Eindrapportage-formulier TRIAS projecten
Final report format for TRIAS projects.

When a TRIAS project has finished, or is about to finish, a Final Report is required. This report serves several goals simultaneously:

- it enables the program commission to check whether the project has met its goals,
- it enables NWO-ALW to finalize the project administratively, e.g. pay the final part of the personnel costs of the project,
- it provides some of the information needed for evaluation purposes,
- it provides information which can be publicized, e.g. via a web site.

We have integrated the questionnaires from TRIAS and ALW into one, in order to prevent the need to fill in the same answers twice.

Please send in the filled out forms within a month after the project is completed to:

Netherlands Organisation for Scientific Research
Earth and Life Sciences
Carmen van Meerkerk and/or Theo Saat
P.O. Box 93510
2509 AM The Hague

Part I

General information, also intended for publication through the TRIAS website

01 Project Title.
Biogeochemical constraints for sustainable development of floodplains in riverine regions

02 TRIAS/ALW project number or file number
TRIAS: 835.80.010

03 Research period, at what date did the project start, at what date did it end.
May 1, 2002 – February 23, 2007

04 Names of the researchers involved, the names and addresses of the institutes where the research work was carried out.

Ir. Roos Loeb (PhD student)
Prof. dr. Jan G.M. Roelofs (promotor)
Dr. Leon. P.M. Lamers (co-promotor)

Radboud Universiteit Nijmegen, Aquatic Ecology and Environmental Biology, Institute for Wetland and Water Research, Toernooiveld 1, 6525 ED Nijmegen, the Netherlands

05 Short scientific summary (500 words) in English of: main research objective, research methods, results and conclusion

The main research objective of the project "Biogeochemical constraints for sustainable development in riverine regions" was to pinpoint constraints for the development of biodiverse and characteristic floodplain vegetation types the Dutch riverine areas by human alterations in water quality, soil quality and flooding regime. Within this project, the subproject of the Radboud University Nijmegen focused especially on the unraveling of the biogeochemical processes underlying possible constraints. Special attention was given in this project to sulfate in combination with the high concentrations of phosphate in floodplain soils, as a result of agricultural fertilization practices. From fen systems it is known that sulfate reduction to sulfide could lead to the release of phosphate, and hence eutrophication, by the binding of sulfide to iron in iron phosphates. Additionally, phytotoxicity of sulfide threatened characteristic vegetation types in those systems. This project investigated among others whether these processes would also form a constraint for vegetation development in riverine areas.

The project was started with a extensive field survey, in cooperation with the other partners in the project, the University of Utrecht and the NIOO-KNAW, in which the vegetation composition, soil chemical properties, pore water quality and surface water quality of floodplains in various regions of the Netherlands and abroad were recorded. The data collected in this survey were used as a basis for experimental, mainly mesocosm, studies.

Phytotoxicity of sulfide, resulting from the reduction of sulfate in river water, only plays a role in a limited number of floodplain types: only in vegetation types on soils low in iron concentration, in which sulfide is not bound by iron, sulfide toxicity can play a role in the vegetation. This is for instance the case in iron poor floating fen systems (total concentration around 100 µmol Fe g^{-1} dw), which are at present very rare in Dutch riverine areas, but which are also very valuable from a nature conservation perspective. In these systems sulfate forms an extra threat, as it serves as a redox buffer, preventing the formation of methane, which is important for the buoyancy of the peat substrate. In soils rich in iron (> 600 µmol Fe g^{-1} dw), which appeared to be very common, sulfate enrichment could lead to a release of extra phosphate, if enough degradable organic matter was present. However, this release was considerably smaller than the release of phosphate that takes place upon flooding and concomitant reduction of iron(hydr)oxides onto which phosphate is adsorbed. During the

inundation experiment, concentrations of P in the pore water rose to 2-90 times the initial concentrations. Phosphate release was not directly related to the geographic origin of the soils.. The relative release of phosphate to the pore water upon inundation in floodplain soils was shown to be very predictable from the ratio between the iron bound phosphate to the amount of amorphous iron in the floodplain soils. The seasonality of flooding determines the effects on biogeochemical processes to a large extent, as process rates are much smaller at low temperatures than at high temperatures. This implicates that flooding during the growing season will result in strong biogeochemical effects, whereas winter flooding has only modest effects, which is highly relevant for the prediction of flooding effects in riverine management.

In the Haringvliet estuary, at the moment a stagnant freshwater lake, sluices will be opened in future to restore a salinity gradient and tidal regime. A mesocosm experiment revealed that the high concentrations of sulfate and chloride in sea salt had no effect on the phosphate concentrations in the soil pore water. The tidal regime, correlated with a higher salinity, provided higher redox potentials, decreasing the reduction of iron and sulfate and the formation of methane. Phosphate concentrations in soil pore water were decreased, probably as a result of oxygen intrusion. Although nitrogen availability seemed to be increased by tidal regimes, biomass did not respond. Therefore, it is not possible to speculate about the nature of nutrient limitation. Toxic effects on the vegetation of increased chloride concentrations in the oligohaline water were shown. We assume that in future this will enable characteristic salt tolerant species to return by increased competitive strength, provided that dispersal if diasporas does not form a constraint.

Nutrient limitation played an important role in characteristic, species rich hayland vegetation from two floodplain along the Overijsselse Vecht. Both vegetation types were limited by nitrogen and one of was also limited by potassium after a year. This emphasizes that supply of nutrients with the river water or with sediment in the river water still forms a potential threat for the biodiversity in this type of floodplain vegetation, by the stimulation of highly competitive plants at the expense of slower-growing species.

06 Popular summary to inform the general public (1/2 to 2 pages of text) in Dutch. The funding organisations of TRIAS (SKB, NWO-ALW and Delft Cluster) want to inform a more general audience about the results of the TRIAS Research projects. That is why we ask you to give an executive summary of the project in a popularising way and written in the Dutch language.

In het beschermingsbeleid tegen hoogwater is er na de hoogwaters van 1993 en 1995 voor gekozen de rivier meer ruimte te geven naast het verhogen en verzwaren van de binnendijken. Hiertoe worden dijken teruggezet, uiterwaarden en de rivierbedding verlaagd en worden er mogelijk gebieden aangewezen waar overtollig water tijdelijk kan worden opgeslagen. Tegelijkertijd worden veel uiterwaarden die in agrarisch gebruik waren, omgevormd tot natuurgebieden. De ongunstige samenstelling van de bodem en kwaliteit van het rivierwater (eutrofiëring, sulfaatverrijking) kunnen echter de ontwikkeling van soortenrijke en karakteristieke vegetaties belemmeren.

Sinds de jaren ’70 is de kwaliteit van het water in de Rijn en de Maas sterk verbeterd. Toch zijn de concentraties van sommige stoffen, zoals sulfaat en nitraat, in het water nog steeds verhoogd ten opzichte van het begin van de 20^{e} eeuw. Ook de bodem van uiterwaarden is op sommige plekken vervuild. Waar er tot voor kort bemest werd, kunnen hoge concentraties aan meststoffen, met name fosfaat, in de bodem aanwezig zijn. In dit onderzoek is er gekeken naar de effecten van deze vervuiling en naar de interacties tussen water- en bodemkwaliteit.

Niet alleen in het binnenland is er sterk ingegrepen in het rivierenlandschap, maar ook in het estuarium van de Rijn en de Maas, waar deze rivieren de Noordzee instromen. Als onderdeel van de Deltawerken is in 1970 het Haringvliet afgedamd, waardoor het Haringvliet veranderde van een brakwatergetijdengebied in een zoet, stagnant meer. Zowel in het Haringvliet als in de Biesbosch is hierdoor de oorspronkelijke plantengroei grotendeels verdwenen. Om de zoutgradiënt en het getij deels te herstellen, zullen de Haringvlietsluizen in de toekomst gedeeltelijk geopend worden. Ook de effecten van deze maatregelen zijn in dit project onderzocht.

Tijdens overstroming verdwijnt het zuurstof in de bodem. Afbraak van organische stof gaat vervolgens verder zonder zuurstof, waarbij bepaalde stoffen worden gereduceerd. Door de reductie van ijzer in de bodem, blijkt er in dit onderzoek veel fosfaat vrij te komen. Fosfaat is een belangrijke voedingsstof voor planten. Als er veel fosfaat vrij komt, kan dit leiden tot (blauw)algenbloei, wat niet gewenst is. De hoeveelheid fosfaat die vrijkomt blijkt goed te voorspellen te zijn aan de hand van de verhouding tussen het fosfaat dat aan ijzer is gebonden in de bodem ten opzichte van de totale concentratie ijzer in de bodem. Aan de hand van deze verhouding is het mogelijk om gebieden uit te zoeken waar waterberging minder negatieve gevolgen heeft voor de natuur. Ook sulfaat uit het rivierwater kan worden gereduceerd. Hierbij ontstaat sulfide, dat toxisch is voor planten. Bij voldoende aanwezigheid van ijzer in de bodem, wordt dit sulfide gebonden en is het niet meer toxisch. Het is bekend dat ijzer- en sulfaatreductie tegelijk op kunnen treden in bodems. De meeste bodems in de uiterwaarden bevatten veel ijzer (300-1000 µmol Fe g^{-1} dw ofwel is 1.2-6%)., waardoor het niet vaak voorkomt dat er giftige concentraties van sulfide aanwezig zijn. Toch zijn er ook bodems die erg weinig ijzer bevatten (100 µmol Fe g^{-1} dw). Drijftillen, die erg zeldzaam en vanuit natuurbeheersoogpunt erg waardevol zijn, zijn hier een voorbeeld van . Bij langdurig contact met rivierwater kan sulfide hier ophopen tot voor planten giftige concentraties. Sulfaat heeft nog een belangrijk ander effect op drijftillen: door de aanwezigheid van sulfaat in het water kan er geen methaan gevormd worden. Omdat drijftillen voornamelijk op methaanbelletjes drijven, kunnen ze hierdoor zinken. In bodems die wel veel ijzer bevatten, kan de binding van sulfide aan ijzer leiden tot het vrijkomen van extra fosfaat, doordat het sulfide het fosfaat van het ijzer verdrijft. In praktijk blijkt de hoeveelheid fosfaat die hierdoor vrijkomt in uiterwaardbodems erg klein te zijn ten opzichte van het fosfaat dat al vrijkomt bij reductie van ijzer tijdens overstroming.

Bij al deze processen is het seizoen waarin de overstroming plaatsvindt, erg belangrijk. Bij een zomeroverstroming, waarbij de temperaturen hoog zijn, verlopen de bovengenoemde afbraak- en reductieprocessen veel sneller dan in de winter. Zomeroverstroming heeft hierdoor, naast directe effecten op planten die niet tegen overstroming kunnen, ook indirect grotere negatieve effecten op de plantengroei.

Stikstof (nitraat) kan ernstige effecten hebben op de vegetatiesamenstelling van soortenrijke uiterwaarden. Uit onderzoek aan biodiverse hooilanden met een zeer zeldzame plantensamenstelling langs de Overijsselse Vecht, is gebleken dat aanvoer van extra stikstof leidt tot extra groei van grassen, waardoor zeldzame soorten minder kansen krijgen.

Bij het herstellen van de getijdenbeweging in het Haringvliet kan er meer zuurstof in de bodem doordringen. Afbraak van organische stof vindt hierdoor voornamelijk met zuurstof plaats, waardoor er minder sulfide wordt gevormd en er minder fosfaat vrijkomt in de bodem. Het zoute water zorgt ervoor dat planten die nu in rond het Haringvliet groeien en gevoelig zijn voor zout, minder snel gaan groeien. Hierdoor zullen brakwaterplanten die van oorsprong in het gebied voorkwamen, zich op den duur weer kunnen vestigen.

07 What impact and relevance has this project's outcome for practicing soil protection and / or soil remediation? Again, please motivate.
The outcome of this project is highly relevant for protection of floodplain soils and their vegetation, as the results make clear which soils are vulnerable when used for water storage and which soils are less vulnerable, based on soil chemical properties. It also indicates how soil quality and water quality may provide interactive effects on floodplain vegetation.

08 Please list the presentations held in connection to this project
Oral presentations

- Ecoflood- Towards natural flood reduction strategies, Warsaw 2003, *The effects of river water quality on the development if wet floodplain vegetation in the Netherlands*
- Soil&Water, Zeist 2004, *Assessing the eutrophication risks of water retention and water storage*
- Soil&Water, Zeist 2005, *Effects of increased salinity and tide in the Haringvliet on biogeochemical processes; a mesocosm experiment*
- International Symposium on Wetland Pollution – Dynamics and Control, Ghent 2005. *Assessing the eutrophication risks of water retention and water storage in riverine wetlands*
- World Conference on Ecological Restoration, Zaragoza 2005, *Differential effects of increased sulfate concentrations on the restoration of riverine wetlands; the role of sediment type*
- IWWR PhD day, Nijmegen, 2005. *How water quality and sediment type influence ecological development in riverine wetlands*
- Werkgroep Restoration Ecology, Utrecht 2006, *How water quality and sediment type influence ecological development in riverine wetlands*

- NecoV Wintersymposium, Nijmegen 2007, *Ruimte voor de Rivier: natuurkwaliteit op bemeste bodems met vervuild water?*

Poster presentations

- Bodemdiep, Zeist, 2002
- NCR Congress, Wageningen 2003
- The 7th Intecol International Wetlands Conference, Utrecht 2004

09 Please list publications (published and submitted) in connection to this project. Please indicate publication took place in either a refereed journal, a non-refereed journal (incl. conference proceedings); whether it was published as a chapter of a book, as a monography or as a dissertation.

Peer reviewed publications:

- R. Loeb, E. van Daalen, L.P.M. Lamers & J.G.M. Roelofs. How sediment characteristics and water quality influence the biogeochemical response to flooding in riverine wetlands. Biogeochemistry, in review
- R. Loeb, L.P.M. Lamers, J.G.M. Roelofs. Prediction of phosphate mobilization in inundated floodplain soils. Submitted
- R. Loeb, A.M. Antheunisse, M. Miletto, L.P.M. Lamers, P.L.E. Bodelier, H.J. Laanbroek, J.T.A. Verhoeven, J.G.M. Roelofs. Effects of restored salinity and tidal regime on biogeochemical processes and vegetation in the Rhine-Meuse Estuary; a mesocosm experiment. Marine Ecology Progress Series, in review
- R. Loeb, L.P.M. Lamers, J.G.M. Roelofs. Effects of winter versus summer flooding and subsequent dessication on soil chemistry in a riverine hayland. Submitted soon
- R. Loeb, L. Kuijpers, C.J.H. Peters, L.P.M. Lamers, J.G.M. Roelofs. Nutrient limitation in a species rich floodplain hayland. Submitted soon
- L.P.M. Lamers, R. Loeb, A.M. Antheunisse, M. Miletto, E.C.H.E.T. Lucassen, A.W. Boxman, A.J.P. Smolders & J.G.M. Roelofs, 2006. Biogeochemical constraints on the ecological rehabilitation of wetland vegetation in river floodplains, Hydrobiologia 565: 165-186
- A.M. Antheunisse, R. Loeb, L.P.M. Lamers & J.T.A. Verhoeven, 2006. Regional differences in nutrient limitation in floodplains of selected European rivers: implications for rehabilitation of characteristic floodplain vegetation, River Research and Applications 22: 1039-1055
- A.M. Antheunisse, R. Loeb, M. Miletto, L.P.M. Lamers, H.J. Laanbroek and J.T.A. Verhoeven. Response of nitrogen dynamics in semi-natural and agricultural grassland soils to experimental variation in tide and salinity. Soil and Water, in review
- M. Miletto , P.L.E. Bodelier, A.M. Antheunisse, R. Loeb, A. Loy, M. Wagner, H.J. Laanbroek. Effect of salinity and tide on soil sulfate-reducing microbial communities of the Haringvliet lagoon (the Netherlands). Submitted soon

Thesis:

R. Loeb. On biogeochemical processes influencing eutrophication and toxicity in riverine wetlands. Dissertation, Radboud University Nijmegen, pending

10 Please list Patent applications or other professional products (including contracts, articles in the popular media, contributions to documentaries or scientific television or radio programs, CD-ROMS, DVD or other (electronic) media).

Part II

Detailed information, primarily intended for administrative and statistical use by NWO-ALW

11a Under item 5 you have filled in the main research objectives. Please list all the original research objectives as indicated in the project's application and both indicate as well as motivate, to what extent these goals were realised, and/or whether the original research objectives had to be adapted.

The central questions for the whole research project are indicated with some answers provided by the this subproject (in italics):

1. Given the new river management, what are the biogeochemical constraints for sustainable ecological development of characteristic riverine vegetation types, and which conditions are needed to combine space for rivers with ecological goals like biodiversity?

Biogeochemical constraints are formed by high concentrations of nutrients (phosphor and nitrogen) in soil. Sulfate can also form a constraint under certain circumstances. For characteristic oligohaline estuarine vegetation types the lack of chloride in the river water forms a constraint.

2. Given the pollution of soils, sediments and surface water with potentially toxic substances, which parts of the river floodplain areas are suitable for the development of characteristic, species-rich ecosystem types?

For species-rich vegetation types, areas that are not polluted with nutrients seem to have the best chances. For long-term inundated/semi-aquatic vegetation types on soils with a low iron-bound-phosphate to iron ratio are less impacted by phosphate release. For the development of floating fen mats feeding with groundwater discharge and a low connectivity with the river water is important, as long as sulfate and nitrate concentrations in the river water are high.

3. Given the soil conditions in river floodplains, which hydrological regimes are appropriate for the sustainable ecological development?

This depends completely on the kind of target vegetation and the local soil conditions.

4. Given the strong eutrophication of many floodplains due to agricultural use, which methods (such as removal of the top layer) are available to make them suitable for sound ecological development?

Removal of the top soil is only useful if underlying layers are less rich in nutrients. Given the high nutrient concentrations and heavy metal concentrations in the river water in the past, deeper layers are not necessarily "cleaner" than the top soil. As nitrogen seems to be an important nutrient to reduce, measures as haymaking are more appropriate than soil removal, as nitrate is highly mobile. For phosphate it turned out that neiter agricultural heritage nor phosphorus concentrations in the soils determine the phosphate release upon inundation. In this process, iron concentrations are of great importance. A practical tool was developed for risk assessment.

Furthermore, several detailed, process-oriented sub questions were formulated, and here also answers provided by this subproject are given (in italics) :

1. How are redox conditions, nutrient cycling and the accumulation (free) sulfide and ammonium affected by the altered flooding-desiccation regimes in floodplains?

Upon inundation redox potential drops, nitrate disappears and ammonium is accumulated. By the reduction of iron, phosphate is mobilised. Free sulfide is only formed if iron concentrations are low. As in most floodplain soils iron concentrations are high, no free sulfide is present. Instead, toxic concentrations of reduced iron can be formed. This does, however, not have to be a constraint, but can be a selective quality for adapted, characteristic species.

A more frequent water level fluctuation does not necessarily lead to lower redox potentials. In the former intertidal areas the restoration of tidal flooding led to a more aerobic situation in which denitrification rates are lower, less iron is reduced, less phosphate is mobilised, less sulfate is reduced and less methane is produced.

2. How do these regimes affect overall decomposition and mineralisation, sulfate reduction rates, nitrification and denitrification rates?

Overall, anaerobic decomposition rates are slower than aerobic decomposition rates. A change in flooding regime in the Haringvliet area stimulated aerobic decomposition.

3. What are the interactions of the above processes with river water and groundwater chemistry (sulfur, nitrogen, salinity) and soil/sediment characteristics (clay and organic matter fractions)?

Sulfate pollution may only lead to sulfide toxicity if soils are poor in iron and rich in organic matter. Both nitrate and sulfate in the river water and iron in the soil may act as redox buffers, preventing methanogenesis. Increased salinity (oligohaline range) of the river water does not permanently slow down decomposition rates, but at most temporarily. The absence of easily degradable organic matter in some parts of the floodplains prevents reduction processes and hence the formation of certain toxins and methane.

4. How do soil microbial communities linked to sulfur cycling react to these hydrological and hydrochemical changes (structure and functioning) and what is their quantitative role in nutrient cycling?

This subproject has not specifically addressed this question.

5. How do different vegetation types and macrofauna respond to these biogeochemical changes, with respect to primary production and species composition?

Nitrogen pollution can increase primary production, at least in nitrogen limited species rich haylands along the Overijsselse Vecht. This also causes a shift in species composition towards fast growing grasses. Exchange of phosphate from the soil pore water to the surface water may cause algal blooms. In this project, we did not examine the macrofauna, but it can be expected that no toxic effects of sulfide to the macrofauna will arise in most of the riverine areas because of complete precipitation with iron, in contrast to the original expectations of the research project.

11b Did the project also include objectives which were not scientific? For instance, did the project also intend to apply research results, or strengthen the economic position of certain businesses?

One of the aims of the project also was to provide knowledge for nature managers and policy makers which can directly be applied in river management. For this purpose an article will be written for a Dutch nature conservation or water management journal.

11c Did the project's aims include the expanding the (international) network of contacts (at what level), providing education, improve communication, serve as input for policy drafting or policy decisions, etc.? Please motivate.

Yes, see above.

12 Do the results obtained match the original objectives? Please provide a short motivation why they do or don't.

This subproject gave insight in the biogeochemical processes that take place upon flooding and dessication and the interactions between soil chemical properties, river water quality and river water pollution. In this way this research provided a sound base for answering the original research questions.

13 Will the results of this project serve as input for an initiative integrating/and or generalizing input from several projects, for instance into a (numerical) model, or into more understanding at the higher/system level? If so, was this intended and optimised from the beginning or did it occur by chance/ spontaneous? Please elaborate.

The results of the vegetation, soil and water surveys are used in a database made by Research Centre B-ware for the State Forestry Service (Staatsbosbeheer) in which these kind of data from all kind of systems throughout the Netherlands are integrated.

14 To what extent has this research project pointed the way in which further research has to be undertaken? Please motivate the guiding role perceived.

Further research to clarify vegetation patterns and the presence/absence of certain target species should be carried out multidisciplinary, focussing not only on biogeochemical processes, but at hydrological, geomorphological processes, ecophysiology and seed dispersal as well. This study could function as a base for the biogeochemical processes involved.

15 In what way, and to what extent, are the results reached of importance to research done by others? Please motivate or elaborate

The results obtained were used by the other researchers of the project. They are also important for other research done within the Environmental Biology group of the RU Nijmegen, for instance in a research project on sustainable integrated water management in the river Vistula basin in Poland, carried out together with the Catholic University of Lublin.

16 Are you aware of any essential gaps or obstacles standing in the way of applying the results from your research project? Please elaborate.
Communication to nature managers is of vital importance for the application of the results (See 11b).

17 Which new research questions were generated through this project? Were these new questions addressed within this research project itself? Or will these new questions, or the results from your research project lead to new research projects (to be) funded by either 1st , 2nd,or 3rd category funding or funding through international funding agencies? Please elaborate.
New questions raised during the research:
- To what extend do biogeochemical processes determine vegetation development compared to other, e.g. (geo)morphological and hydrological processes?
- Does iron toxicity play a role in vegetation development in floodplains (a pilot study was done during the project)?
- Does chloride toxicity play a role in species competition in estarine vegetation types? New plans for fundraising are in preparation.

18 In what way did you link this project to other projects within the TRIAS-program or link it to projects outside TRIAS? Did you cooperate within the TRIAS-program and did this cooperation lead to integrated results?
There was a close cooperation between the three subprojects of this research. This will lead to the publication of, in total, 5 joint peer-reviewed articles in international journals.

19 Can you elaborate on the impact on society as a whole of your results (e.g. societal organisations, NGO's, businesses, schools, municipal authorities, etc.)
Our results are very useful for nature conservationists and policy makers for appointing new nature development areas and water storage areas. The outcomes of this research enable policy and management to base on prognosis rather than trial and error, improving efficiency levels. The outcomes could also be used for making the objectives of the Water Framework Directive more concrete.

20 What actions were taken to disseminate the results in the direction of the general public, besides the usual scientific channels?
Part of the results of this subproject were already used by STOWA/Alterra for an overview of knowledge of water storage and nature for water managers. An article for possible Dutch users will be written. At time of the defence, university will send out a press release.

21 Have the researchers involved obtained a new position or employment after the project came to an end? Please specify and elaborate!
Not yet.