remain one of the most difficult elements to assess.

Indeed, detritic organic matter present in the water column originate from 3 sources :

- mortality of the various biomasses present in the river (phyto-, zoo-, and bacterio-plankton). These inputs are explicitly calculated by the model;

- non-point inputs from the catchment. These inputs are taken into account by an input function (equals to the product of the discharge of a given tributary by a concentration, different for each variable). Currently, these concentrations are considered constant in the entire basin, but could vary for example as a function of land use;

- direct and point inputs to the river by urban and industrial wastewater. Estimating these inputs involves some methodological difficulties. Indeed, they are often estimated by the simple concept of the inhabitant-equivalent (for example, in France, it is defined as 57 g Mox + 15 g nitrogen + 4 g phosphorus). However, if this concept is relatively adequate to estimate non-treated wastewater inputs, it is no longer the case when treated inputs are considered, or when industrial inputs are to be estimated. In those cases,
  - the relative proportion of carbon/nitrogen/phosphorus may vary strongly according to the type of wastewater treatment used;
  - for a given variable (carbon, for example), the proportion degradable/non-degradable may be very different.

Keeping that in mind, we modified the way in which the direct inputs are introduced, based on the experience gained from the PEGASE model.

We introduced a file named "industrial wastewater" which makes it possible to inject, for example, an input containing only phosphorus devoid of any carbon or nitrogen.

The concept of inhabitant-equivalent, for municipal wastewater inputs, has been completed by the introduction of a type of wastewater input. Unitary loads (for the various constituents - degradable carbon, ammonia, ...) are therefore different according to the type of wastewater input (raw sewage directly into the river, or flowing through a wastewater treatment unit, before reaching the surface water, ...).

3. Microbial processes and water quality

(see **annex 3** for formulations)

3.1 Degradable particulate organic carbon

(two variables : quickly or slowly degradable)

The inputs originate from :
+ allochtonous sources (soil and waste inputs) (entry data);
+ autochtonous productions resulting from the mortality and excretion of the various biomasses living in the river.

The loss processes are :
+ degradation by planktonic heterotrohic bacteria and biofilm bacteria; this degradation is oxygen-consuming;
+ sedimentation (function of current velocity), which results in an increase of the benthic stock of degradable particulate carbon.

3.2 Non-degradable particulate organic carbon

The inputs originate from :
+ allochtonous sources (soil and waste inputs) (entry data);
+ autochtonous productions resulting from the mortality and excretion of the various biomasses living in the river.

The loss process is sedimentation (function of current velocity and depth), which results in an increase of the benthic stock of non-degradable particulate carbon.

3.3 Degradable dissolved organic carbon

Same input and disposal processes as degradable particulate organic carbon, with the exception of sedimentation.

3.4 Non-degradable dissolved organic carbon

Same input and loss processes as non-degradable particulate organic carbon, with the exception of sedimentation.

3.5 Particulate organic nitrogen

Same input and loss processes as degradable particulate organic carbon; the degradation of nitrogen-containing organic matter produces ammonia NH_4^+.

3.6 Degradable dissolved organic nitrogen

Same input and loss processes as degradable dissolved organic carbon.

3.7 Non-degradable dissolved organic nitrogen

Same input and loss processes as non-degradable dissolved organic carbon.

3.8 Ammonia NH_4^+

The inputs originate from

+ soils and waste inputs (entry data);
+ degradation of degradable organic nitrogen (particulate and dissolved);
+ degradation of particulate organic nitrogen present in the bottom sediment by benthic heterotrophic bacteria.

The loss processes are :

+ oxidation to nitrates by planktonic autotrophic bacteria and biofilm bacteria; this process is oxygen-consuming and produces nitrates;
+ consumption (assimilation) by planktonic heterotrophic bacteria;
+ consumption (assimilation) by planktonic and benthic vegetation.

3.9 Nitrates

The inputs originate from

+ soils and waste inputs (entry data);
+ the oxidation of ammonia by planktonic autotrophic bacteria.

The loss processes are :

+ consumption (assimilation) by planktonic and benthic vegetation;
+ denitrification, essentially on the river bottom, depending on the organic content of the sediment.

Note : the assimilation of nitrogen by planktonic and benthic vegetation concerns either ammonia or nitrates; in the model, we consider that assimilation of nitrogen is achieved on either of those two sources, as a function of the affinity of the various types of plants for different nitrogen sources (ammonia being generally preferred) and as a function of the availability of those forms in the environment.

3.10 Particulate organic phosphorus

The inputs originate from

+ soils and waste inputs (entry data);
+ mortality and excretion of the biomasses living in the river.

The loss processes are :

+ degradation by planktonic heterotrophic bacteria and biofilm bacteria; this process produces orthophosphates (PO_4^{3-});
+ sedimentation (function of current velocity), which results in an increase of the benthic stock of particulate organic phosphorus.

3.11 Dissolved organic phosphorus

The input and loss processes are the same as for particulate organic phosphorus, with the exception of sedimentation.

3.12 Orthophosphates PO_4^{3-}

The inputs originate from

+ soils and waste inputs (entry data) and the inputs from tributaries, calculated by the model;
+ degradation of organic phosphorus (particulate + dissolved) by planktonic heterotrophic bacteria and biofilm bacteria;
+ degradation of particulate organic phosphorus present in the bottom sediment, by the benthic heterotrophic bacteria.

The loss processes are :

+ consumption (assimilation) by planktonic bacteria (heterotrophic and autotrophic);
+ consumption(assimilation) by planktonic and benthic vegetation.
+ adsorption on solid suspended particles, with the formation of insoluble complexes that settle onto the bottom (as a function of current velocity).

3.13 Planktonic algal biomass (phytoplankton)

Phytoplankton growth rate is dependant upon

+ incident light energy (entry data)
+ light energy in the water column, which is a function of incident light, water transparency (calculated by the model, see above) and depth;
+ temperature;
+ nitrogen availability (NH_4^+, NO_3^-);
+ phosphorus availability (PO_4^{3-}).

The photosynthetic activity and growth of phytoplankton consumes CO_2, nitrogen (NH_4^+, NO_3^-) and phosphorus (PO_4^{3-}), assimilated to build living organic matter (incorporation of C, N and P); it produces dissolved oxygen.

Phytoplankton loss rate implies

+ a mortality rate dependent upon temperature; this mortality feeds the stocks of dead organic matter (dissolved and particulate);
+ a respiration rate dependent upon temperature; respiration consumes oxygen;
+ a sedimentation rate dependent upon water velocity and depth; sedimentation increases the benthic stock of organic matter;
+ a predation (grazing) rate through zooplankton feeding.

The present version of the model calculates TWO categories of phytoplankton, which differ with respect to their maximum photosynthetic rate (K_{opt}), their optimal temperature for photosynthesis (T_{opt}), their light saturation constant (I_k). For each category, K_{opt} varies with temperature with a maximum at T_{opt} (with a slope depending on a coefficient dTe, different for each category), and I_k varies as a function of an estimate of daylight in the water column. The distinction is a simple representation of a « spring » phytoplankton, able to grow at low temperature, and of a « summer » algal assemblage, which prefers high temperature. The two categories also differ with respect to their respiration rate, mortality rate and edibility by zooplankton.

3.14 Benthic vegetation

This compartment has been added to the model to limit the phytoplankton development in the non-canalised sections. Indeed, the development of benthic macrophytes reduces the phytoplankton production by shading. The macrophyte development is simulated by a submodel which takes into account a maximal attainable biomass and several reduction factors, depending on slope and organic load. The seasonal effect is rendered by a typical pattern : absence of benthic plants in winter, growth throughout the spring, maximal biomass in summer and progressive decrease in autumn.

In addition to shading phytoplankton, macrophytes take up nutrient and influence the oxygen budget by their photosynthesis and respiration. As for phytoplankton, O_2 production/consumption can be simulated at a timestep of an hour or half an hour depending on the availability of incident light data.

3.15 Zooplankton biomass

Zooplankton growth rate is set to be equal to zooplankton grazing on phytoplankton multiplied by zooplankton growth performance; this growth performance is defined as the fraction of the food ingested which is converted into structural biomass (excluding all reserve substances). The value of this parameter is set at 0,15 or at 0,10, for small and large zooplankton (see below).

The zooplankton loss rate is constituted by :

+ a mortality rate dependent upon temperature; this mortality feeds the stocks of dead organic matter (dissolved and particulate);
+ a respiration rate dependent upon temperature; respiration consumes oxygen.

In the present version, the model describes « small » zooplankton and « large » zooplankton, in order to represent the rotifers and the crustaceans, respectively. The two forms differ essentially with regard to their grazing rate, which results in different growth rate, so that the « large » zooplankton will be able to develop only at low discharge and high temperature, provided that enough edible phytoplankton is available.

3.16 Benthic filter-feeders

The addition of this new compartment results directly from the field and laboratory studies of the CREUM, which have shown that various benthic animals colonise the bottom of the river Moselle with high densities downstream of Metz. Most of these animals feed on suspended organic particles, i.e. mainly on the plankton, by filtering the water. The areal density of the two most abundant taxa, *Dreissena* and *Corbicula*, have been used for estimating total density in successive stretches of the river. Owing to the large dispersion of the field data from the same stretch, the median was used for setting a constant biomass per stretch. The filtration activity is calculated mainly by reference to *Dreissena*, based on the results of the CREUM and on literature data. For instance, the filtration rate is 100 ml (g wet weight)$^{-1}$ h^{-1} at 20°C, and the maximum rate is reached at 25°C. Similarly, we considered that all benthic filter-feeders have the same ingestion behaviour as *Dreissena*, i.e. that they ingest phytoplankton and zooplankton; however, reduction factors have been applied to limit zooplankton ingestion, but small zooplankton (rotifers) can be ingested by the mollusks.

Dreissena mussels are known to select food particles, using their gills, and to reject non edible particules in pseudofaeces : plankton in pseudofaeces is considered as no longer viable, and is decomposed by bacteria. This is a process which induces an O_2 demand depending on the filtration activity of the mussels. In addition, mussels may have a strong influence on the O_2 concentration by their respiration, which can be considered as an addition to benthic O_2 consumption. In this model, the O_2 demand by the two processes, decay of rejected plankton and mussel respiration, is represented by adding the biomass of ingested plankton to the pool of particulate organic matter.

3.17 Planktonic autotrophic bacterial biomass

These bacteria perform the conversion of ammonia (NH_4^+) present in the water column to nitrates (NO_3^-);

The planktonic autotrophic bacterial biomass growth rate is dependant upon :
+ a nitrification rate dependant upon temperature;
+ the availability of ammonia.

The growth of this bacterial biomass results in the assimilation of carbon, inorganic nitrogen and phosphorus, and the production of nitrates as well as the consumption of dissolved oxygen.

The planktonic autotrophic bacterial biomass loss rate is dependent upon temperature. The mortality of that biomass increases the stock of dead organic matter.

3.18 Planktonic heterotrophic bacterial biomass

These bacteria perform the degradation of the dead organic matter present in the water column.

The planktonic heterotrophic bacterial biomass growth rate is dependant upon :
+ the temperature;
+ the concentration of degradable organic matter (dissolved or particulate).

The growth of that biomass results in assimilation of carbon, organic nitrogen and phosphorus; it produces CO_2, ammonia and orthophosphates, and goes along with the consumption of dissolved oxygen.

The planktonic heterotrophic bacterial biomass loss rate is dependent upon temperature. The mortality of that biomass increases the stock of dead organic matter.

3.19 The activity of the bacterial biofilm

Those bacteria also perform, like the planktonic bacteria, the degradation of the organic matter present in the water column; this biomass is not explicitly, but well indirectly represented, through the calculation of biofilm activity (its role becomes very secondary in the highly regulated sections of rivers).

The degradation activity of the biofilm depends upon :
+ the temperature;
+ the concentration of degradable organic matter in the river.

The activity of the biofilm induces a decrease in organic matter and the production of CO_2, ammonia NH_4^+ and orthophosphates PO_4^{3-}; it goes along with the consumption of dissolved oxygen.

3.20 The activity of benthic bacteria

Those bacteria perform the degradation of the organic matter that settled onto the bottom and contributes to the sediment; this biomass is not explicitly, but well indirectly represented, through the calculation of its degradation activity.

This degradation activity depends upon :
+ the temperature;
+ the flow of organic matter to the sediment, originating from the sedimentation of particulate organic matter and phytoplankton.

This degradation activity results in a decrease in organic matter and in the production of CO_2, ammonia NH_4^+ and orthophosphates PO_4^{3-}; it goes along with the consumption of dissolved oxygen.

3.21 Dissolved oxygen concentration

The only term of oxygen production within the river is the input through phytoplanktonic primary production.

The oxygen-consuming processes in the river are :
+ the consumption through respiration by phyto- and zooplankton;
+ the consumption by planktonic autotrophic bacteria;
+ the consumption by planktonic heterotrophic bacteria;
+ the consumption by the biofilm bacteria;
+ the consumption by the activity of benthic bacteria.

The dissolved oxygen content of the water therefore results from :
+ the solubility of oxygen in the water, which is expressed by a saturation concentration dependant upon temperature;
+ all the production and consumption fluxes;
+ an exchange flux through the water/atmosphere interface ("reaeration").

This flux depends upon the difference between the dissolved oxygen content and the saturation concentration, and upon the current velocity and the depth of the river; the oxygen is transferred from the atmosphere to the water if the dissolved oxygen content is lower than the saturation value, and inversely if the content is greater than the saturation value. Additional reaeration at the level of the dams and if strong navigation exists is normally also included in the model, but it has been set to zero in the present simulations, according to decision made at the last modelling meeting (in Luxemburg in July).

3.22 Concentrations calculations

The concentrations in the water column of each of the aforementioned constituents are calculated by combining the following processes :
+ transportation by the current (calculated by the model);
+ the inputs and the potential dilution effects of the tributaries (calculated by the model);
+ the inputs from the soil (calculated by the model) and the sum of all waste inputs (entry data);
+ the internal processes of production and losses (calculated by the model);
+ the potential exchanges with the atmosphere (calculated by the model).

4. Validation of the model : reference simulations

The validation of the model has been performed by runs in the weather and discharge conditions for the years 1993 to 1995. As indicated above, the input data are hourly light energy, daily water temperature and daily discharge. The hydraulic data are given in **annex 1**.

The pollution load includes point and non-point sources : for point sources, details can be found in **annex 2** (tables of industrial and urban wastewater discharges). Non-point sources are taken into account as described in the chapter devoted to model description.

4.1 Longitudinal profiles

Longitudinal profiles are given only for the year 1993, at different dates from spring to autumn. It is important to note that this kind of simulation gives a picture of the situation all along the course of the river on the same day, and do not describe the changes in a given water mass during its downstream transfer (i.e. like the BfG model, for instance).

Figs a.5.1. to **a.5.4.** in annex 5 show the simulations (**line**) for phytoplankton, zooplankton and dissolved oxygen, compared to the measurements (**dots**). Except in some cases, plankton biomass changes are correctly simulated, especially in summer, which is the critical period for water quality. Oxygen concentrations (the two lines represent the maxima and minima over the diel cycle) are satisfactorily calculated (e.g. in May and July); however, in some instances, the model overestimates dissolved O_2 (D.O.) in the downstream stretch (Sierck, Grevenmacher), particularly at low discharge. The profiles of 1994 (not shown) are globally similar to those of 1993, with a good agreement between data and calculations. By contrast, plankton biomasses simulated for 1995 are often higher than those observed : this may result from the particular turbidity conditions due to dredging operations in some stretches of the Moselle that year.

As shown in **figs a.5.5.** to **a.5.8.**, ammonium, dissolved phosphates and total phosphorus are correctly simulated.

By comparison with earlier simulations with this model (..., 1994) carried out at the end of the first phase of the study, a significant improvement has been obtained in simulating zooplankton biomass. This is due to the implementation of the zoobenthos compartment : zooplankton biomass decreases and remains low in the downstream stretches, because rotifers are preyed upon by benthic filter-feeders, which, at the same time, feed on phytoplankton. By contrast, without the influence of zoobenthos filtration, the earlier version of the model calculated a zooplankton biomass which was always too high in the downstream part. This demonstrate the importance of these benthic animals in the summer phytoplankton decline in the River Moselle, even though the « zoobenthos submodel » is rather simple and based on rough estimates of the biomass of two taxa (*Dreissena* and *Corbicula*) and of their filtration activity.

As for the overestimation of D.O. around Sierck-Grevenmacher, the explanation is still unclear. These overstimates are observed in low discharge conditions, when decreased velocity and high temperature allow a rather rapid elimination of the wastewater inputs, which are mostly decomposed upstream of Sierck. Similarly, according to the available data, it seems that most of the phytoplankton mortality occurs between Metz and Thionville, so that it should have a lesser influence downstream. Moreover, the good simulations of ammonium prove that nitrification is correctly calculated. A tentative explanation might be in the fact that a term of O_2 consumption, as respiration by zoobenthos, has not been taken into account.

4.2 Temporal profiles

Reference simulations for the year 1994 are presented in **figs. a.5.9.** to **a.5.14.** It is clear that the agreement between simulations and observations is not good at all times. Particularly, very high phytoplankton biomasses were measured at the end of June : they do not likely correspond to the algal biomass in the main stream, while the model calculates mean concentration over the cross-section. By contrast, the measured chlorophyll ***a*** was very low in August and September : as the fit is better for 1993, it is hard to say whether the simulation overestimates the phytoplankton biomass, or if the data are wrong. Similar discrepancies appear for zooplankton (high value in June), as for oxygen. However, the fit between observed and calculated oxygen concentration is better for Hauconcourt (except a very high value in June again). For Sierck, it seems that the model overestimates dissolved oxygen in summer.

Despite these discrepancies which may be due to sampling in places which do not represent the main flow, the general tendency of downstream decrease of phytoplankton, zooplankton and dissolved oxygen is well rendered by the model. Nevertheless, the model, as pointed out above, overestimates the summer oxygen concentration in Sierck, especially in the conditions of 1994.

For ammonium, dissolved phosphate and total phosphorus, there is an overall good fit between observed and calculated concentrations.

4.3 Budget calculations

Tables in annex 4 show oxygen budgets calculations for the year 1993 for the sectors Hauconcourt-Koenigsmacker, Koenigsmacker-Palzem and Palzem-Grevenmacher.

5. Exploration of factors responsible for oxygen deficit

5.1 Effects of algal dynamics vs wastewater discharge

5.1.1 Algal growth set to zero ***(figs a.6.1. to a.6.4., in annex 6)***

The main effect of phytoplankton suppression is a decrease of oxygen concentration, well marked at the upstream site, where the algal biomass is normally high all over the growing season (scenarios are represented by **bold lines** while reference simulations are noted by **dotted lines**); logically, the effect is less important in the downstream stations where the phytoplankton is usually less developed. This demonstrate the positive influence of phytoplankton on dissolved oxygen in the river, in most situations. The nutrient concentrations are almost not affected, but in Hauconcourt for ammonium (more ammonium when phytoplankton develops, probably because decay of dead algae results in ammonium release).

5.1.2 Removal of point carbon and nitrogen inputs ***(figs a.6.5. to a.6.8.)***

As expected, removing the input of waste water (carbon and nitrogen, but not phosphorus) results in dissolved oxygen improvement, essentially at the downstream sites. Ammonium concentration sharply decreases everywhere, while both forms of phosphorus present a slight increase.

5.2 Effects of river morphology

5.2.1 Increase of 50% in water level ***(figs a.6.9. to a.6.11.)***

Increasing the depth of the river results in phyto- and zooplankton decrease at all stations, most of the time. Accordingly, the amplitude of diel oxygen variations is reduced, but the mean O_2 concentration is scarcely affected (probably a compensatory effect of the improvement of water transparency brought about by lower phytoplankton). Ammonium and phosphorus are only slightly changed (not shown).

5.2.2 Decrease of 50% in water level ***(figs a.6.12. to a.6.14.)***

In these conditions, phytoplankton would achieve much higher summer maxima at all sites, and zooplankton would follow and reach high biomass in the downstream stations. These effects results from net primary production enhancement by a lower Zm/Zeu ratio, and from faster transfer time (which explains why the spring algal biomass does not increase as much as the summer biomass). The excess of algae adversely affects dissolved oxygen (larger amplitudes and lower minima), while ammonium and dissolved phosphorus (not shown) slightly increase, likely from recycling of dead phytoplankton.

5.3 Effects of algal predators

*5.3.1 No grazing **(figs a.6.15. to a.6.20.)***

The effect of removing all grazers (zooplankton and benthic filter-feeders) is spectacular : instead of a downstream decrease of phytoplankton, there is a downstream increase, and the difference between the scenario and the reference gets larger as going downstream. The result on dissolved oxygen is positive, with both higher maxima and higher minima, except on some occasions in Sierck : the level of algal biomass reached is probably high enough to create oxygen problems from algal respiration and decay of dead algae. This organic pollution is confirmed by an ammonium increase during summer, while dissolved phosphorus, being assimilated by the abundant phytoplankton, has a lower concentration.

It is important to notice that the summer diminution of dissolved oxygen in the critical stretch of the river is no longer observed, which supports the hypothesis of the role of grazers in the water quality problem. This is clearly shown by the longitudinal simulation of July 5 (**fig. a.6.20.**).

*5.3.2 No zooplankton **(figs a.6.21. to a.6.26.)***

The result of zooplankton removal is globally similar to the former scenario, with less contrast. Again, the oxygen improvement in Sierck is neat, as the minimum concentration approaches the maximum of the reference simulation.

*5.3.3 No benthic filter-feeders **(figs a.6.27. to a.6.32.)***

Suppression of filtration by zoobenthos does not change the situation as much as removal of zooplankton : this can partly be explained by their presence over a rather short stretch and by a compensation due to the release of predation on zooplankton, which multiplies in the stretch where it normally declines. As a consequence, there is most of the time, in Sierck, a bit more phytoplankton and mean oxygen is slightly affected; end of June, at Sierck, maximum oxygen only just reaches minimum of the reference simulation. In the upper stretches, the water quality is not greatly affected.

6. Management scenarios

6.1 Phosphorus treatment

*6.1.1 Reduction of phosphorus inputs by 80%, either in large (>10000 EH) treatment plants (**figs a.7.1. to a.7.6. in annex** 7), or in the whole basin (**figs a.7.7. to a.7.12.**)*

The improvement of water quality reached by this measure is significant, particularly in Hauconcourt, but it is less visible in Sierck. The diminution of phytoplankton is more marked in the upstream sector, and this affects zooplankton development along the river course, resulting in reduced grazing in the downstream stretches. Reducing phosphorus inputs in all waste water discharges (except those from the industries) would not allow to get better results.

6.2 Nitrogen treatment

*6.2.1 Nitrification of waste water in all treatment plants (**figs a.7.13. to a.7.18.**)*

This measure would not change greatly the water quality of the river Moselle : indeed, if the ammonium concentration is (obviously) lowered, the oxygen concentration in the critical stretches is not greatly affected : however, an increase is noticed at Hauconcourt, but it is slighter in Sierck. This confirms the view that the water quality is more affected by waste water in Hauconcourt than in Sierck, where it depends more on ecological effects.

*6.2.2 Denitrification of waste water in all treatment plants (**figs a.7.19. to a.7.24.**)*

Denitrifying the waste water would produce the same effects as nitrification.

7. Conclusions

The various implementations of the « Meuse model » during the study have allowed to improve the representation of the ecological and water quality conditions in the river Moselle. This is particularly true for the plankton dynamics in the stretch located downstream of Metz, which are influenced by the development of several species of filter-feeders. Introducing a constant biomass of filter-feeders, which feed on phytoplankton and on small zooplankton, has resulted in better simulations, explaining why zooplankton declines in the stretch instead of increasing as would be expected. Most likely, competition for algal food and direct predation are responsible for zooplankton decline.

Still, the model often overestimates oxygen concentration in summer around Sierck-Grevenmacher, for reasons which are still unclear. Provided that waste water inputs are likely to be correctly taken into account, an hypothesis for such a local effect would be, again, an inadequate description of zoobenthos, and possibly, an additional oxygen loss which may come from respiration of these animals.

The various exploratory runs and water treatment scenarios lead to the following conclusions :

- the role of phytoplankton photosynthesis as an important term of the oxygen budget is confirmed (no phytoplankton would make the situation even worse); hence, phytoplankton losses may be harmful for dissolved oxygen in this river system;

- grazing by zooplankton and benthic filter-feeders is an important loss term for phytoplankton downstream of Metz, and explains the summer decline observed in the rather « dry » years; zooplankton alone is potentially more effective in controlling phytoplankton, but is probably counteracted by competition with and predation by the benthic filter-feeders; these animals seem to interfere locally with the plankton, and may be part of the explanation of the water quality problems in the river;

- a first exploration of the management measures which could be applied has shown that advanced waste water treatment could improve the water quality of the river : directly, by decreasing the carbon and ammonia inputs (thereby diminishing the oxygen demand in the river water) and, indirectly, by removing phosphorus at the largest treatment plants; the latter measure would delay phytoplankton development, thereby delay zooplankton development even further, and possibly alleviate the grazing control in the critical stretches. However, more advanced modelling, based on a detailed description of point and non-point pollution sources, would be needed to recommend practical measures to be taken to improve water quality in the River Moselle.