

Spatial planning for lowland-stream basins using a bioeconomic model

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Abstract Most lowland-stream drainage-basins have a high population density and the land-use is very intensive. The permeable subsoil acts as an integrating medium, thus providing a widespread dispersal of leached nutrients and transmission of watertable lowering. This leads to desiccation and eutrophication of stream ecosystems. For providing suggestions with respect to cost-effective and sustainable spatial planning solutions the ‘WATERWISE’ bioeconomic model was developed. It combines the accuracy of simulation models with the versatility of optimization techniques to generate land-use patterns along with the appropriate water management, taking into account the preferences of stakeholders with respect to peak

discharges, nutrient loading on groundwater and surface water, the biological value of nature areas, and the revenue from agriculture. Computational experiments with the model show for instance that a certain goal for the N-load on surface water can be reached at a 40% lower cost if the measures are 'tailored' to the region instead of using generic-style measures towards the same end.

Key words: lowland; stream; agriculture; nature; desiccation; flooding; nutrients; simulation; optimization; spatial planning; bioeconomic model; stakeholder

INTRODUCTION

Lowland-stream basins have traditionally attracted dwellers owing to their easy accessibility and high land-use potential. A high population density and intensive land-use are the result. The dense network of channels and the permeable subsoil act as an integrating medium, thus providing a widespread dispersal of leached nutrients and transmission of watertable lowering. This endangers the drinking water supply and leads to desiccation and eutrophication of stream ecosystems, both the aquatic systems in the streams and the terrestrial systems in the stream valleys. The biological value of the latter is due to the presence of shallow watertables in combination with calcium-enriched upward seepage. The latter provides excellent conditions for vegetation requiring pH-buffered soils. Apart from the degradation of nature areas and pollution of groundwater, climate change is adding extra problems; especially the increase of the flooding hazard is becoming manifest.

For combating the deterioration of river basins the European Community has issued a 'Framework Directive in the field of water policy' ([http://europa.eu.int/scadplus/printversion/-](http://europa.eu.int/scadplus/printversion/)

en/lvb/128002b.htm) stipulating the achievement of several water-related environmental objectives by the year 2015. Given the ambitious goals of the directive it is clear that in many parts of Europe a substantial reallocation of land use will be needed. For providing suggestions with respect to cost-effective and sustainable spatial planning solutions the 'WATERWISE' protocol has been developed (Van Walsum *et al.*, in press). It combines the accuracy of simulation models with the versatility of optimization techniques to generate land-use patterns along with the appropriate water management, taking into account the preferences of stakeholders.

MODELS

Simulation of the regional system

For predicting effects of measures on a regional hydrologic system and its dependent functions the following models have been coupled:

- SIMGRO (Querner & Van Bakel, 1989; Veldhuizen *et al.*, 1998) for the regional hydrology; SIMGRO is an integrated finite-element model with a timestep-by-timestep two-way coupling of submodels for soil water, groundwater and surface water;
- ANIMO (Groenendijk & Kroes, 1999) for leaching of nitrates and phosphates to groundwater and surface water; ANIMO is a process-based simulation model that simulates all relevant components of soil chemistry, including the carbon-cycle; for the reason of computational efficiency use has been made of a simplified 'metamodel' based on regression analysis of a large number of computational experiments (Mol-Dijkstra *et al.*, 1999);

- NATLES (Runhaar *et al.*, 1999) for evaluating soil and water site-conditions in terms of the potential type of natural vegetation that can develop;
- DRAM (Helming, 1997) for the development of agriculture, modelled as a ‘regional farm’; DRAM is a regionalized mathematical programming model of agriculture in the whole of the Netherlands.

The coupling mentioned above is of the conventional type; the models are run one after each other. Questions can be answered of the type ‘What is the effect of removing all agricultural drainage on the (potential) value of wet nature areas?’ The models can, however, not be used for answering questions of the type ‘What is the most cost-effective way to increase the percentage of valuable wet mesotrophic natural grasslands by 10%?’ For being able to answer such questions a model is needed that is more full integrated. We developed such a ‘bioeconomic’ model using large-scale linear programming (LP) as the integration framework.

Bioeconomic model

For obtaining an LP-model of a regional hydrologic system and its dependent functions there broadly are two techniques available, as e.g. explained in Gorelick (1983). The first is that of *embedding*, which involves the wholesale inclusion of (part of) a model. The second is that of first deriving a *repro-function*, that reproduces the behaviour of the simulation model for a specific type of measure. The repro-function is then included in the LP-model. Both techniques have been used for constructing the bioeconomic model ‘WATERWISE’.

SIMGRO is a complex dynamic simulation model, requiring the repro-function approach for including it in the bioeconomic model. A simple – but very computationally intensive – method for deriving the repro-functions would be to let a land and water

management option ‘walk’ through the study region and then each time do a simulation run to register the effects on the nature areas. Since one simulation run with SIMGRO takes about 10 hours, this method is not feasible. Instead, an analytical multi-layer steady-state groundwater model is used for computing the effect of raising (or lowering) the watertable in a spatial planning unit s_1 on the conditions in a planning unit s_2 . The analytical method is applied for each combination of spatial planning units, which yields the so-called influence matrix (see for instance Gorelick, 1983). The matrix can be used for the superimposition of effects, due to the linear nature of the differential equation describing the steady-state groundwater flow. The influence matrix is calibrated on the results of sensitivity analysis runs with SIMGRO; in each of these runs a certain measure is uniformly applied to the whole agricultural area in the region. For the calibration a regression method is used. The result is a modelling chain with the following components that are shown in the scheme of Fig. 1:

- 1) measures in agriculture areas, defined in terms of land-use, subsurface drainage, and sprinkling;
- 2) effects of measures on local watertable conditions in agriculture areas, in terms of effects on the Mean Spring Watertable and the Mean Lowest Watertable (from the sensitivity analysis runs with SIMGRO);
- 3) effects on the steady-state aquifer heads below nature areas, by applying the influence matrix to the watertable effects calculated in step 2);
- 4) effects on the dynamics of aquifer heads below nature areas, by applying regression a function to the effects calculated in step 3);
- 5) effects of changes in aquifer head dynamics on the watertable conditions in nature areas, extracted in the form of tables from the sensitivity analysis runs with SIMGRO;
- 6) effects of watertable conditions in nature areas on the natural vegetation that can develop, extracted in the form of tables from NATLES-evaluations of SIMGRO sensitivity runs.

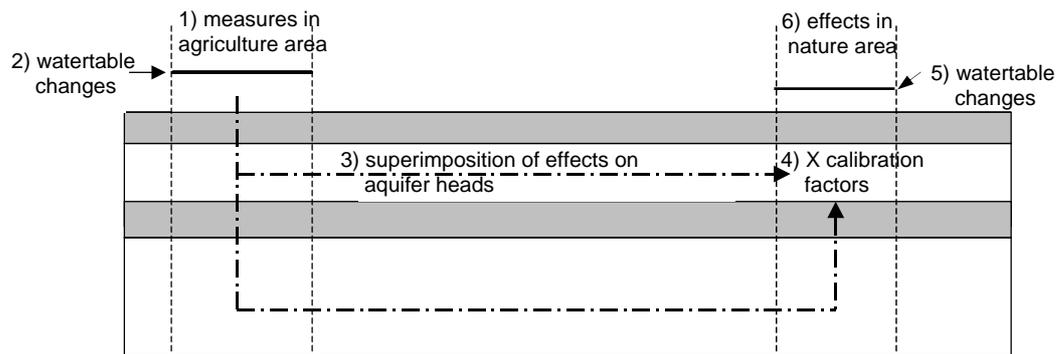


Fig. 1 Modelling chain for calculating effects of measures in agriculture areas on nature areas

The model NATLES for effects on the potential value of vegetation in nature areas requires data with respect to the management (mowing or grazing of grasslands), soil type, and groundwater conditions. The groundwater conditions are given in terms of the so-called Mean Spring Watertable (*MSW*), the Mean Lowest Watertable (*MLW*), and the gross seepage to the root zone. (See Van Walsum *et al.*, 2002, for the coupling between SIMGRO and NATLES; the ‘mean’ watertable refers to over-the-years averaging.) These data are then transformed to suitability maps through a stepwise procedure involving grids in an ArcView software shell (ESRI, 1996). NATLES is incorporated in the bioeconomic model through the repro-function method in its most simple form: results of sensitivity analyses with the regional hydrologic model SIMGRO are routed through the ArcView shell of NATLES, and are stored in tabular form for use in the bioeconomic model, in the step 6) of the procedure given above.

The model DRAM (Helming, 1997) is a national model for agriculture in the Netherlands. Most of the model equations are in a linear form. That made it possible to realize a style of integration symbolized in Fig. 2: WATERWISE overlaps with a substantial part of

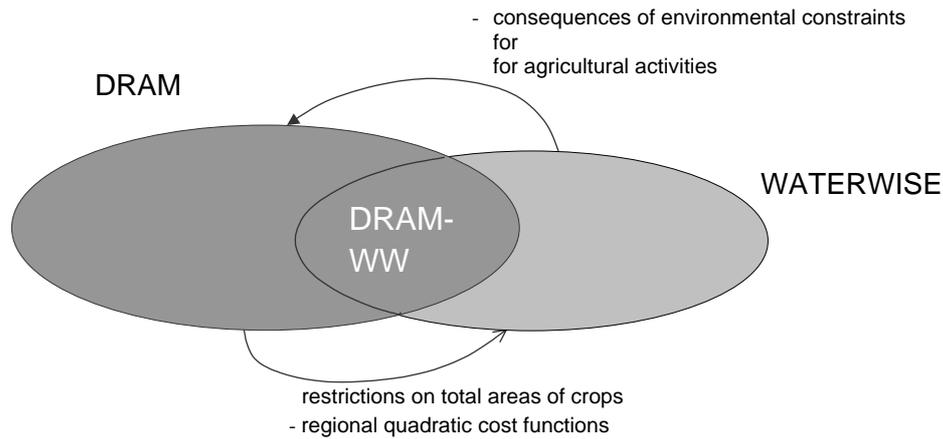


Fig. 2. Embedding part of the national agricultural model DRAM in the regional bioeconomic model WATERWISE.

DRAM. So here the embedding technique has been used. The embedded part DRAM-WW concerns the land balances, the manure balances, and the nutrient balances in terms of the nutritional value of N and P for crops, the balances of the fodder for livestock, and finally the revenue from agriculture. The latter goal function contains terms for the yield of arable land crops, the yield of intensive livestock farming, the yield of dairy farming, and the subsidies on special types of agricultural land-use that are ‘nature friendly’. The revenue function also contains terms for the costs of chemical fertilizer, the costs of manure application, the costs of manure export to other regions, the local costs of changing the type of land-use, and the regional costs of expanding a certain type of production. The latter term is derived using the PMP approach (Positive Mathematical Programming, see Howitt, 1995) taking into account the simulated markets at a national scale. Since this part of DRAM is not explicitly included in the bioeconomic model itself, the functions are delivered to it in the form of quadratic regional cost functions. The resulting convex form of the total revenue function reflects the law of decreasing marginal returns on increasing production – it is a well-known ‘trick’ that such functions can be modelled with LP by using a piece-wise linear representation. The

manner in which the quadratic cost term is derived and included in the model is a typical example of the *repro-function* method.

For relating land and water management measures to peak discharges of the streams the sensitivity analysis runs with SIMGRO are analysed in terms of the incremental flow contribution that each spatial planning unit makes in a period with high rainfall. These contributions are then stored as coefficients of the bioeconomic model. For relating land-use measures to the leaching of nutrients the results of the sensitivity analyses with SIMGRO are routed through the ‘metamodel’ of ANIMO (Mol-Dijkstra *et al.*, 1999) using nutrient surpluses derived from the agricultural model DRAM. Nutrient surpluses are defined in terms of land application minus the crop uptake. The registered effects on the nitrate and phosphate leaching to surface water and groundwater are stored as coefficients. For modelling the spreading of leachates in the aquifers a simple mixing cell model is used as show in Fig. 3. The mass balance equations of the cells (for the equilibrium state) are embedded as equality constraints in the LP-model. The equations include a decay term for the denitrification of nitrate under anaerobic conditions.

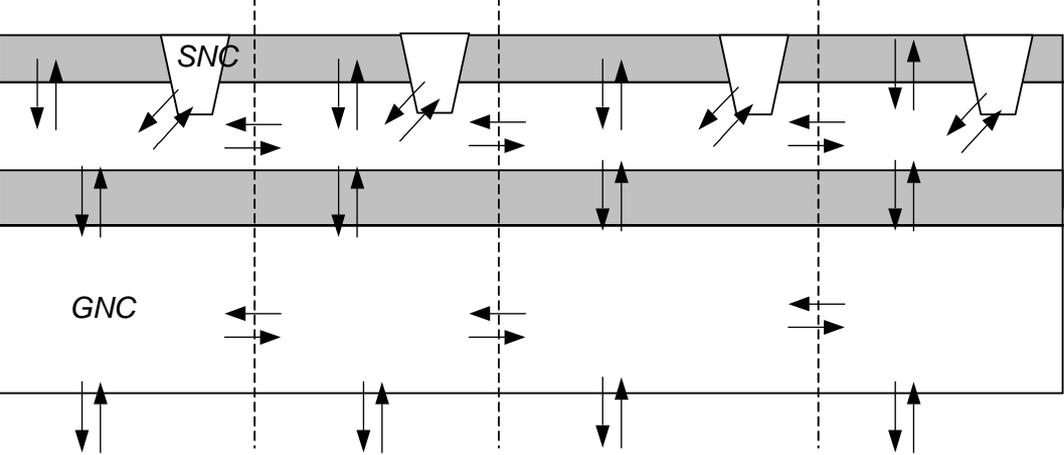


Fig. 3 Mixing cell scheme for simulating the transport of nitrates in the aquifers; the mass balances of the cells area embedded as equality constraints in the bioeconomic model, with the concentrations in surface water (*SNC*) and in groundwater (*GNC*) as decision variables; the flows are considered to have fixed values for the water quality calculations

For handling the multiple goals the simple constraint method is used: The user/stakeholder sets constraints on the desiccation of nature areas, the reduction of the peak discharges (taking also into account the possible effects of climate change), and the reduction of the nitrate leaching. The bioeconomic model first ascertains whether there is a solution at all, and (if there is one) then finds the land and water use pattern that satisfies the constraints and at the same time optimizes the revenue from agriculture.

The bioeconomic model has been implemented with the Xpress-mathematical programming package of DASH (DASH, 2001). The Newton Barrier algorithm of DASH is used for solving the resulting linear programming problem. This recently developed 'interior point' method drastically reduces computation times of large-scale problems.

RESULTS

The WATERWISE model has been applied to the Beerze & Reusel stream basins in the Netherlands. The twin basins cover an area of some 45 000 ha. The nature areas cover roughly 15 000 ha of the area; about 22 000 ha is in use by agriculture. For the bioeconomic model the study region was divided into 4 000 spatial units. The implemented model has roughly 200 000 functional decision variables, 60 000 active equations, and about 2 million coefficients in the LP-matrix. On an 800 Mhz Pentium III with 512 Mb RDRAM memory the solution time is 1.5 hrs.

An example of the efficacy of the bioeconomic model is provided by the policy measures considered with respect to the nitrogen losses of agriculture. In order to reduce nitrate leaching it is being considered to set a maximum loss of 60 kg N ha⁻¹ year⁻¹ for each and every location in the Netherlands; this limit refers to the *total* loss of nitrogen to

groundwater and surface water from a certain field location. When applied to the study area this 'generic-style' measure reduces the nitrogen load on surface water from 9.5 mg N l^{-1} to 4.5 mg N l^{-1} at the outlet of the basin. Roughly half of this load consists of nitrogen that reaches surface water by surface runoff and by shallow leaching to groundwater and subsequent drainage to surface water at the field scale. The other half reaches the surface water after deep infiltration to groundwater, transport through the groundwater (modelled with the mixing cells of Fig. 3), upward seepage, and finally drainage to surface water in the streams. (The 'concentrations' are in fact loads, and not the real concentrations; nitrogen processes in surface water are not modelled). The computed loss of revenue from agriculture is 19%.

A computational experiment was made with the bioeconomic model to see whether the same 4.5 mg N l^{-1} could be achieved at a lower cost. The model showed that the 4.5 mg N l^{-1} could also be achieved at a revenue loss of only 11%. As can be seen from the comparison of the nitrate concentrations in Fig. 4 the generic-style measures produce a concentration pattern (Fig. 4a) that is much more evenly distributed than if the measures are tailored for a minimum loss of agricultural revenue (Fig. 4b). In the latter case the concentrations in uplands are much higher, because in these parts of the region the bioeconomic model does not remove all of the high-intensity dairy farming like the generic-style measures do. The reasoning behind this strategy is that if the high nitrogen concentrations are in the uplands, the travel times through the deep subsoil are the longest, and therefore the denitrification of the nitrate can have reduced the concentrations by the time the water reaches the surface water system through upward seepage and drainage: in the right hand map (Fig. 4b) the concentrations near the streams are in general lower than in the left-hand map (Fig. 4a) of the generic-style measures. By making use of the groundwater as a 'denitrification machine' the bioeconomic model achieves the same environmental goal

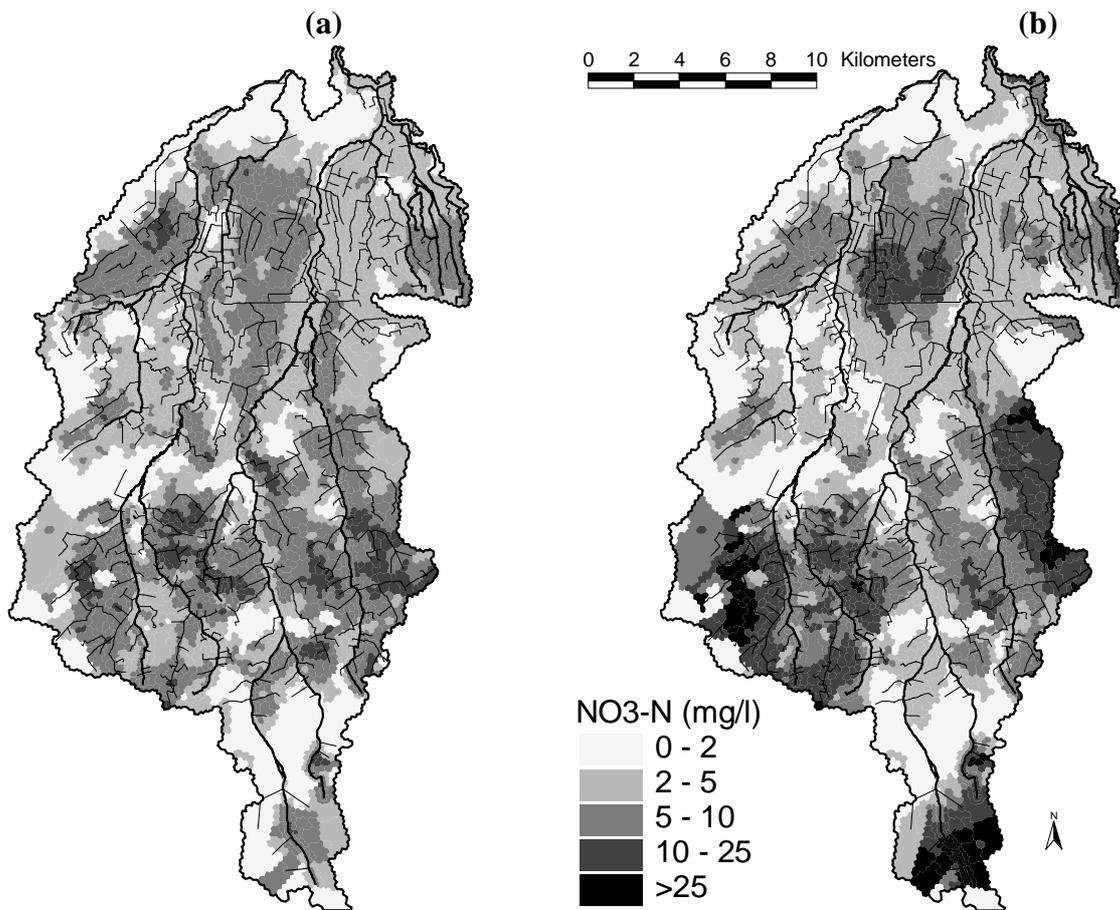


Fig. 4 Generated patterns of the nitrate concentration in the first aquifer for generic-style measures to decrease the amount of nitrogen losses to the environment (a) and for tailor-made measures using the bioeconomic model (b)

(4.5 mg N l⁻¹ at the basin outlet) at a 40% lower cost. The model coefficients with respect to nitrogen loading and denitrification are, however, very uncertain, because much is not yet known about the underlying processes. But this example does demonstrate how the bioeconomic model can take advantage of the way a regional system functions in order to achieve environmental goals at the lowest possible cost.

Crucial to the success of the simplified modelling in the bioeconomic model is that the submodels are accurate enough to facilitate the computational process of searching for a cost effective solution. For the final estimation of the goals that actually are achieved the

simulation models are needed. The verification with SIMGRO-NATLES for the effects of measures aimed at combating desiccation showed that the results of this simplified submodel were accurate within 10-15% of the simulation models.

CONCLUDING REMARKS

A bioeconomic model has been developed for spatial planning of integrated land and water management in lowland stream basins. The technique of linear programming has been used as a framework for the integration of models. The system owes its practical relevance to:

- the possibility for the user/stakeholder to specify goals and constraints for the desiccation of nature areas, the nutrient loading on groundwater and surface water, peak discharges, and the revenue from agriculture;
- the predictive accuracy of the simplified submodels incorporated in the bioeconomic model, based on results of simulations with complex dynamic models; simulation models are also used for verification of the spatial solutions found by the bioeconomic model;
- the use of state-of-art optimization technology, providing a spatial resolution of 10 ha for basins of up to 50 000 ha, within acceptable computation times that are needed for facilitating a decision-making process.

The latter point has been demonstrated by the successful implementation for the Beerze & Reusel drainage basin in the Netherlands. The model is now being implemented in a new case study commissioned by the waterboard 'Stichtse Rijnlanden' in the central part of the Netherlands. We expect that in the near future the model will play a role in discussions about the implementation of the 'Framework Directive in the field of water policy' issued by the European Community.

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REFERENCES

- DASH. 2001. *XPRESS-MP Reference Manual*. Dash Associates, Blisworth (UK).
- ESRI, 1996. *Avenue. Customization and Application development for ArcView*. Environmental Systems Research Institute, New York.
- Gorelick, S.M. 1983. A review of distributed parameter groundwater management modelling methods. *Water Resources Research*. Vol. 19, No. 2. 305-319.
- Groenendijk, P. & J.G. Kroes, 1999. *Modelling the nitrogen and phosphorus leaching to groundwater and surface water with ANIMO 3.5*. Alterra report 144. Alterra, Wageningen (NL).
- Helming, J.F.M. 1997. *Mogelijke ontwikkelingen van landbouw en milieu bij een strengere milieubeleid voor de Nederlandse landbouw (UK: Possible developments of agriculture and the response of Dutch agriculture to stricter environmental measures.)* Publication 1.30 LEI, The Hague (NL).
- Howitt, R.E. (1995). Positive Mathematical Programming. *American Journal of Agricultural Economics*, 77(May), pp 329-342
- Mol-Dijkstra, J.P., Akkermans, W., Roest, C.W.J. and Jansen, M.J.W. (1999). *Metamodels to predict nutrient losses to groundwater and surface waters (in Dutch)*. DLO Winand Staring Centre for Integrated Land, Soil and Water Research, Technical Document 61, Wageningen, The Netherlands.
- Querner, E.P. & P.J.T. van Bakel, 1989. *Description of the regional groundwater flow model SIMGRO*. Report 7. DLO Winand Staring Centre, Wageningen (NL).

- Runhaar, J., H.L. Boogaard, S.P.J. van Delft & S. Weghorst. 1999. *Natuurgericht Landevaluatiesysteem (NATLES)*(UK: *Nature oriented land evaluation system*). Rapport 704 SC-DLO, Alterra, Wageningen (NL).
- Van Walsum, P.E.V., P.F.M. Verdonschot & J. Runhaar. 2002. *Effects of climate and land-use change on lowland stream ecosystems*. Nationaal Onderzoek Programma Mondiale Luchtverontreiniging en Klimaatverandering (NOP). Report 523, Alterra, Wageningen (NL). (download from: <http://www.alterra.nl/english>)
- Van Walsum, P.E.V., J.F.M. Helming, E.P.A.G. Schouwenburg, L.C.P.M. Stuyt, C.J.A.M. de Bont, P.H. Vereijken, C. Kwakernaak, P.J.T. van Bakel, L.C. van Staalduinen, P. Groenendijk & K.W. Ypma. in press. *Waterwijs; plannen met water op regionale schaal* (UK: *Waterwise; spatial planning based on water at a regional scale.*) Report 433. Alterra, Wageningen (NL). (www.alterra.nl/english)