MODELLING THE IMPACT OF HYDROLOGIC CHANGES ON TERRESTRIAL ECOSYSTEMS WITH THE SIMGRO-NATLES MODEL COMBINATION.

J. Runhaar [1], P.E.V. van Walsum [1]

Abstract: A serious problem in hydro-ecologic modelling is that ecologic models often need different or more detailed information than hydrologic models normally provide. In this article we describe some solutions to solve this problem, using the SIMGRO-NATLES model combination as an example. In this model combination we use ecologically relevant hydrologic variables, of which we know how they influence site conditions and organisms: mean spring groundwater level, mean lowest groundwater level, moisture stress, upward seepage flux and alkalinity of the seepage water. The spatial variability of these variables is considerable. As a result, there can be large differences in site conditions and vegetation patterns within spatial units that are considered to be homogeneous in the hydrologic model. To solve this problem we used downscaling techniques. Detailed information on topography in the form of a Digital Terrain Model can be used to determine the variation in groundwater levels relative to the soil surface within the nodal domains of the hydrologic model. Upward seepage of groundwater is often a prerequisite for pH buffering of terrestrial sites. Problem is that only the seepage water that reaches the root zone is relevant for this buffering. Therefore an estimate has to be made of this fraction; the remainder directly drains to the surface water.

[1] Department of Water and Climate, Alterra, P.O. Box 47, 6700 AA Wageningen, han.runhaar@wur.nl

INTRODUCTION

Modelling the impact of hydrologic changes on terrestrial ecosystems is not always an easy task. Our knowledge of how groundwater influences site conditions and species composition is still incomplete, and the scale on which hydrologic systems are modelled is often not detailed enough to give information about the processes that are relevant for ecosystem functioning. In this article we will give an example of how these problems are dealt with in our SIMGRO-NATLES model combination, in which the hydrologic model SIMGRO and the hydro-ecologic model NATLES are used for predicting the impact of hydrologic changes on terrestrial ecosystems. This model combination is mainly used in optimisation studies, where the aim is to find ways of restoring groundwater-dependent ecosystems without disproportionate negative economic impacts on surrounding areas. But it can be also used for a number of other purposes, for example in predicting the indirect effect of climate changes through changes in hydrologic conditions.

THE SIMGRO AND NATLES MODELS

For coming to grips with integrated water management issues it is necessary to have a model that covers the whole (regional) system, including plant-atmosphere interactions, soil water, groundwater and surface water. SIMGRO (Van Walsum et al., 2004) was developed for that purpose. It is a mechanistic distributed model with a numerical groundwater model at its core. The saturated-unsaturated flow is modelled in a unified manner, using a dynamic ‘meta’-modelling concept. By the latter is meant that the model relies on ‘intelligent’ data that are obtained by a series of computational experiments with a comprehensive model for a plant-soil column extending into the groundwater. Such a type of meta-concept is also used for the dynamic modelling of surface water. In this way an acceptable degree of accuracy is achieved at a relatively low computational cost.

Natles (Runhaar et al. 1999, 2003) is written as an extension of the popular GIS-model ArcView, and should be used in combination with the grid-extension of Arcview, Spatial Analyst. The input consists of grid maps with information on soil, hydrology and management. The output consists of grid maps with information on resulting site conditions and ecosystem types/vegetation types. The impact of hydrologic changes on site conditions such as acidity, moisture stress and nutrient availability is calculated using transformation matrices, which can also be seen as meta-models. These transition matrices are based on calculations with mechanistic models, empirical data and expert knowledge.

ECOLOGICALLY RELEVANT ECOLOGIC VARIABLES

When linking hydrologic and ecologic models one of the main questions is what the ecologically relevant hydrologic variables are. These are the variables that should be included in the results of the hydrologic model. Another question is how these variables influence site conditions and plant functioning. This knowledge is necessary for predicting changes in site conditions and species composition.

In the SIMGRO-NATLES combination the following hydrologic variables are considered to be the most relevant for ecosystem functioning: mean spring groundwater level (MSGL), moisture stress, upward seepage flux that reaches the root zone, and seepage-water carbonate content and mean lowest groundwater level (MLGL). In the following we will explain why these variables have been chosen, and how they influence site conditions and plant growth.

MEAN SPRING GROUNDWATER LEVEL

As shown by Runhaar et al. (1997) groundwater levels in spring are important for the occurrence of hygrophytes, i.e. species that are adapted to living in permanently or temporarily anaerobic conditions. An example is the presence of aerenchyme tissues that can transport oxygen down to the roots. In sites with mean spring groundwater levels of less than 0.2 m below soil surface they dominate the vegetation. The soil texture seems to have little influence on this fact.

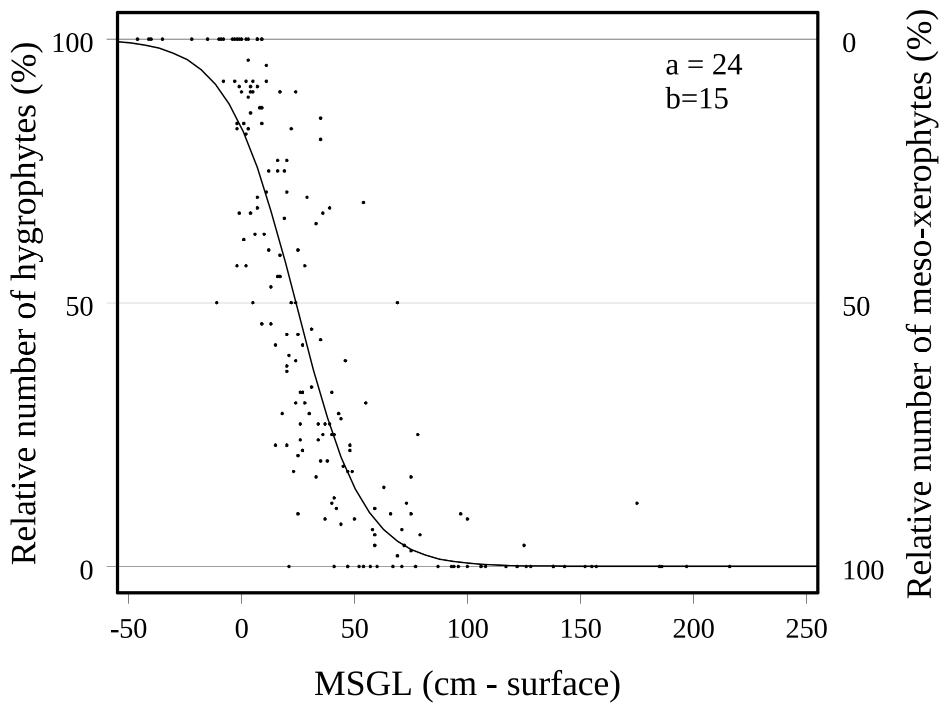

Figure 1. Relationship between relative number of hygrophytes in the vegetation and mean spring groundwater level (MSGL). The relationship can be described by a sigmoid function, y = 100/(1+EXP((MSGL-a)/b)), with parameters a=midpoint and b=steepness. Source: Runhaar et al. 1997.

Although aeration is probably the causal factor in the relationship between the spring groundwater level and the number of hygrophytes, aeration is not – or at least not yet – incorporated in our models. Instead, a direct relationship between spring groundwater level and the number of hygrophytes is used, based on the data represented in Figure 1.

MOISTURE STRESS

At deeper groundwater levels (mean spring groundwater level ≥0.5 m below soil surface) the aeration of the root zone hardly ever forms a problem. However, the supply of water may become critical at deeper groundwater levels. Jansen et al. (2000) found that the moisture stress, defined as the average number of days with a soil water pressure head of less than -12 m in the top soil, is a good predictor for the number of xerophytes (Fig. 2). These are species adapted to dry conditions in a number of different ways. For example, by being able to reduce the transpiration in dry periods, or by surviving dry periods in the form of seed. The moisture stress not only depends on groundwater levels, but also on soil texture, evaporative demand and precipitation. In the present Dutch climate serious moisture stress is only to be expected in sandy soils with a deep groundwater level. But in more arid climates serious moisture stress may also occur on loamy and clayey soils.

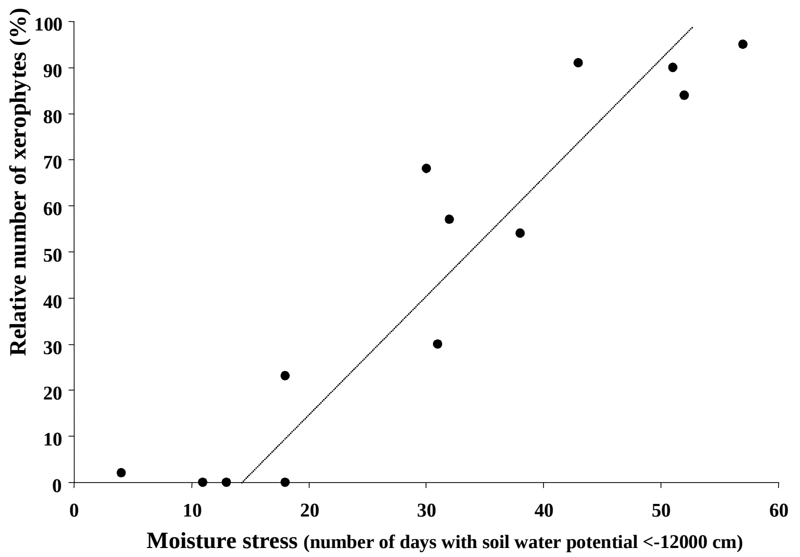

Figure 2. Relationship between relative number of xerophytes in the vegetation and moisture stress. Source: Jansen et al. 2000.

To calculate the moisture stress use is made of a hydrologic model for the unsaturated zone, SWAP (Kroes and Van Dam (eds.) 2003). The outcomes of this model are used for calculating soil-type and climate specific functions that give the moisture stress as a function of mean lowest groundwater level. These functions are incorporated in the NATLES model.

UPWARD SEEPAGE AND CHEMICAL COMPOSITION OF SEEPAGE WATER

The most complex dependent relationships concern pH-buffering. In Dutch lowland stream areas upward seepage with bicarbonate-rich groundwater is often a prerequisite for conserving pH-buffered mesotrophic grasslands, as the soils contain little or no carbonate of themselves. The resulting pH of the soil depends upon the bicarbonate and carbonate content of soil and groundwater and the balance between rainwater infiltration and upward seepage to the root zone. To calculate the pH in seepage areas, use is made of a one-dimensional chemical top-soil model, SMART (Kros et al. 1995). The outcomes of this model are used to fill transformation matrices that give the pH as a function of soil type, upward seepage to the root zone, mean spring groundwater level and the alkalinity of the groundwater. For infiltration areas the pH is directly based on the soil type, using relationships derived from empirical data and expert knowledge. Calculation of the pH-class of grid cells takes place in the NATLES model.

FLOODING

The pH-buffering of the soil can also be the result of flooding with bicarbonate-rich water. Flooding with river water can also raise the nutrient availability of the site, and lead to a higher productivity of the vegetation. The effects of flooding depend upon the intensity of the flooding, the amount of sediments deposited and the chemical composition of river water and sediments. However, these relationships are still far from clear and have not yet been incorporated in our model.

MEAN LOWEST GROUNDWATER LEVEL

Groundwater levels play a role in moisture supply, as indicated in a previous paragraph. However, in some habitats there are indications that lowest groundwater levels are already critical at a depth of less than a meter, in situations where moisture stress is not to be expected. This is especially the case in wet habitats dominated by helophytes. Probably the lowest groundwater levels are critical in these wet sites because they determine the length of the period with anaerobic conditions. Although the relationship between species composition and lowest groundwater levels in wet habitats is still far from clear, for some vegetation types (especially *Magnocarion* and *Calthion* vegetations) the mean lowest groundwater level is treated as a critical factor. Critical ranges are based on observed groundwater levels in sites with these vegetation types.

DOWNSCALING OF HYDROLOGIC INFORMATION

One of the problems in hydro-ecologic modelling is that the scale of the hydrologic model seldom suits the scale on which ecologically relevant processes function. This holds both for calculated groundwater levels and for calculated seepage fluxes.

In most hydrologic models average groundwater levels are calculated for spatial units that are rather large, ranging from 250*250 m^2 for models that are used on a regional scale down to 25*25 m^2 for models used on a local scale. But even in the latter case the units are rather large compared to the scale of groundwater-related gradients in nature areas. For the vegetation, the groundwater level relative to the soil surface is the most important factor, and this relative groundwater level is much more variable than the absolute groundwater level above sea level. Luckily, in the Netherlands there is detailed information available on the topography. On the basis of laser altimetry a digital terrain model (DTM) with 5 x 5 meter grids is available for the whole country. This DTM is used in combination with the absolute groundwater levels per SIMGRO-node to calculate the groundwater levels relative to the soil surface in the following three steps (Fig. 3)

1) an interpolation function is constructed from the simulated groundwater levels at the nodes of the model;
2) the function is interpolated at the centre points of the 5 X 5 m grids (or 25 X 25 m grids, depending on the detail of the available digital terrain information);
3) the interpolated level is subtracted from the DTM of the soil surface

An experiment in a study area (Van Walsum et al., 2002) revealed that groundwater levels for nodal subdomains with a mean diameter of 240 m that are downscaled to 25 x 25 m grids on the basis of a DTM closely match the results of a detailed model with nodal subdomains having a mean diameter of 50 m.

For upward seepage similar scale problems can be observed. But here there is an extra complication. Most hydrologic models only calculate seepage fluxes within the saturated zone at the transitions between layers of the geohydrologic schematization. But the seepage entering the bottom of the top layer is ecologically irrelevant because most of it usually drains directly to surface water without making any contact with the soil substrate. For the buffering of terrestrial sites only the fraction of the seepage water that actually reaches the root zone is relevant.

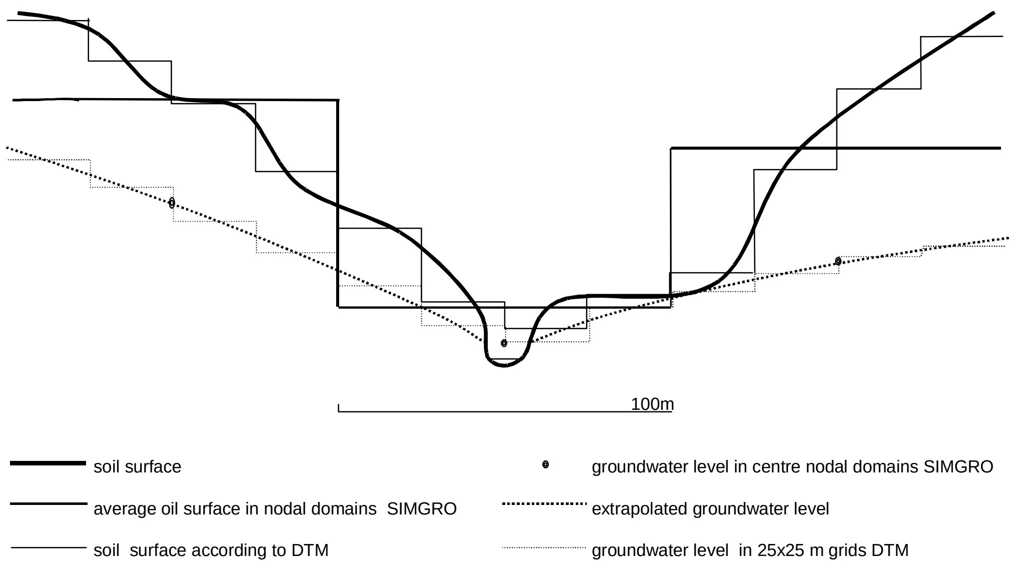

Figure 3. Downscaling of groundwater levels predicted with SIMGRO using a detailed Digital Terrain Model with grids of 25 x 25 m.

In Figure 4 a schematic diagram is given of the manner in which this seepage is computed as a post-processing step of the model SIMGRO.

The mechanism at play involves the build-up of a precipitation lens on top of the groundwater that seeps up from the deeper aquifer (area enclosed by water table and dotted line in Fig. 4). This lens is thickest in winter and becomes thinner during the summer half-year. A simple approach is followed for computing the seepage to the root zone, by making an upper-bound estimate. The assumption is made that as long as there is water in the precipitation lens and at the same time there is drainage to ditches, the drainage water will purely consist of precipitation water stored in the lens. In reality some of the drainage to ditches will consist of deep seepage water long before the precipitation lens has completely vanished. So the lens will exist longer than is predicted in the simplified approach, and thus the seepage to the root zone will in reality be less than what is calculated (for more details about the method, see Van Walsum et al., 2002).

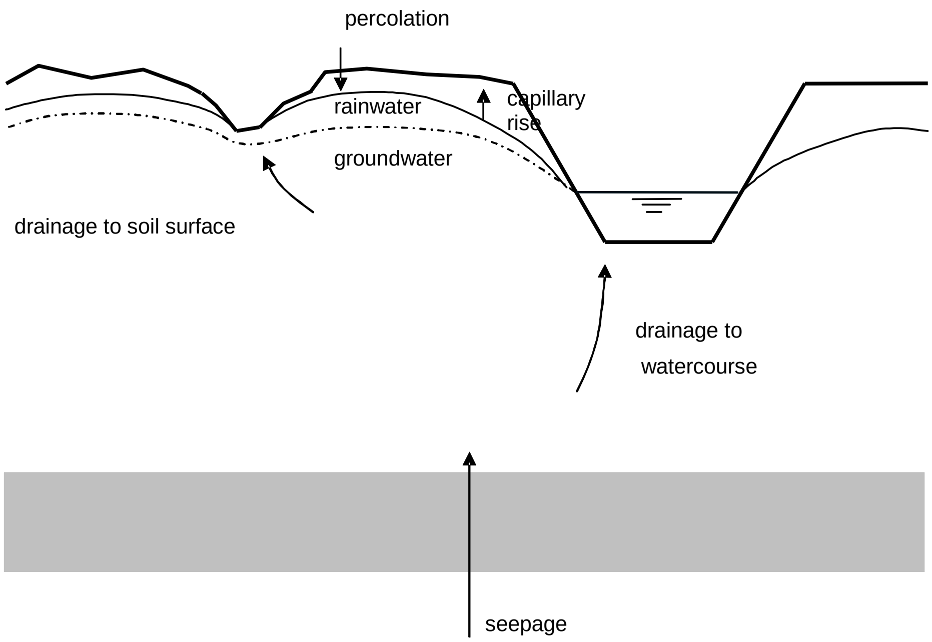

Figure 4. Scheme for the simplified calculation of the ‘gross seepage flux to the root zone’, involving a dynamic simulation of the thickness of the precipitation lens (‘rainwater’)

RESULTS

The SIMGRO-NATLES model combination can be used to generate rather detailed maps of predicted ecosystem- and vegetation patterns in both the present situation and the situations after changes in management and hydrology. Figure 5 gives an example from a land evaluation study in which measures are planned for the restoration of wet mesotrophic grasslands. The scale of the model results depends on the scale of the input data, but grid data with a grid size of 25 x 25 m are most commonly used for regional studies.

The results are expressed in terms of (changes in) site conditions and ecosystem type, using an ecosystem classification in which ecosystem types are distinguished on the basis of vegetation structure and ecologically relevant site conditions (aeration, moisture supply, nutrient availability, salinity, acidity) (Stevers et al. 1987, Runhaar et al. 1994, 1999). The plant species composition of these ecosystem types is described using ecological ‘species groups’. These species groups are based on (amongst others) the Ellenberg indicator values (Ellenberg et al. 1992) and have been adapted to the Dutch situation using a large set of relevés that are representative for the vegetation in the Netherlands (Runhaar et al. 1997, 2004; see Tamis et al 2004 for most recent classification of individual plant species). But it is also possible to express the results in terms of vegetation types, using a database that links vegetation types to site conditions. For the relationship with the vegetation type use is made of a database containing information on the environmental site requirements of Dutch vegetation types, based on empirical data and expert knowledge (Runhaar et al. 2003a).

The model is mainly used for land evaluation studies, especially in studies involving changes in water management. But it has also been used in a scenario study to predict the impact of climate changes (Van Walsum et al. 2002, Runhaar et al. 2002)

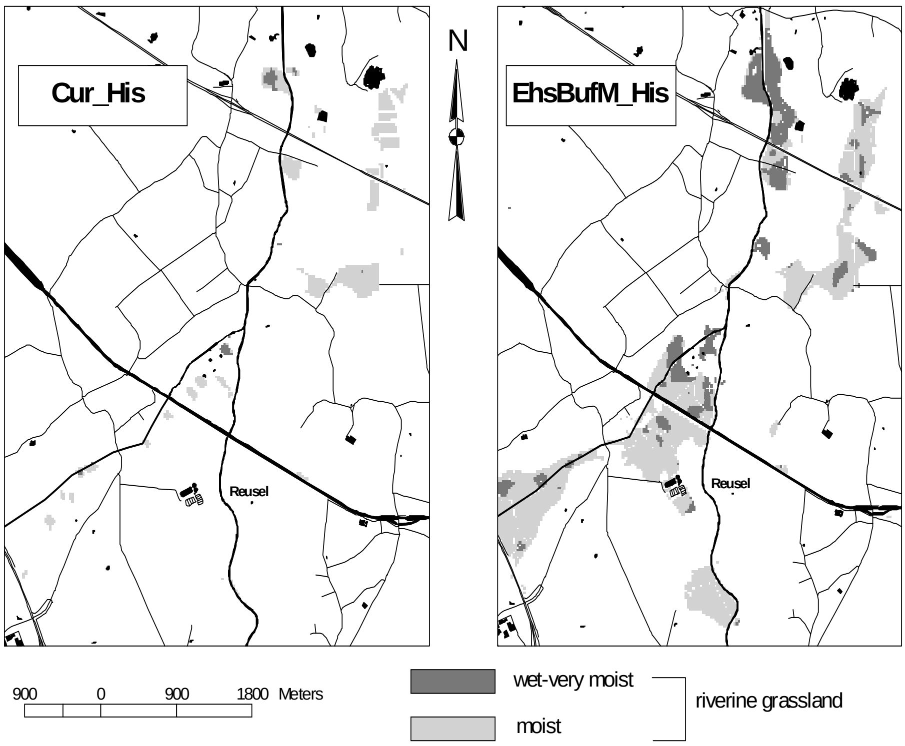

Figure 5. Example of a land evaluation study in a brook-valley area where SIMGRO and NATLES are used for predicting the effects of hydrologic measures on the restoration of wet mesotrophic grasslands. Left: present situation. Right: after restoration. Source: Runhaar et al. 2002.

DISCUSSION

USING CAUSAL RELATIONSHIPS BETWEEN HYDROLOGY AND ECOLOGY

In the SIMGRO-NATLES model we have explicitly chosen for a causal approach, using hydrologic variables of which we know how they affect plant functioning. This does not necessarily lead to more reliable or more detailed results than correlative models, in which vegetation patterns are directly linked to hydrologic patterns on the basis of empirical data. These correlative models can range from relatively simple models, in which correlations between the occurrence of vegetation types and groundwater frequency distributions in the form of 'duration lines' are used for predicting the impact of hydrologic changes on the vegetation (Niemann 1963, Grootjans et al. 1990, Jansen 1993), to sophisticated statistical models in which multiple logistic regression is used for establishing relationships with a large number of site conditions (Ertsen 1998, Ertsen et al. 1998, Noest 1995; see also description of ITORS and HYCAM models in Venterink & Wassen, 1997). Whether or not a causal approach leads to more reliable predictions largely depends on the extent of our knowledge of underlying causal relationships.

However, an advantage of the causal approach is that relationships can more easily be extrapolated to different areas, as long as the physical principles underlying the relationships are the same. As a result, there is less risk of making false predictions than on the basis of non-causal relationships. For example, serious miss predictions can be made when using correlations between vegetation types and frequency distributions established for sandy soils for predicting the effects of hydrologic changes on loamy or peaty soils. Because of the differences in water retention and capillary rise the relationship between species composition and groundwater levels is expected to be different for differing soil types. This has been shown by De Haan (1993) for *Ericetum* vegetations on sandy and peaty soils. Another advantage of using causal relationships is that use is made of explicit hypotheses on the relation between hydrology and vegetation. These can be justified or falsified on the basis of monitoring data and so contribute to a better understanding of the underlying relationships. A further advantage of using causal relationships is that they – with care – can be used for predicting the 'indirect' hydrologic effects of climate change (Van Walsum et al., 2002).

It should be noted that the SIMGRO-NATLES model is not a completely mechanistic model, based upon explicit causal relationships. As indicated in the previous paragraph, the relationship between ecologically relevant site conditions and species composition is mainly based upon correlations in the field between site conditions and the occurrence of plant species and vegetation types. A completely mechanistic prediction of the species composition is difficult because competition between species is an important factor in the establishment of plant communities. Even in rather species-poor ecosystems the number of possible interactions between species is so large that it makes mechanistic modelling at best a cumbersome task. Therefore mechanistic modelling of species interactions is mostly restricted to very simple species-poor ecosystem types or the species composition is simplified by distinguishing only growth forms (see for example Oene et al. 1999). For predicting the species composition of groundwater-dependent ecosystems, which are often very species-rich, mechanistic modelling is not a feasible option.

BRIDGING THE SCALE GAP BETWEEN HYDROLOGY AND ECOLOGY

The use of digital terrain models for the downscaling of hydrologic models can greatly improve the prediction, as topography is one of the main factors that determine the impact of regional groundwater systems on local site conditions and vegetation. However, the use of a digital terrain area is not a panacea that solves all problems. One of the main remaining problems is the heterogeneity of the underlying substrate. Even in well investigated areas the number of geologic drillings is too small to get an accurate 3D-view of the substrate. Furthermore, nature areas of special interest have a tendency to be located in areas with a special geohydrology; for example on sites where aquitards are perforated, resulting in strong but very local upward seepage. No downscaling procedure is able to solve that problem, only more detailed geologic research can be of help. Hydro-ecologic models like the SIMGRO-NATLES model described here can however be useful in this respect. In the calibration phase large discrepancies between model predictions and observed vegetation patterns can be a trigger to locally investigate the geo-hydrologic situation in more detail.

CONCLUSION

A serious problem in hydro-ecologic modelling is formed by the differences in types of variables used in hydrologic and ecologic models and by the differences in scale on which hydrologic and ecologic processes operate. In this article we show some solutions that can be used for bridging the gap between hydrology and ecology. Because they are based on causal relationships these solutions are generally applicable throughout the temperate climatic zone. We do not want to suggest that we were able to solve all problems. But we feel that we have made good progress in unravelling the relationships between hydrology and ecology and in tackling the scale differences between hydrologic and ecologic models.

REFERENCES

De Haan, M.W.A., 1993. *Duurlijnen van natte heiden, typering van het grondwaterstandsverloop van een regenwaterafhankelijk vegetatietype*. In: Jansen. A.J.M. (ed), Van hydrologische ingreep naar ecologische effectvoorspelling, Mededeling 122, KIWA, Nieuwegein.

Ellenberg, H., H.E. Weber, R. Düll, V. Wirth, W. Werner & D. Pauliszen, 1992. *Zeigerwerte von Pflanzen in Mitteleuropa*. Scripta Geobotanica IX, Gottingen, 2. auflage.

Ertsen, A.C.D., J.W. Frens, J.W. Nieuwenhuis & M.J. Wassen, 1995, *An approach to modelling the relationship between plant species and site conditions in terrestrial ecosystems.* Landscape and Urban Planning 31: 143-151.

Ertsen, A.C.D., 1996. *Ecohydrological response modelling. Predicting plant species response to changes in site conditions*. Thesis, University of Utrecht (the Netherlands).

Grootjans, A.P., R. van Diggelen, H. Esselink, A. Wierda, R. Burkunk, J. Hoogendoorn en N.P.J. de Vries, 1990. *Hydro-ecologisch onderzoek Gorecht. Deel 2: Ecologische effectvoorspelling terrestrische systemen*. Laaglandbekenproject rapport nr. 22. State University of Groningen.

Jansen. A.J.M. (1993). *Van hydrologische ingreep naar ecologische effectvoorspelling*. In: Jansen. A.J.M. (ed), Van hydrologische ingreep naar ecologische effectvoorspelling, Mededeling 122, KIWA, Nieuwegein.

Jansen, P.C., J. Runhaar, J.P.M.Witte & J.C. van Dam, 2000. *Vochtindicatie van grasvegetaties in relatie tot de vochttoestand van de bodem.* Alterra-rapport 57. Alterra, Wageningen.

Kroes, J.G. and J.C. van Dam (eds.) 2003. *Reference manual SWAP 3.0.3.* Alterra-report 773. Alterra, Wageningen.

Kros, J., G.J. Reinds, W. de Vries, J.B. Latour en M.J.S. Bollen, 1995. *Modelling soil acidity and nitrogen availability in natural ecosystems in response to changes in acid deposition and hydrology.* SC-report 95. DLO-Staring Centrum, Wageningen.

Niemann, E., 1973. *Grundwasser und Vegetationsgefüge*. Nova Acta Leopoldina suppl. nr. 6, Band 38, Leipzig.

Noest, V. (1994). *A hydrology-vegetation interaction model for predicting the occurrence of plant species in dune slacks*. J. Environ. Manag. 40: 119-128.

Oene, H. van, F. Berenendse & C.G.F. de Kovel, 1999. *Model analysis of the effect of historic CO2 levels and nitrogen inputs on vegetation succession*. Ecological Applications 9: 920-935.

Olde Venterink, H & M.J. Wassen, 1997. *A comparison of six models predicting vegetation response to hydrological habitat change*. Ecological Modelling 101: 347-361.

Runhaar, J., Groen, C.L.G., Van der Meijden, R., Stevers, R.A.M. 1987. *Een nieuwe indeling in ecologische groepen binnen de Nederlandse flora* [A new division in ecological groups in the flora of the Netherlands] Gorteria 13: 277-359. [Engl. Summary]

Runhaar J., Udo de Haes, H.A. 1994. *The use of site factors as classification characteristics for ecotopes.* In: F. Klijn (ed), Ecosystem classification for environmental management, pp. 139-172. Kluwer Academic publishers, Dordrecht.

Runhaar, J., J.P.M. Witte & P.H. Verburg, 1997. *Ground-water level, moisture supply, and vegetation in The Netherlands*. Wetlands 17: 528-538.

Runhaar, J., 1999*. Impact of hydrological changes on nature conservation areas in the Netherlands*. Thesis, University of Leiden.

Runhaar, J., H.L. Boogaard, S.P.J van Delft en S. Weghorst, 1999*. Natuurgericht Landevaluatie-systeem (NATLES)*. Rapport 704. Staring Centrum, Wageningen.

Runhaar, J., P.E.V. van Walsum & A.H. Prins, 2002*. Effects of climate and land use change on hydrological conditions and species composition in Dutch riverine grasslands (Calthion, Junco-Molinion*. Ecohydrology & Hydrobiology 2: 219-226

Runhaar, J., H. Kuijpers, H.L. Boogaard, P.C. Jansen en E.P.A.G. Schouwenberg 2003. *Natuurgericht Landevaluatiesysteem (NATLES) versie 2.1*. Alterra-rapport 550. Alterra Wageningen.

Runhaar, J., G.W.W. Wamelink, S.M. Hennekens en J.C. Gehrels, 2003a. *Realisatie van natuurdoelen als functie van de hydrologie*. Landschap 20(3): 143-153.

Runhaar, J., W. van Landuijt, C.L.G. Groen, E.J. Weeda en F. Verloove, 2004. *Herziening van de indeling in ecologische soortengroepen voor Nederland en Vlaanderen* [Revision of the ecological species groups for the Netherlands and Flanders] Gorteria 30(1): 12-26. [Engl. Summary]

Stevers, R.A.M., Runhaar, J., Udo de Haes, H.A., Groen, C.L.G. 1987. *Het CML-ecotopensysteem, een landelijke ecosysteemtypologie toegespitst op de vegetatie* [The CML Ecotope system: a national typology of ecosystems, focused on the Vegetation] Landschap 4: 135-150. [Engl Summary]

Tamis, W.L.M., R. van der Meijden, J. Runhaar, R.M. Bekker, W.A. Ozinga, B. Odé & I. Hoste, 2004. *Standaardlijst van de Nederlandse flora 2003* [Standard list of the flora of the Netherlands 2003]. Gorteria 3: 101-194. [Engl Summary]

Van Walsum, P.E.V. van, P.F.M. Verdonschot, and J. Runhaar (eds.). 2002. *Effects of climate and land-use change on lowland stream ecosystems*. Wageningen, Alterra, Alterra report 523.

Van Walsum, P.E.V., A.A. Veldhuizen, P.J.T. van Bakel, F.J.E. van der Bolt, P.E. Dik, P. Groenendijk, E.P. Querner, M.F.R. Smit, 2004 in prep. *SIMGRO; Description of theory and model implementation.* Wageningen, Alterra, Alterra-report xx.