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Groundwater management by monitoring water gathering areas using remote sensing and GIS

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Introduction

Groundwater management nowadays is mainly governed by hydrogeological aspects of groundwater occurences. However focussing on groundwater as a natural rescource of the landscape, there is a deficit in spatial information about the ecological factors influencing the water balance. It becomes more important to assess the ecological role of groundwater in accordance to its quality and quantity as well as to predict risks by changes in the landscape such as lowering groundwater level and nitrate leaching.

Due to high spatial diversity in the pattern of land use, relief attributes and soil properties, ecological data have to distinguish different homogeneous site units. Remote sensing data with high resoluted geometrie would have the potential to improve the spatial information about landscape and its water balance.

In many regions an aggravating deficit between the groundwater consumption and the recharge of groundwater can be observed. This situation is characterised by two effects:

1. Increasing groundwater consumption:

   Especially high densely populated or highly industrialised urban areas are covering the water requirements by means of groundwater resources of their close and remote surrounding. Groundwater consumption in agriculture and horticulture is also increasing by irrigation.

2. Decreasing recharge of groundwater:

   Generally, the infiltration into the unterground is reduced in the landscape. A larger partition of precipitation is drained off by drainage in agriculture. By rural engineering in the last decades most wet lowlands and hollows have been drained.

   A higher level of surface sealing can be found in agriculture as well as in urban areas.

   Evapotranspiration in plant production has increased. By intensification in agriculture plant production has generated more biomass and crop yield. But for every unit of yield and biomass, the plant has to transpirate additional soil water. Therefore, higher intensity in farming is related to higher water consumption by the process of evapotranspiration.

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By these reasons, the groundwater balance resource is often exhausted in a long run. The effect is a lowering groundwater level.

With the intensification in agriculture it can also be observed, that the leaching of nitrate is increasingly exceeding the critical load of groundwater. This is the reason why groundwater quality is actually a prevailing aspect in groundwater protection.

The described impacts on the landscape water balance have consequences for other natural resources too. For example, changes in the ecosystems can be detected by shifts in spatial and time pattern of plant growth, displacements in faunistic and floristic diversification of species and a loss of wetland habitats.

In view of these effects on groundwater quality and quantity, many water supply companies have started to exploit the deep groundwater sheets, although the longterm yield of this kind of aquifereous layers is quite unknown. This situation of decreasing groundwater resources is not only limited to semiarid or mediterranian areas with dry periods. It is also a problem in the humidity of Germany with its relative high precipitation in summer as in winter.

Ultimately, the groundwater occurence in a landscape can only be recharged by border infiltration and, mainly, by infiltrating precipitation. Therefore, in the longterm view, groundwater consumption must be adjusted to this input, if the groundwater balance is intended to be preserved or restored. For this, a regional landscape groundwater management is needed with the aims

1. to preserve the longterm groundwater use by maintaining a suitable well-poised landscape water balance
2. to protect the groundwater quality by avoidance critical loads of deposits

To manage groundwater as a longterm available and balanced property of landscape, we have to take in consideration the influences on landscape water balance. The main factors, to be included in the view of groundwater management, are climate, soil and geology, relief and vegetation. A landscape-ecological orientated management has to base on these factors. But the course of management action can not influence the climate and the relief, of course. Also the soil attributes can not be changed in an economical way. Mainly land use can be adjusted by the way of planning kind and intensity of farming and foresting, plant rotation, nutrient supply, etc..

Therefore, longterm groundwater management is managing land use in accordance to the regional climate as well as the relief and soil attributes of fields and sites. The aim is to avert economical and ecological risks, caused by the changes in the hydrological balance of nature. Remote sensing can be used for monitoring ecological changes and for improvement of spatial information.

Investigation area

The investigated area is within a hilly landscape of Hessian, Germany. In a pilot project a water gathering area has been selected, representing a region with typical properties in geology, soil, relief, land use and climate conditions.

The area is about 1000 ha. The longterm average precipitation is about 640 mm per year. Lontern average temperature is 8 °C. The elevation is between 250 m and 400 m above sea level.

The landscape is characterised by long extended, slightly inclined hilltops, interupted by valley cuts with steep slopes. A high diversity is charactristic for geology and soils in this area. Dominated by Devonian limestone, calcites and dolomites of Zechstein, we also find sediments of triassic bunter and quartarian deposits as well as loess and solifluction layers.

The diversity of soil is related to the variety in relief and geology. The dominating soils are brown-earth of different development state, sometimes with characteristics of similigley, sometimes with triassic clay in the subsoil. The hilltop soils are mainly rendzina. In hollows and valleys colluvisols are predominating. On loess covered eastside slopes para-brown earth has developed. The land use is dominated by arable farming (78%) and grassland (12%) (HARRACH & PETER 1990).

Site based map of water balance classification:

The water balance of sites and gathering areas is mainly dependent on climate, relief, soil, geology and vegetation. The properties of relief, soil and geology are constant factors in the landscape and can be used to deduce types of soil water balance. These types are describing the prevailing characteristic and movement of soil water. Some main types are percolation type, inflow type, outflow type, storage type, backwater type, overflow type, infiltration type, etc. Two preliminary tasks have been realised:

1. A transformation code (BENNE et al. 1990) had to be adjusted to the conditions of the investigated region, to analyse the german soil taxonomy data.
2. to deliminate morphographic units of relief, digital relief analysis of terrain models (KLEEFISCH & KÖTHE 1993) was necessary.

In a GIS-based analysis, combining the transformed soil taxonomy data with results of relief analysis and geological map, the definition of soil water balance types has been derived as well as their spatial pattern.

Analysis of remote sensing data

Spatial monitoring activities have been based on remote sensing and are focused to the pattern of fields and sites. This could not be realised by the geometric resolution of satellites. Because the resolution is higher and the planning of survailling flights is more flexible, the testsite has been remotely sensed by an airborne scanner (Daedalus AADS 1268) with a pixel size of 3 m and 1.5 m. By its 11 channels, wavelength of 420 nm to 13 µm have been measured.

The remote sensing data were intended to be used in combination with geocoded data, terrain models and GIS maps. Therefore, the remote sensed images had to be converted into a multispectral map.

The scanner data have been processed by the image processing system *Xdibias* (MÜLLER et al. 1992). The geometric rectification and merging of 4 scanner tracks to a geocoded map has been realised by processing programs of flight orientation and position and reference point rectification. The course of image processing is shown in the following figure (figure 1).

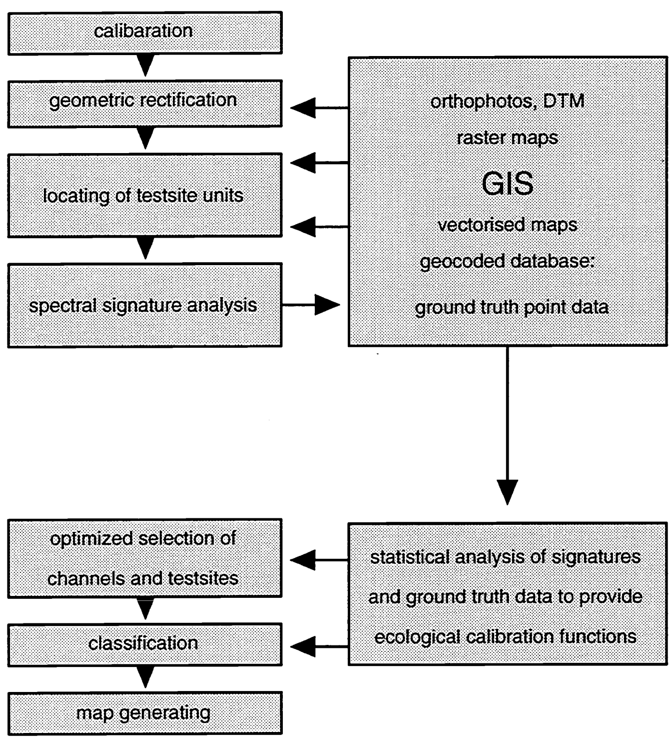

Figure 1: The course of image processing joining a geographic information system and a statistical program package

Parcel-precise map of land use

As a first step in monitoring, a land use map has been generated by supervised classification procedures. A separability analysis of land use classes has been adapted from the system proposed by REINARTZ (1989). The selection of spectral channels was based on this analysis. The highest measure of separability has been given by the six channel combination of the channels 2, 4, 5, 7, 9, and 10. For the following classifications the procedure of maximum-likelihood and the new classificator *Gontax* (KRITIKOS 1993) have been used.

Land use has been charactrised by 17 vegetation classes and 8 non-vegetation classes, representing roofs, asphalt, pavement and different classes of bare soil. The vegetation classes represent the crops of arable farming, pastures and meadows, fallow land, hedges, coniferous and deciduous forest.

Site based map of crop development

Sustainable agricultural systems which consider both crop production and environmental effects to groundwater, such as nitrate leaching and recharge of groundwater, have to be based on a site specific management. Within agricultural fields differentiation in plant growth is typical. For ground truth mapping of the investigated test sites, a code procedure has been developed to assess the state of plant. This plant taxonomy code is related to biomass, leaf area index, height, etc.. By the example of winter wheat it will be shown that the ontogenetic development as well as biomass production depend on the site properties, mainly the available water content (AWC)(figure 2).

Because of this correlation the plant, its state and taxonomy can be used as a bioindicator of the available water content.

Also a correlation between biomass and crop yield has been found. The level of biomass production indicates the level of yield. Because of this, crop biomass can also be used as bioindicator of crop yield (SELIGE 1993).

The different biomass was visible in most spectral channels of the scanner. The combination of channels 5, 9, 10 and 11 gave the best result of classification (figure 3).

The site based differentiation in plant growth, affected by the available water content, leads to different evapotranspiration, which could easily be detected by surface temperature, measured by the thermal channel of the scanner. If soil taxonomy maps are not available, site based monitoring of biomass production can give better spatial information corresponding to the water balance.

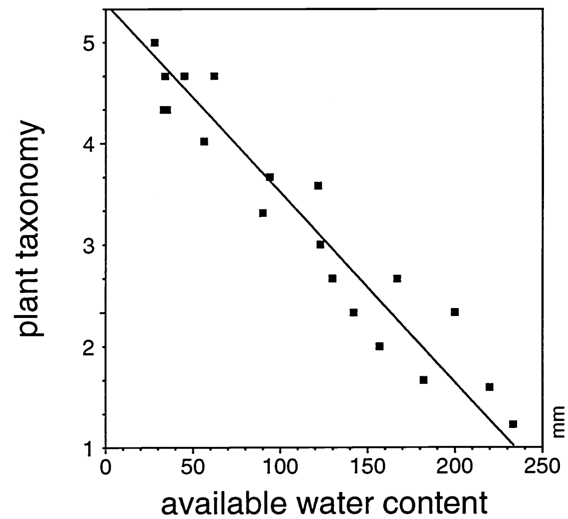

Figure 2: plant growth of winter wheat in dependence of available soil water content.

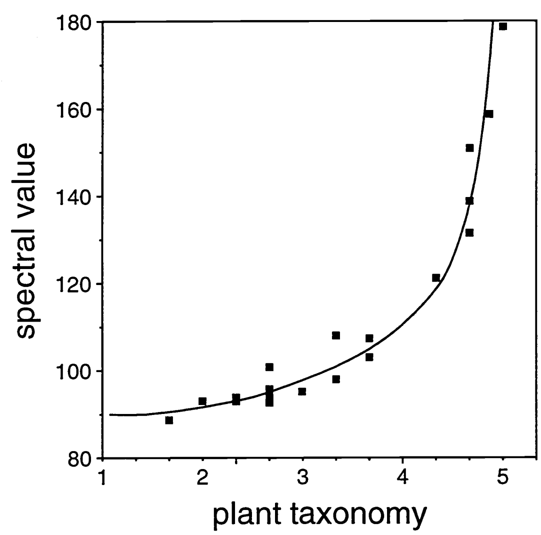

Figure 3: Correlation between plant growth and spectral characteristic by a combination of channel 5, 9, 10 and 11.

Recharge of groundwater

The recharge of groundwater has been calculated by the approach of RENGER et al. (1990), but with the integration of the water balance classification, to heed the impact of relief and soil properties. Evapotranspiration has been calculated by the PENMAN-equation. Therefore, radiation has been calculated, considering the relief parameters exposition and inclination. Some results of calculating the recharge of groundwater in dependence of different land use and available soil water content are given in table 1.

Table 1: Recharge of groundwater based on longterm average s of climate conditions, the available soil water content (AWC) and superior land use classes

AWC	farmland	grassland	forest
50	266	224	132
140	198	96	58
200	174	51	32

These results give an impression on the importance of site properties such as available water content and land use to the recharge of groundwater. Ist decrease is obvious under forest use. The dependence of the decrease on AWC is also evident. Two conclusions can be drawn from the table:

1. the higher the available soil water content of a site the less the recharge of groundwater.
2. the higher the biomass of the land use system the less the recharge of groundwater.

Both are affected by varying evapotranspiration. The higher the quality of site, described by the available soil water content, the higher is the biomass production. This leads to an increase of evapotranspiration and a decrease in recharge of groundwater.

For this reason, the main task of a landscape-ecological groundwater management is to control the evapotranspiration. Because of the variety of soil and relief the management has to act according to the properties of sites. These can be detected by monitoring land use with geometric highly resoluted remote sensing data and by using the plant growth as bioindicator for soil properties.

Landscape-ecological management of groundwater

The aim of management is to adjust land use systems to the site properties, to maintain a high level of groundwater recharge, without inducing an increase in erosion, acidification, leaching of chemicals, overland flow and soil compaction.

Therefore, groundwater management is planning irrigation to reduce unproductive water consumption and planning of crop rotation, especially intercrop growing.

The influence land use can have to the groundwater recharge of the investigation area can be appear by the following calculation. The calculated recharge of groundwater in the investigated area was about 1.2 million m^3 by actual land use. On the hypothesis of afforestation of all restockable sites in the area, the calculated recharge of groundwater would be cut down to 574.089 m^3/year. That would be less than the actual taking out by the groundwater wets.

The actual task in the development of the groundwater management system is to calculate the site dependent recharge of different crop rotation systems as well as changes in the intensity of grassland use in accordance to erosion and nitrate leaching. The use of remote sensing has given the possibility to work on the spatial pattern of sites in the landscape.

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