Ecohydrological Stress – Groundwater To Stress Transfer

Theory and manual version 2.0

KWR 2013.088
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Preface

Researchers from KWR Watercycle Research Institute and the VU University Amsterdam have been collaborating in the project 'Biodiversity in a changing environment: predicting spatio-temporal dynamics of vegetation' (of the Dutch national research programme Climate change Spatial Planning). The main objective of the project, which ran from 2005 – 2012, was to predict the effects of climate change on the spatial distribution of ecosystems. In order to do so, researchers aimed at a habitat distribution model, named PROBE , based on climate-robust relationships. PROBE allows to predict the impact of climate change and of adaptive measures, especially in water management, on vegetation composition. The model output supplies organizations that are responsible for the conservation of nature (e.g. drinking water companies, nature organizations and governmental bodies) with spatial information to evaluate, conserve and create biodiversity.

In the framework of PROBE, process-based habitat factors for soil moisture and their relationships with vegetation characteristics have been developed. The results have been published in several peer-reviewed journals and a PhD-thesis. We have shown that our process-based habitat factors oxygen stress (*OS*) and drought stress (*DS*) outcompete more traditional and relatively simple habitat factors. We therefore advocate to use *OS* and *DS* in ecohydrological impact assessments.

However, in order to acquire these climate versatile habitat factors, extensive modelling and specific knowledge is required. Therefore, we developed GTST (Groundwater to Stress Transfer), a tool to derive soil- and climate specific transfer functions between groundwater level characteristics and *OS* and *DS*. Once transfer functions have been derived for the soil types and climate in a specific area, measured or modelled groundwater levels can be easily transferred to *OS* and *DS*, which are input for ecohydrological prediction models like PROBE.

This report describes GTST, the tool that generates the transfer functions for *OS* and *DS*. Chapters 1 and 2 provide in-depth information on process-based habitat factors of soil moisture. Chapter 3 describes GTST. Both chapters are not needed to apply the tool: for those who only want to use GTST it is sufficient to merely read Chapter 4, the actual manual of GTST.

I hope that GTST facilitates users to apply our novel and robust habitat factors for soil moisture in their ecohydrological impact assessments.

Ruud Bartholomeus

Nieuwegein, September 2013

Contents

1 Introduction

1.1 Habitat distribution models and process-based stresses

The vegetation of terrestrial ecosystems depends on a variety of site factors. Besides factors like dispersal capacity and biotic interactions that determine plant species distribution, abiotic factors like soil moisture, acidity and nutrient availability are important. Quantitative knowledge of the demands of plant species is required in order to analyse the vegetation response to changes in habitat conditions as induced by e.g. climate change. Habitat distribution models provide such a quantitative basis.

Many habitat distribution models describe the habitat conditions of plant species by statistically derived (e.g. by generalized regression, environmental envelopes or Bayesian modelling) response curves of a set of habitat factors. Various explanatory habitat factors have been proposed, ranging from elevation, slope and geology, to soil moisture and air temperature. The correlative nature of those relationships and as a result the lack of a mechanistic understanding of these relationships, is a reason to question the reliability of habitat distribution models once applied outside their calibrated range [*Douma et al.*, 2012a]. To predict the impacts of new environmental conditions in a reliable manner, process-based relationships between environmental conditions and vegetation characteristics are a prerequisite.

The development of generally applicable, process-based relationships has been identified as one of the main objectives in ecological modelling [*Guisan and Zimmermann*, 2000]. In contrast to indirect and correlative relationships, process-based relationships are more robust in the sense that they are better capable of assessing effects of unprecedented new environmental conditions, such as may occur due to climate change.

Soil moisture, in concert with nutrient availability and soil acidity, is the most important habitat factor of plant species, as it determines the availability of both oxygen and water to the roots. Because of their correlative and indirect nature, current proxies of soil moisture, like characteristic groundwater levels, are inadequate for extrapolations. Therefore we developed and applied process-based habitat factors for oxygen and drought stress, *OS* and *DS* respectively [*Bartholomeus*, 2009; *Bartholomeus et al.*, 2012a; *Bartholomeus et al.*, 2008; *Bartholomeus et al.*, 2011; *Bartholomeus et al.*, 2012b]. These factors incorporate in detail the interacting processes in the soil-water-plant-atmosphere interface, making them generally applicable, even for climate projections. We demonstrated that, in contrast to *OS* and *DS*, indirect proxies could produce systematic prediction errors. We therefore advocate to use our process-based habitat factors *OS* and *DS* in ecohydrological impact assessments.

However, in order to quantify *OS* and *DS*, extensive modelling and specific knowledge is required, which makes *OS* and *DS* difficult to derive. Therefore, we developed a tool to derive statistical relationships (transfer functions) between groundwater characteristics and *OS* and *DS* for different climate scenario's and soil types. With these relationships, groundwater levels (which are generally measured or modelled) can be easily translated into *OS* and *DS*. These relationships facilitate the user to derive *OS* and *DS* and to use these for robust ecohydrological projections.

1.2 Ecohydrological Stress – Groundwater To Stress Transfer

The tool GTST consists of automated modelling of interacting hydrological and plant physiological processes, which will ultimately result in statistical relationships between groundwater levels and the habitat factors *OS* and *DS*.

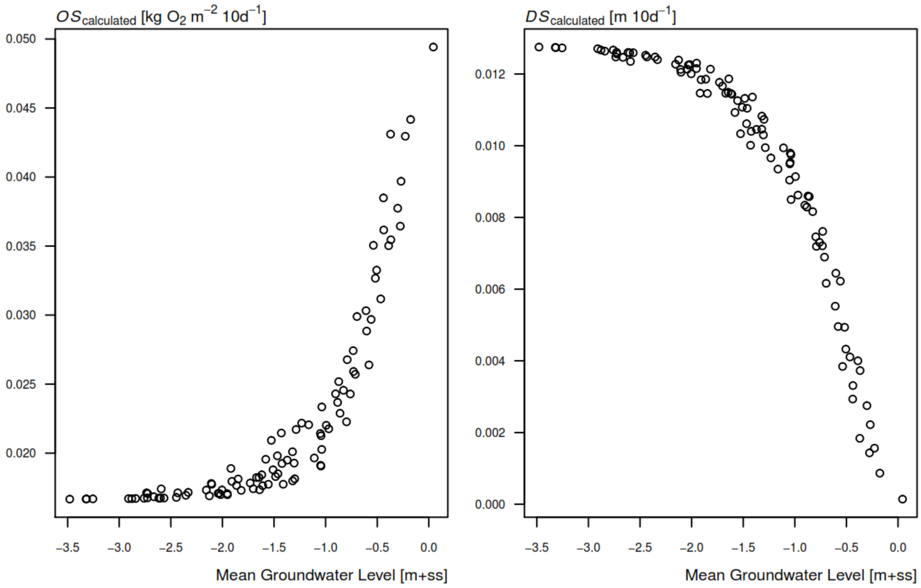


Figure 1: simple representation of simulations of mean groundwater levels and OS *(left) and* DS *for a specific soil type and meteorological station (current climate). Each dot presents an automated model run (for these relationships, SWAP and the routines for calculating* OS *and* DS *were invoked 100 times with different bottom boundary and drainage criteria). The transfer functions from GTST are based on such simulations, but in reality they use more explanatory characteristic groundwater levels than in this example (see Chapter 4).*

GTST is developed within 'R' (open source statistical software, [*R_Development_Core_Team*, 2010]) and it uses the model for the unsaturated zone SWAP (Soil-Water-Atmosphere-Plant, www.swap.alterra.nl, [*Kroes et al.*, 2009; *Van Dam et al.*, 2008]) to simulate the hydrological processes in the root zone. First, GTST creates time series of groundwater levels, soil moisture conditions and soil temperature for each combination of soil type, drainage situation and meteorological conditions (or climate scenario). Then, based on these results *OS* and *DS* are calculated. Finally, GTST produces *OS* and *DS* as a function of soil type, meteo-station and characteristic groundwater levels. The derived relationships are tailored to the area in which the user is interested. A more extensive description of the methods applied in the tool is provided in Chapter 3.

Examples of simulated characteristic groundwater levels and *OS* and *DS* are given in Figure 1; by fitting a relationship on these points, a transfer function between the mean groundwater level and *OS* and *DS* can be established. These relationships will differ for different soil types and meteorological conditions. Once transfer functions have been derived for the soil types in a specific area, measured or simulated groundwater levels can be easily transferred to *OS* and *DS*, which are input for ecohydrological prediction models like PROBE [*Douma et al.*, 2012b; *Witte et al.*, 2010]. Figure 2 shows an example of stress maps that can be created. These maps are used as input to PROBE, which predicts vegetation patterns on the basis of vegetation characteristics [*Douma et al.*, 2012b; *Witte et al.*, 2010] (Figure 3).

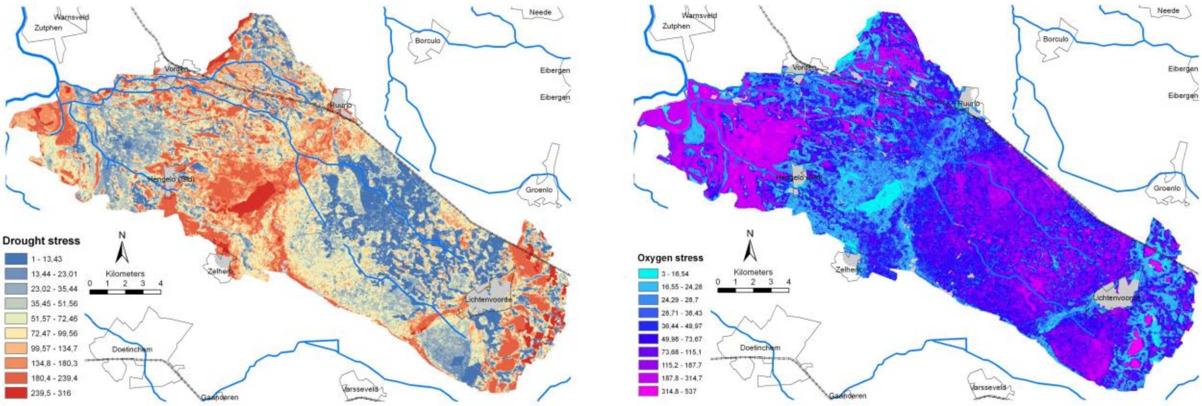


Figure 2: Example of stresses derived with transfer functions from GTST and the results of a hydrological model. Simulated groundwater levels are transferred to DS *(left) and* OS *(right), using transfer functions that are derived for the soil types and meteorological conditions (current climate) of the model area; i.e. tailored to the area of interest (in this case: the Baakse beek catchment, an area of 280 km² in the east of the Netherlands).*

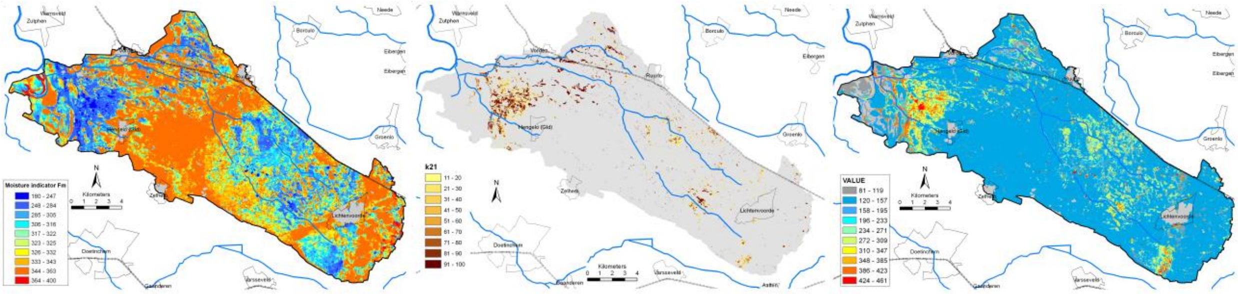


Figure 3: Examples of PROBE output: vegetation characteristic of the soil moisture regime, which is a function of both OS *and* DS *(left); the occurrence probability of a certain vegetation type (grassland of wet, nutrient-poor and acidic soils) (centre); the conservation value of the Baakse beek catchment (right).*

The following chapters provide more in-depth background on (the need for) process-based ecohydrological stresses *OS* and *DS* (Chapter 2) and a description of the tool GTST that generates transfer functions between groundwater level characteristics and both stresses (Chapter 3). Chapter 4 provides a description on how the tool should be used and which input data need to be provided by the user.

2 Theoretical background on process-based ecohydrological stresses

2.1 Plant traits in relation to soil moisture

With recent climate change, extremes in meteorological conditions are forecast and observed to increase globally, which will affect vegetation composition. More prolonged dry periods will alternate with more intensive rainfall events, both within and between years, which will change soil moisture dynamics. In temperate climates, soil moisture, in concert with nutrient availability and soil acidity, is the most important environmental filter in determining local plant species composition, as it determines the availability of both oxygen and water to plant roots. These resources are indispensable for meeting the physiological demands of plants.

The existence of relationships between soil moisture and vegetation has been recognized for a long time. In Biblical times, the prophet Isaiah related rainfall and groundwater to plant species occurrence [*Batelaan and Witte*, 2008; *Ross*, 2007]. The Roman architect and engineer Vitruvius, also wrote about plants and groundwater. He related specific plant species to the occurrence of groundwater. Systematic research on the relationship between groundwater and vegetation started at the end of the 19th century. *Schimper* [1898] *fide Batelaan and Witte* [2008] divided plant species into different groups regarding their preference for water, based on their morphology; *Meinzer* [1927] introduced phreatophytes as plants that obtain their water supply from saturated soil, while *Tüxen* [1954] *fide Wierda et al.* [1997] related the vegetation composition to a certain groundwater regime. The long history of research led to an increased understanding of the mechanisms behind the interaction between soil moisture and vegetation, with a clear movement from direct observations to a more process-based understanding.

The direct influence of the availability of soil moisture on plant species is twofold:

- A surplus of water and herewith a shortage of soil oxygen causes oxygen stress and reduces plant respiration, negatively affecting the energy supply for plant metabolism. Plants respire to obtain energy for growth and maintenance. Plant roots usually obtain a sufficient amount of oxygen for their respiration directly from gas-filled pores in the soil. If the soil becomes too wet, however, air in the soil pores will be replaced by water. Subsequently, the availability of oxygen may become limiting for root respiration and plants may suffer from oxygen stress. Root respiration is the first physiological process in plants that is restricted by oxygen deficiency. Many secondary responses of the vital functions of plants have also been reported, such as growth and water and nutrient uptake. Reductions in these processes, however, are the consequence of a restricted root respiration rate [*Glínski and Stępniewksi*, 1985].

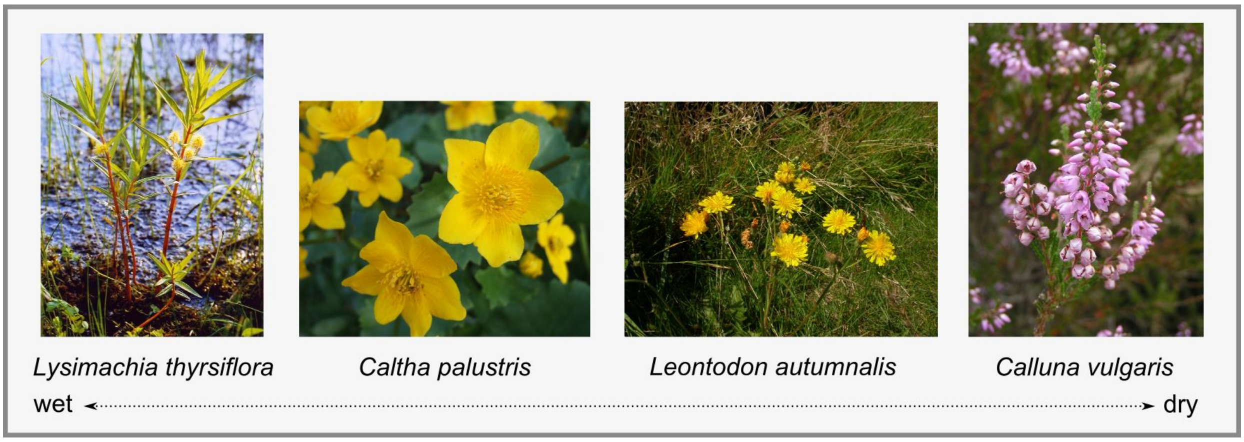


Figure 4: Characteristic species with specific adaptations to different soil moisture conditions, i.e. oxygen stress (left) and drought stress (right).

- A shortage of water, on the other hand, causes drought stress and reduces plant transpiration, negatively affecting both photosynthesis and cooling. Plants need water for biochemical reactions and to maintain turgor, but most of the water taken up by the roots is transpired to the atmosphere through the stomata [*Jackson et al., 2000*]. This transpirational water loss, which prevents the occurrence of heat stress, coincides with the plant's uptake of CO_2 from the atmosphere, which is needed for photosynthesis. If the soil becomes too dry, however, the transpirational water loss is regulated by the stomata to avoid plant damage due to low xylem pressure and low tissue water status [*Jackson et al., 2000*]. While transpiration is the first process to be limited by moisture deficiency or so-called water stress, photosynthesis will be limited indirectly [*Kruijt et al.*, 2008].

Many different physiological adaptations exist for individual plant species to survive at specific soil moisture conditions. These adaptations are most directly represented by functional plant traits, which depict process-based characteristics of plants [*Suding et al.*, 2008]. For instance, some species are able to grow on very dry sites due to internal water storage by means of a succulent structure (such as *Sedum acre*) or by reducing the transpirational water loss by having hairy leaves (such as *Hieracium pilosella*). Other species are able to grow on very wet, anoxic sites; they are adapted e.g. by having aerenchyma, which provide their roots with oxygen (e.g. *Phragmites sp.*), by rooting only superficially (e.g. *Drosera sp.*) or by the absence of root-like organs (e.g. *Sphagnum sp.*). Species that grow on a specific site are all somehow adapted to the prevailing site conditions (see Figure 4 for some characteristic species).

Plant survival is primarily affected by soil moisture through deficiencies of oxygen and water. Hence, process-based relationships between soil moisture and vegetation should have oxygen and drought stress as dependent variables. Some hydrological background information on the processes that determine the availability of oxygen and water in the root zone is given below.

Plants usually obtain sufficient oxygen and water from the soil. If the availability of oxygen or water in the root zone is insufficient to meet the plant's requirements (for respiration and transpiration, respectively), plant species that have no physiological adaptations to these conditions will suffer from oxygen stress or drought stress.

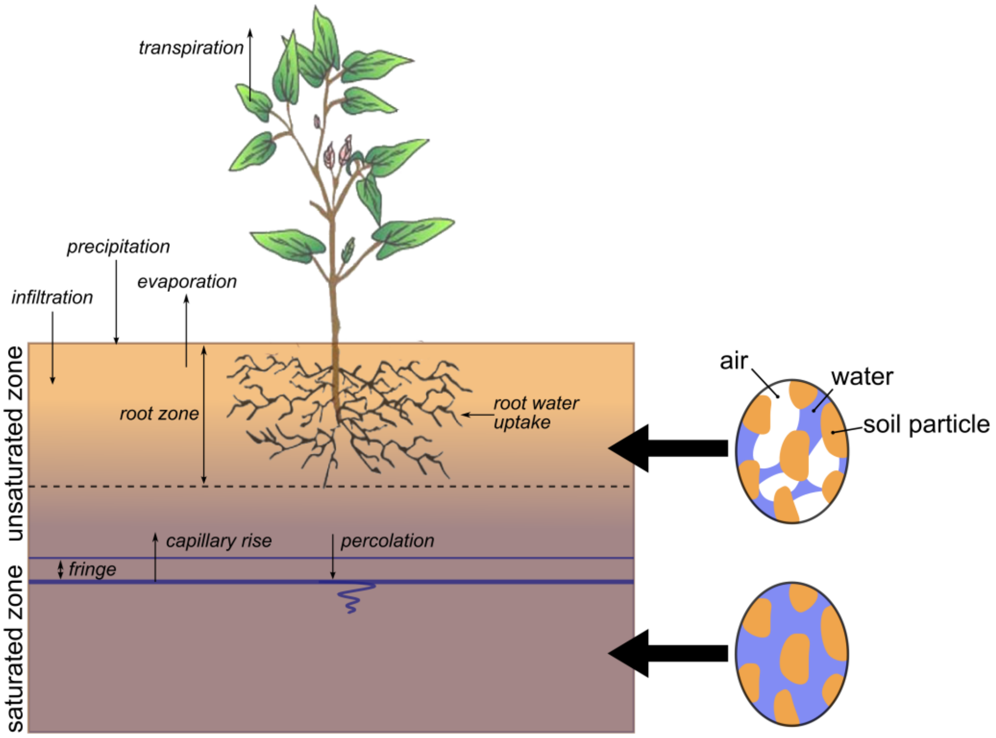


Figure 5: The division of the soil subsurface into the saturated and unsaturated zone, with hydrological processes that determine the moisture conditions in the root zone.

The subsurface of the soil can be divided in two main zones: the water-saturated zone, which comprises the zone below the groundwater table and the capillary fringe (i.e. the part of the saturated zone directly above the groundwater table), and the unsaturated zone, which is the zone above the capillary fringe (Figure 5). Plant roots generally prevail in the unsaturated zone. In contrast to the saturated zone, the soil pores in the unsaturated zone contain both air and water, supplying both oxygen and water to the plant roots. The moisture content, and herewith the gas filled porosity of the unsaturated zone, strongly depends on the groundwater table, soil type, root water uptake, precipitation and soil evaporation, and is strongly variable in both time and space. The groundwater table indirectly influences the amount of oxygen and water in the unsaturated zone, namely by capillary rise. The amount of capillary rise strongly depends on soil texture and organic matter content.

Groundwater recharge (i.e. the process of water percolating through the soil and to the groundwater table) and therewith the variation of the groundwater table, mainly depends on the precipitation surplus, and thus on climate. The precipitation surplus is defined as the difference between precipitation and actual evapotranspiration (the water loss to the atmosphere through both soil evaporation and plant transpiration), and varies within and between years. Consequently, the prevailing meteorological conditions in a period are reflected in the course of the groundwater table and the soil moisture content in the root zone. Groundwater levels alone, however, do insufficiently account for the moisture conditions, and thus oxygen and drought stress, in the root zone.

2.2 Process-based habitat factors

Apart from the availability of water and oxygen, climate also determines the plant requirements for these resources, since potential transpiration depends on global radiation, humidity, wind speed, temperature and atmospheric CO_2 concentration [*Monteith*, 1981]; potential respiration is temperature dependent [*Amthor*, 2000]. Hence, in order to define (climate-)robust relationships between soil moisture and vegetation, relevant interacting processes of the soil-plant-atmosphere system should be considered. GTST provides calculations of the site factors oxygen and drought stress based on modeling procedures that include these processes.

We developed the process-based habitat factors oxygen stress (*OS*) and drought stress (*DS*) for terrestrial vegetation plots [*Bartholomeus et al.*, 2011; *Bartholomeus et al.*, 2012b]. We use the reductions in respiration and transpiration due to low oxygen and water availability, respectively, to characterize these stresses. Respiration reduction accounts for the effects of both extreme rainfall events and high temperatures, known to affect vegetation composition *[Drew, 1983; Sojka et al., 1972]*. Transpiration reduction accounts for the effects of both prolonged dry periods and high atmospheric demand for plant transpiration, i.e. factors that determine drought stress of plants [*Porporato et al.*, 2004].

In order to make an unbiased comparison of the occurrence of *OS* and *DS* among sites, and following *Dyer* [2009], the daily respiration and transpiration reduction are simulated for a hypothetical reference grassland instead of the actual vegetation. By doing so, stress measures are obtained that reflect the moisture and oxygen status of the soil, independent of the actual vegetation [*Bartholomeus et al.*, 2011; *Bartholomeus et al.*, 2012b]. Our reference vegetation is defined as a temperate natural grassland not adapted to oxygen and drought stress, i.e. a grassland as defined by *Bartholomeus et al.* [2008]. The use of a reference vegetation improves the applicability of models in which stress measures are implemented, especially in predicting climate change effects [*Dyer*, 2009]. The use of a reference vegetation allows defining a reference stress, as a habitat characteristic, instead of having to deal with the various ways in which the actual vegetation could acclimate, among those plasticity in rooting, physiology and morphology. This actual stress level is not needed when inferring vegetation responses to the habitat stresses (which is a strength of our approach).

We assessed *OS* and *DS*, i.e. the oxygen and drought status of the soil at which the actual vegetation persists, by a dynamic process-based modeling procedure. To quantify *OS* and *DS*, we focused on interacting meteorological, soil physical, microbial, and plant physiological processes in the soil-plant-atmosphere system (see Chapter 3).

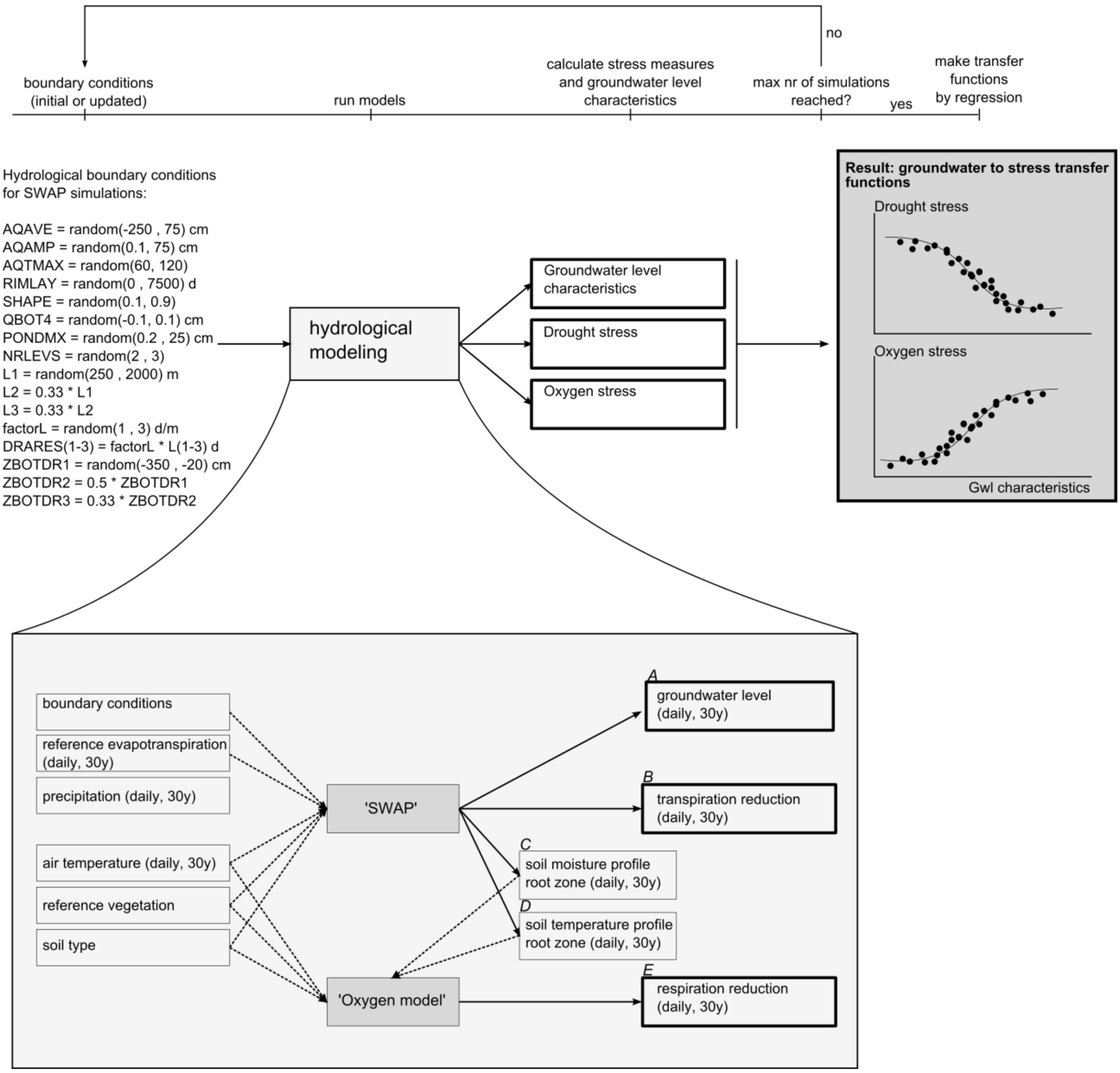


Figure 6: Schematic overview of the automated generation of transfer functions between groundwater level characteristics and OS and DS.

3 Derivation of transfer functions with GTST

3.1 General

The core of GTST consists of the automated modelling of respectively groundwater levels, and *OS* and *DS*. For a given soil type and time series of meteorological conditions, the hydrological modelling procedure is invoked *n* times, with different drainage and bottom boundary conditions for the widely applied dynamic Soil-Water-Atmosphere-Plant model SWAP [*Van Dam et al.*, 2008] for the unsaturated zone. For each run characteristic groundwater levels and *OS* and *DS* are derived. The final transfer functions between groundwater characteristics and *OS* and *DS* are based on these simulations. This automated procedure is given in Figure 6.

For a given set of meteorological conditions, lower boundary conditions (section 3.2.1) and soil type, SWAP is used to simulate daily soil moisture and temperature (Figure 6: C and D, respectively). SWAP also gives the daily transpiration reduction (Figure 6: B) and daily groundwater levels (Figure 6: A). Daily respiration reduction (Figure 6: E) is simulated with the model for oxygen stress to plant roots by *Bartholomeus et al.* [2008], which involves macro scale and micro scale oxygen diffusion, as well as the plant physiological demand of oxygen. Daily transpiration and respiration reduction are used to calculate the integrative measures *DS* and *OS*, respectively. Further details on the calculation of *DS* and *OS* are explained in the next section.

3.2 Simulation of groundwater levels, and drought and oxygen stress

3.2.1 Daily groundwater levels, transpiration reduction and respiration reduction

Meteorological input of the SWAP simulations consists of daily data of precipitation, reference evapotranspiration and minimum and maximum temperature. The soil type is described by the soil hydraulic functions according to *Van Genuchten* [1980]. These data should be provided by the user, as described in Chapter 4 'Using the Ecohydrological Stress tool'. The characteristics of the reference vegetation are fixed and are incorporated in the tool.

The hydrological boundary conditions are also incorporated in the tool and should not be defined by the user. For each of the boundary conditions a relevant range is defined and for each SWAP-run a random number is picked from each of these ranges (ranges are given in Figure 6):

- The bottom boundary in SWAP is the bottom flux calculated from the hydraulic head in a deep aquifer (given by AQAVE, AQAMP, AQTMAX, SHAPE) and the vertical resistance of the aquitard (RIMLAY). QBOT4 describes an additional lateral drainage flux. The fluxes differ for each SWAP-run, as all the variables are taken randomly from a given range.
- The maximum thickness of the ponding layer before runoff occurs is given by PONDMX.
- Drainage to multilevel ditches is described by (Figure 6):
    - The number of drainage levels, NRLEVS
    - The distance between ditches, L
    - The drainage resistance, which is proportionate to L: resistance =factorL * L. The range of factorL is obtained from *Van der Gaast et al.* [2006]
    - The bottom depth of the ditches, ZBOTDR

In each SWAP run, the daily groundwater level is simulated. Additionally, SWAP simulates daily transpiration reduction (the difference between potential and actual transpiration of the reference vegetation). Plants transpire at a potential rate under non-limiting water availability. This potential transpiration depends on the atmospheric demand (global radiation, air humidity, wind speed, air temperature and atmospheric CO_2-concentration) [*Monteith and Unsworth*, 1990]. When water becomes limiting, however, the water uptake by plant roots and herewith plant transpiration is reduced. SWAP [*Van Dam et al.*, 2008] uses the water-limited side of the commonly used Feddes-function for root water uptake [*Feddes et al.*, 1978], based on soil water potential h (for the reference vegetation, reduction starts at h = -800 cm and decreases linearly to zero at h = -10000 cm), to describe this reduction. Daily transpiration reduction, i.e. the difference between the potential and the actual transpiration, was output from the SWAP-model (Figure 6: B). Plant characteristics of the reference grassland (of which the root density decreases exponentially with depth), actual soil type, and daily groundwater level, precipitation, air temperature and reference evapotranspiration are input of the SWAP model.

Daily respiration reduction (i.e. potential minus actual respiration) is simulated with the 'Oxygen model' by *Bartholomeus et al.* [2008], which uses generally applied physiological and physical relationships to calculate both the oxygen demand of, and the oxygen supply to plant roots. Root respiration is determined by interacting respiratory (i.e. oxygen consuming) and diffusive (i.e. oxygen providing) processes in and to the soil. Plant roots respire at a potential rate under optimal soil aeration and thus non-limiting oxygen availability. This potential root respiration is in equilibrium with the oxygen demand of plant roots, which is determined by plant characteristics and soil temperature [*Amthor*, 2000] (as simulated with SWAP) only. Upon increasingly wetter conditions, however, the gas-filled porosity of the soil decreases and oxygen availability becomes insufficient for potential root respiration. For further details we refer to *[Bartholomeus et al., 2008]*.

Simulation of the actual root respiration for the reference grassland requires actual data on soil type, daily soil temperature and daily gas-filled porosity in each soil layer. The latter two variables were output from the SWAP simulations (Figure 6: C and D). The model of *Bartholomeus et al. [2008]* is applied to each of the soil layer of SWAP, to account for layer-specific soil physical properties, moisture contents and temperatures. The difference between potential and actual root respiration is calculated for each soil layer separately and then summed.

3.2.2 Characteristic groundwater levels

Simulated daily groundwater levels are transposed to single characteristic measures. Three types of groundwater level characteristics are used:

- Mean Groundwater levels, according to *Van der Sluijs* [1990], traditionally used in The Netherlands:
    - MGtrad: mean groundwater level [m+ss], based on hydrological years (1 April – 31 March) and data of day 14 and 28 of each month.
    - MLGtrad: mean lowest groundwater level [m+ss], based on hydrological years (1 April – 31 March) and data of day 14 and 28 of each month. For each year the three lowest groundwater levels are selected (LG3), from which the mean value is calculated. These means are averaged over all years, and gives MLGtrad.
    - MHGtrad: mean highest groundwater level [m+ss], based on hydrological years (1 April – 31 March) and data of day 14 and 28 of each month. For each year the three highest groundwater levels are selected (HG3), from which the mean value is calculated. These means are averaged over all years, and gives MHGtrad.
- Transfer functions based on Mean Groundwater levels, derived from daily groundwater data:
    - MG: mean groundwater level [m+ss], based on calendar years (1 January – 31 December) and daily data.
    - MLG: mean lowest groundwater level [m+ss], based on calendar years (1 January – 31 December) and daily data. For each year the lowest groundwater level is selected. MLG is the average of all yearly minimum values.
    - MHG: mean highest groundwater level [m+ss], based on calendar years (1 January – 31 December) and daily data. For each year the highest groundwater level is selected. MHG is the average of all yearly maximum values.

- Transfer functions based on statistical moments derived from the full series of daily groundwater level series:
    - m1: first order moment (mean [m+ss])
    - m2: second order moment (variance)
    - m3: third order moment (skewness; from the R-package 'e1071')
    - m4: fourth order moment (kurtosis; from the R-package 'e1071')

3.2.3 Drought stress and oxygen stress

Simulated daily transpiration and respiration reduction are transposed to the stress measures *DS* and *OS*, respectively, as described in the next paragraph. The integrative measures *DS* and *OS* are based on the fact that plants respond to extreme rather than to average stress conditions.

Suboptimal moisture conditions do not necessarily directly affect the vegetation, because normal metabolism of plants is flexible, responding to moderate fluctuations in environmental changes [*Gaspar et al.*, 2002; *Körner*, 2003]. Therefore, the events that deviate most from the average conditions, i.e. the extremes, will have most impact on the vegetation [*Bokhorst et al.*, 2007; *Chapin et al.*, 1993; *Knapp et al.*, 2002; *Van Peer et al.*, 2004; *Weltzin et al.*, 2003]. To take account of the amplitude of stress [*Knapp et al.*, 2008], we selected for each simulation year, and for each stress, the 10-day period with highest reduction in plant metabolic functioning, i.e. in respiration reduction and transpiration reduction for *OS* and *DS*, respectively. A 10-day period was chosen, because a period of 10 days of either oxygen or drought stress has been shown to hamper the plant metabolism already [*Huang et al.*, 1998; *Poulson et al.*, 2002; *Volaire et al.*, 1998]. These yearly maximum reductions in transpiration or root respiration for a 10-day period were averaged over all 30 simulation years, to represent *DS* and *OS*, respectively.

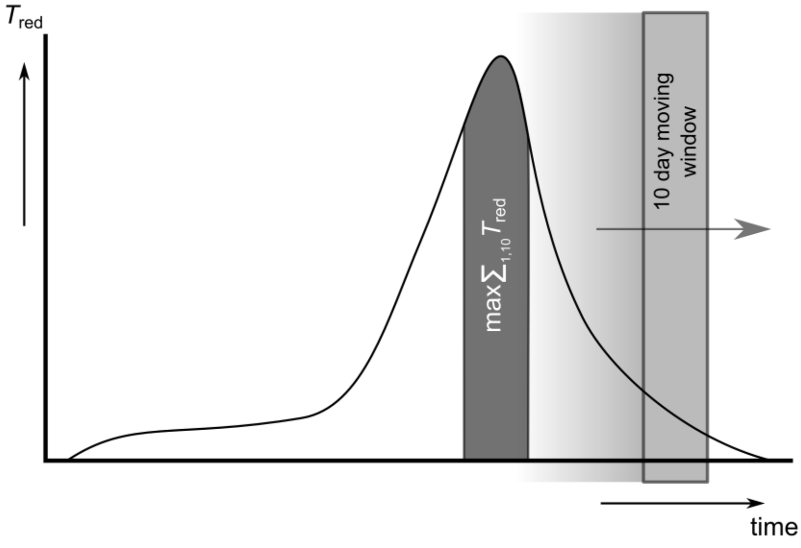
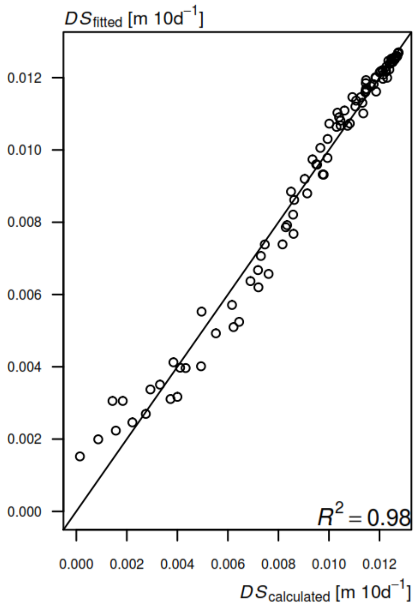
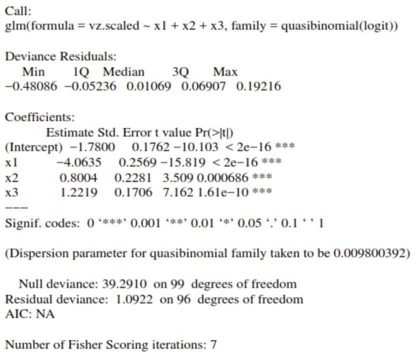


Figure 7: Selection of the yearly 10-day period with highest reduction in transpiration ($\max\sum_{1,10} T_{red}$ *) as used for the calculation of DS. For OS a similar procedure is followed, based on respiration reduction.*

3.3 Correlating stresses to groundwater levels

The relationships between the stresses *OS* and *DS* and groundwater level characteristics are nonlinear. Simulations show, and it can also be reasoned, that the relationships between stress and groundwater levels have a sigmoid shape (see also Figure 1). *DS* for example, will be zero at shallow groundwater levels, will increase with a deeper groundwater level, and will reach is maximum when the root zone gets out of the direct influence of the phreatic groundwater (i.e. groundwater independent systems). Additionally, *OS* and *DS* are regressed on multiple explaining variables, like mean, mean lowest and mean highest groundwater level, which makes it hard to fit a non-linear relationship. Therefore, we fitted relationships between stresses and groundwater level characteristics by Generalized Linear Models (GLM), using a logistic link function. Interactions between the explaining variables were not considered. An example of a fitted relationship of *DS* as function of three explaining variables (i.e. groundwater level characteristics) is given in Figure 8.





```
Call:
glm(formula = vz.scaled ~ x1 + x2 + x3, family = quasibinomial(logit))

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.48086 -0.05236  0.01069  0.06907  0.19216

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -1.7800     0.1762 -10.103  < 2e-16 ***
x1           -4.0635     0.2569 -15.819  < 2e-16 ***
x2            0.8004     0.2281   3.509 0.000686 ***
x3            1.2219     0.1706   7.162 1.61e-10 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasibinomial family taken to be 0.009800392)

    Null deviance: 39.2910  on 99  degrees of freedom
Residual deviance:  1.0922  on 96  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 7
```

*Figure 8: Example of the predicted (*DS*$_{fitted}$), based on the fitted GLM as given at the right, vs. simulated* DS (DS$_{calculated}$).

3.4 Validation

We tested the procedure on 145 vegetation plots [*Hommel et al.*, 2007; *Runhaar*, 1989] for which detailed simulations of *OS* and *DS* were available [*Bartholomeus et al.*, 2011; *Bartholomeus et al.*, 2012b]. For each plot we derived a transfer function with GTST and applied this function to predict *OS* and *DS*. Finally, we compared the output of the transfer function with the *OS* and *DS* as obtained from the detailed simulations (Figure 9). The (systematic) differences are caused by differences in bottom boundary conditions for the hydrological simulations for the 145 plots. *Bartholomeus et al.* [2011] used measured groundwater levels as input for the SWAP simulations, while in the GTST procedure SWAP has been invoked 100 times, with different drainage and bottom boundary conditions. Apparently, the groundwater level series thus created do not fully represent the true groundwater level dynamics at the validation sites. Nevertheless, the differences are within an acceptable range.

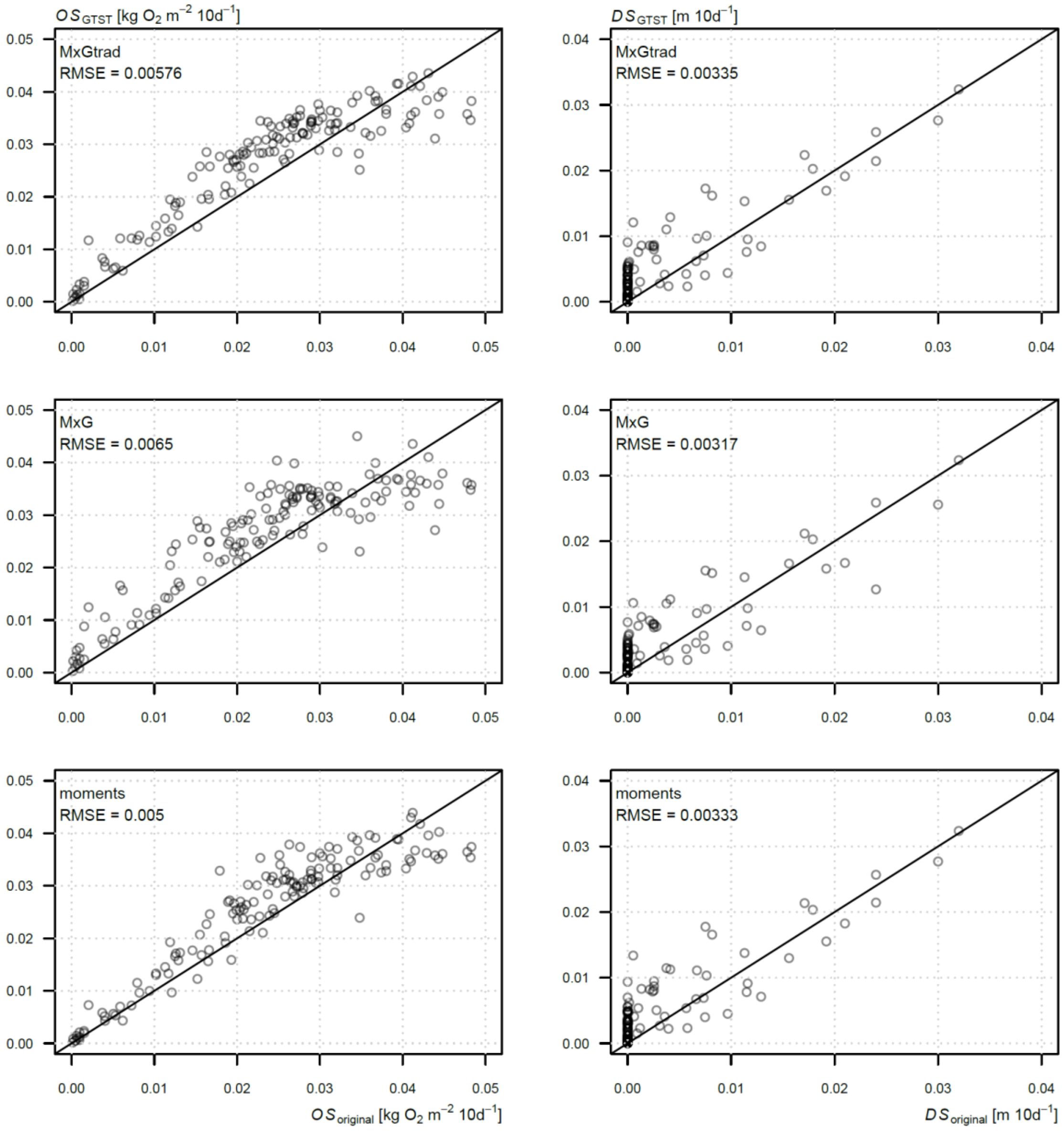


Figure 9: OS *and* DS *for 145 vegetation plots as determined with GTST (vertical axes) using three different groundwater level characteristics (see paragraph 3.2.2) vs. detailed simulations of* OS *and* DS*. Each dot represents a vegetation plot. The lines present the 1:1 line. RMSE = root mean squared error.*

4 Using GTST

GTST facilitates the translation of groundwater levels (measured or modelled) to the process-based habitat factors *OS* and *DS*. Once transfer functions are derived for soil types in your area of interest, groundwater levels can easily be translated to *OS* and *DS*, without having to do extensive simulations for each grid-cell of your spatial model. This allows calculating the stresses for large numbers of grid cells of a hydrological model (Figure 2). The tool consists of two main parts: a library where transfer functions are stored and software to generate transfer functions (Figure 10).

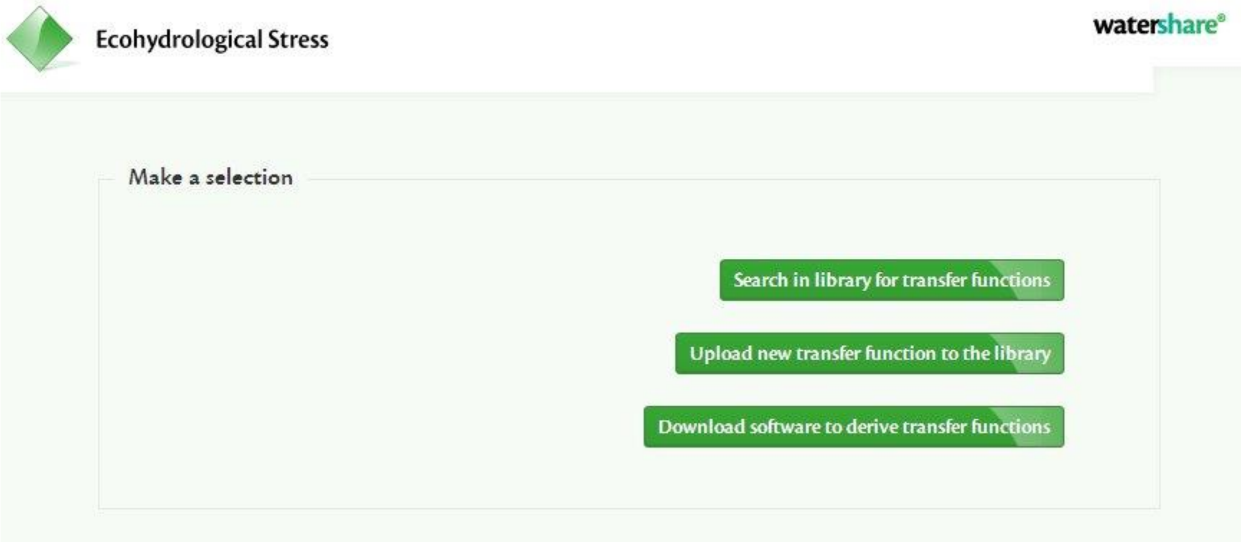


Figure 10: Screenshot of the menu where one can choose between searching for existing transfer functions in the library, or adding new functions to the library that are created with the software (lower button).

4.1 Library with transfer functions

The Ecohydrological Stress tool contains a library with previously derived transfer functions. Through this library, these functions have been made available for other users. One can search for a transfer function in your own country based on the following criteria (Figure 11):

- Meteorological station
- Soil type
- Climate scenario (including the current climate)

Please be aware that relationships between characteristic groundwater levels and *OS* and *DS* are sensitive to the soil physical properties and meteorological conditions chosen. Therefore, we recommend to generate transfer functions tailored to your soil and meteorological data. The generated transfer functions can be added to the library.

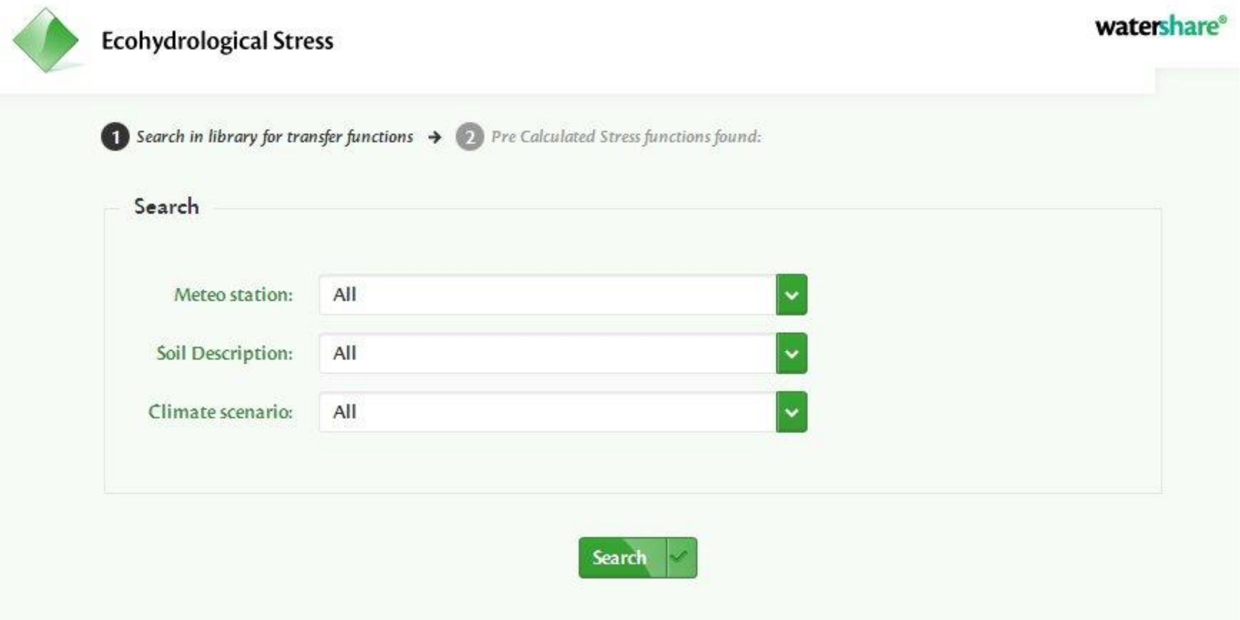
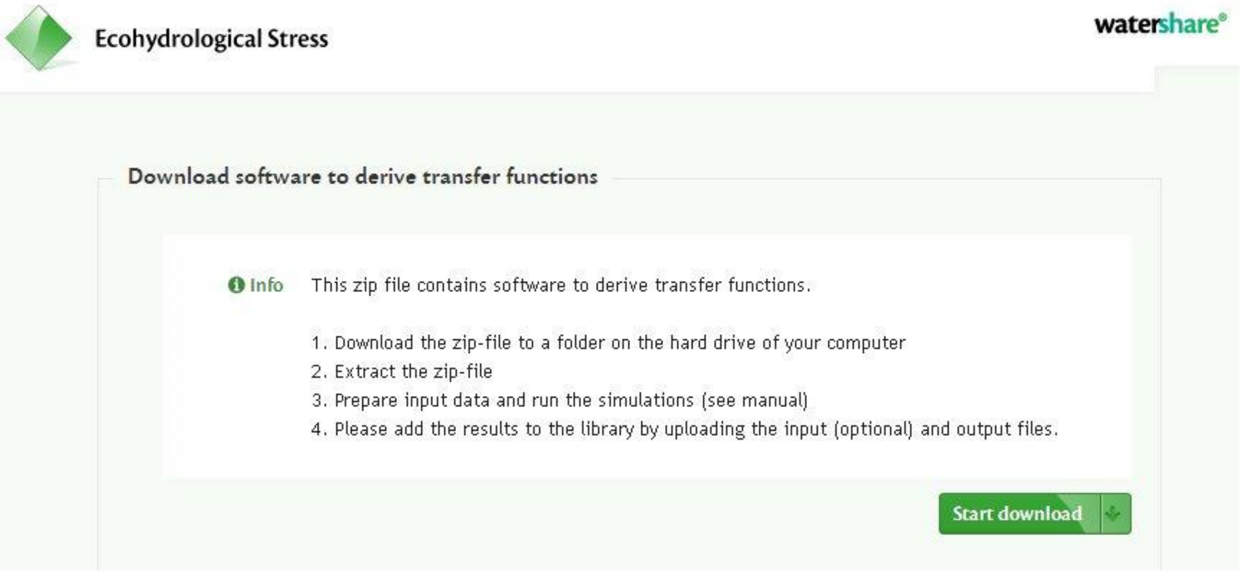


Figure 11: Screenshot of the menu where one can search for existing transfer functions in the library.

4.2 Software to derive transfer functions

Transfer functions can be derived by downloading a zip-file to your computer (Figure 12), extracting it, preparing the input data and running the model. This modelling exercise is fully automated, as described in Chapter 3. Only soil and meteorological data are required as input. The required data and the format is described below.



This zip file contains software to derive transfer functions.

1. Download the zip-file to a folder on the hard drive of your computer
2. Extract the zip-file
3. Prepare input data and run the simulations (see manual)
4. Please add the results to the library by uploading the input (optional) and output files.

Figure 12: Screenshot of the screen where one can download the software to derive transfer functions.

Input

Meteorological data
Provide a text file with the names of the input files with meteorological data (see below) for which transfer functions should be derived. Only provide the file names, so:

meteo_1.txt
meteo_2.txt
Etc.

Provide a text file (*.txt) in the following format for each input file with meteorological data:

YYYY	MM	DD	TN	TX	Rain	EV24
1981	1	1	1	6.6	3.1	0.2
1981	1	2	2.3	7.9	19.6	0
1981	1	3	5	9.5	10.2	0.1
1981	1	4	0.3	5.4	3.7	0.2
1981	1	5	-0.1	2.6	0.9	0.3
1981	1	6	-2.9	0.7	0.7	0.2
Etc.						

With:
YYYY: year number
MM: month number
DD: day number
TN: minimum temperature [degrees Celcius]
TN: maximum temperature [degrees Celcius]
Rain: precipitation depth [mm]
EV24: reference evapotranspiration [mm]

Soil data
Four text-files (*.txt) with soil data need to be provided (see also the SWAP manual www.swap.alterra.nl):

Provide soil physical properties in the following format:

soilID	ISOILLAY1	ORES	OSAT	ALFA	NPAR	KSAT	LEXP	ALFAW	H_ENPR	KSATEXM
1	1	0.0000	0.7700	0.0197	1.1540	6.6700	-1.8450	0.0197	0.0	16.3596
1	2	0.0100	0.8600	0.0123	1.2760	2.9300	-1.5920	0.0123	0.0	18.2644
2	1	0.0100	0.8000	0.0176	1.2930	6.7900	-2.2590	0.0176	0.0	63.5713
2	2	0.0100	0.8600	0.0123	1.2760	2.9300	-1.5920	0.0123	0.0	18.2644
2	3	0.0200	0.3800	0.0213	1.9510	12.6800	0.1680	0.0213	0.0	28.1193
3	1	0.0100	0.5900	0.0195	1.1090	4.5300	-5.9010	0.0195	0.0	59.6812
3	2	0.0100	0.8600	0.0123	1.2760	2.9300	-1.5920	0.0123	0.0	18.2644
Etc.										

With:
SoilID: numbers of the soil types. These must be numbered from 1 to n, in consecutive order.
ISSOILLAY1: number of the soil layer within a soil type
ORES: residual water content [cm3/cm3]
OSAT: saturated water content [cm3/cm3]
ALFA: Van Genuchten Shape parameter alfa of main drying curve [1/cm]
NPAR: Van Genuchten Shape parameter n [-]
KSAT: Saturated vertical hydraulic conductivity (fitted) [cm/d]
LEXP: Van Genuchten Exponent in hydraulic conductivity function, l [-]
ALFAW: Van Genuchten Shape parameter alfa of main wetting curve [1/cm] (can be taken equal to ALFA)
H_ENPR: Air entry pressure head [cm] (may be taken 0)
KSATEXM: Saturated vertical hydraulic conductivity (measured) [cm/d] (if only one Ksat value is available, take KSAT=KSATEXM)

Provide soil texture in the following format:

soilID	ISOILLAY1	PSAND	PSILT	PCLAY	ORGMAT	SOILDENSITY
1	1	0.46	0	0.54	0.475	600
1	2	1	0	0	0.675	350
2	1	0.96	0	0.04	0.625	600
2	2	1	0	0	0.675	350
2	3	0.86	0.14	0	0.015	1550
3	1	0.575	0	0.425	0.075	1300
3	2	1	0	0	0.675	350
Etc.						

With:

SoilID: numbers of the soil types. These must be numbered from 1 to n, in consecutive order.
ISSOILLAY1: number of the soil layer within a soil type
PSAND: fraction sand [g/g mineral parts]
PSILT: fraction silt [g/g mineral parts]
PCLAY: fraction clay [g/g mineral parts]
ORGMAT: organic matter content [g/g dry soil]
SOILDENSITY: soil density [kg/m3]

Provide soil discretization in the following format:

soilID	dstart	dend	isoillay1
1	0	35	1
1	35	500	2
2	0	20	1
2	20	70	2
2	70	500	3
3	0	35	1
3	35	500	2
Etc.			

With:

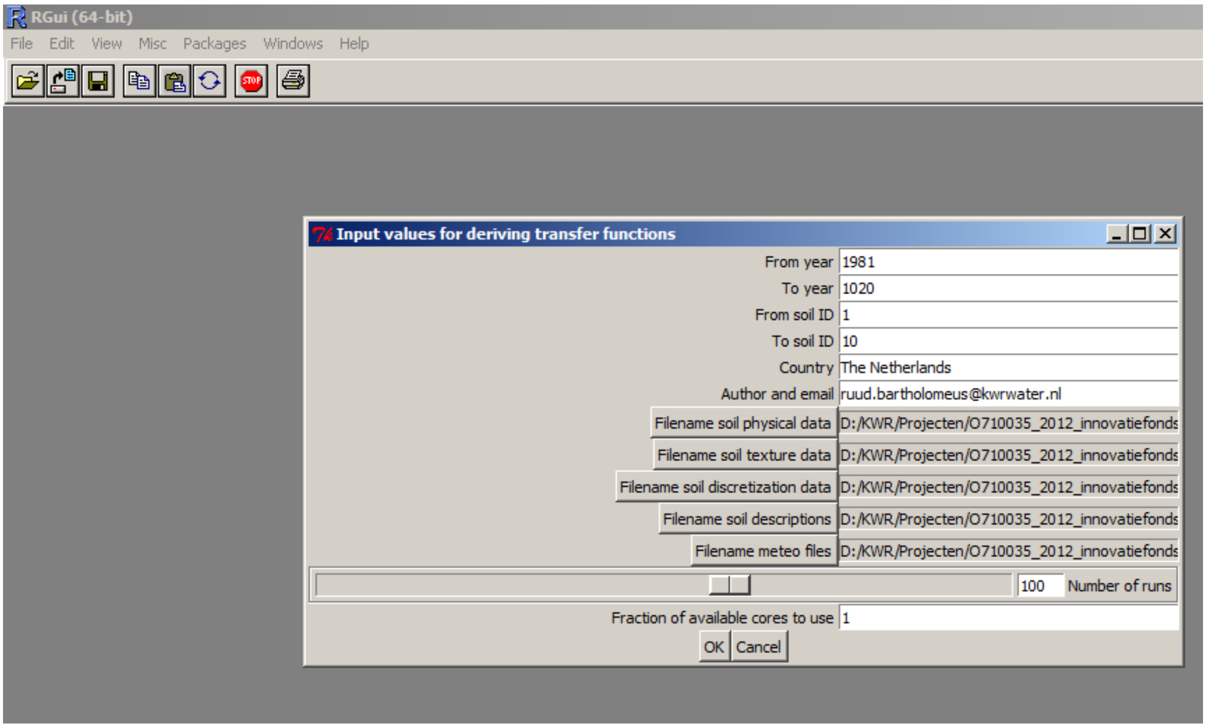
SoilID: numbers of the soil types. These must be numbered from 1 to n, in consecutive order.
dstart: start depth soil layer [cm-ss]; top layer first
dend: end depth soil layer [cm-ss]; maximum depth should always be set to 500 cm-ss
issoillay1: number of the soil layer within a soil type

Provide a description of the soil types in the following format:

soilID	Description
1	soil physical unit 1 The Netherlands
2	soil physical unit 2 The Netherlands
3	soil physical unit 3 The Netherlands
Etc.	

Run the program

If the input data are prepared, the program can be started by a double click on "RUN_EcohydrologicalStress_V2_0.bat". An R-session will start and the following input screen will appear (Figure 13):



Input values for deriving transfer functions

From year 1981
To year 1020
From soil ID 1
To soil ID 10
Country The Netherlands
Author and email ruud.bartholomeus@kwrwater.nl
Filename soil physical data D:/KWR/Projecten/O710035_2012_innovatiefonds
Filename soil texture data D:/KWR/Projecten/O710035_2012_innovatiefonds
Filename soil discretization data D:/KWR/Projecten/O710035_2012_innovatiefonds
Filename soil descriptions D:/KWR/Projecten/O710035_2012_innovatiefonds
Filename meteo files D:/KWR/Projecten/O710035_2012_innovatiefonds
100 Number of runs
Fraction of available cores to use 1

Figure 13: Input values for deriving transfer functions

With:

From year – To year:	start and end of the period for which the transfer functions will be derived
From soil ID – To soil ID:	select the soilID's for which transfer functions will be derived. This can be a subset of the prepared input files
Country:	country for which the transfer functions are derived
Author and email:	please fill in your contact details
Filename soil and meteo:	select files with soil and the filenames of the meteo files
Number of runs:	select the number of runs (simulated groundwater levels and stresses, on which the transfer functions are based. The more runs, the more reliable the transfer functions are. A value of 100 will generally be sufficient.
Fraction of cores to use:	choose the fraction of computer cores may be allocated by the program

By selecting 'OK' the simulations will start. These simulations can take several hours, mainly depending on the number of computer cores that are available for the generation of the transfer functions.

Output

Results are saved in the folder RESULTS_EcohydrologicalStress. A subfolder is created in this folder, based on the current date. Besides an excel-sheet with all transfer functions, for each soilID a report is generated automatically, containing a summary of the meteorological data, the soil data and the transfer functions. The transfer functions link groundwater level characteristics to *OS* [kg O_2 m^{-2} $10d^{-1}$] and *DS* [m H_2O $10d^{-1}$]. Three types of groundwater level characteristics are used:

- Transfer functions based on Mean Groundwater levels, according to *Van der Sluijs* [1990], traditionally used in The Netherlands:
  - MGtrad: mean groundwater level [m+ss], based on hydrological years (1 April-31 March) and data of day 14 and 28 of each month.
  - MLGtrad: mean lowest groundwater level [m+ss], based on hydrological years (1 April-31 March) and data of day 14 and 28 of each month. For each year the three lowest

    groundwater levels are selected (LG3), from which the mean value is calculated. These means are averaged over all years, and gives MLGtrad.

  - MHGtrad: mean highest groundwater level [m+ss], based on hydrological years (1 April-31 March) and data of day 14 and 28 of each month. For each year the three highest groundwater levels are selected (HG3), from which the mean value is calculated. These means are averaged over all years, and gives MHGtrad.

- Transfer functions based on Mean Groundwater levels, derived from daily groundwater data:

  - MG: mean groundwater level [m+ss], based on calendar years (1 January-31 December) and daily data.

  - MLG: mean lowest groundwater level [m+ss], based on calendar years (1 January-31 December) and daily data. For each year the lowest groundwater level is selected. MLG is the average of all yearly minimum values.

  - MHG: mean highest groundwater level [m+ss], based on calendar years (1 January-31 December) and daily data. For each year the highest groundwater level is selected. MHG is the average of all yearly maximum values.

- Transfer functions based on statistical moments derived from the full series of daily groundwater level series:

  - m1: first order moment (mean [m+ss])

  - m2: second order moment (variance)

  - m3: third order moment (skewness)

  - m4: fourth order moment (kurtosis)

OS and *DS* can be calculated from these groundwater level characteristics, using these transfer functions.

If you have any questions about GTST, please contact the authors:

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Moreover, you may contact us for an automated procedure to apply the transfer functions of GTST to the outcomes of your distributed hydrological model, and we may help you to find solutions for modelling vegetation patterns.

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