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Groundwater ecohydrology: GIScience tools to forecast change and sustainability of global ecosystems, studies in Africa, Europe and North America

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Abstract

This study examines the interface between groundwater hydrology and ecology, and addresses a scientific grand challenge to develop a comprehensive, systematic understanding of continental water dynamics by linking the hydrosphere and biosphere. There exists a current lack of data interoperability between groundwater modeling tools due to differences in numerical techniques – Analytic Element Method (AEM), Finite Difference Method (FDM), and Finite Element Method (FEM) – which lend themselves well to either vector or raster data, and legacy input/output file formats that are not well suited across models. Nonetheless, investigative computational tools are all founded in the same conceptualization of hydrologic properties associated with mass, flux, pathways and residence time. A consistent framework is developed using modern Geographic Information Science (GIScience) methods to organize and archive important information from international datasets and previous groundwater ecohydrology studies organized around aquifer and water point, line, polygon and raster features. Case studies illustrate the efficacy of this platform to address existing data interoperability issues for representative groundwater ecohydrology problems of global significance including the impact of human-induced forcings, change in species, and forcings by natural processes on groundwater ecohydrology. In North America, we study the relationships between groundwater pumping in the Ogallala Aquifer and changes in riparian habitat and phreatophyte species composition. In Europe, we study the impacts of changes in forest species composition on groundwater recharge and baseflow to biologically diverse fens and wetlands in the Veluwe sand hill region of The Netherlands. In Africa, we study the wetlands of the Okavango Delta in Botswana that forms an oasis in the midst of the Kalahari Desert and the role of groundwater in flushing salts from this freshwater ecosystem. In each study, we document the current state of knowledge, identify pertinent datasets and previous studies, develop new conceptual and computer models, and summarize findings. This computational platform provides a framework to study sustainability, to forecast the impacts of changes in forcings, and to provide a

scientific underpinning that informs management and public policy debate.

1 Introduction

Ecohydrology is an interdisciplinary field of study crossing the interface between hydrologic and ecologic sciences (Hannah et al., 2004). Hydrologic surficial processes (precipitation, evapotranspiration, runoff and recharge) impact the integrity of freshwater ecosystems that depend upon adequate quantity, quality, timing, and temporal variability of water flow (Baron et al., 2002). Likewise, ecosystem processes impact groundwater hydrology through terrestrial recharge of rain that seeps past the root zone (Jobbágy and Jackson, 2007) and through phreatophyte root uptake of groundwater (Dawson, 1993). These interrelated processes are influenced by the physiological characteristics of vegetation, the pedology of the soil, and the climate (Rodriguez-Iturbe, 2000).

The relationship between groundwater recharge and discharge is one of the most important aspects in the protection of ecologically valuable areas (Batelaan et al., 2003). The rate of recharge to groundwater is strongly impacted by the land cover (Batelaan and De Smedt, 2007), and changes in recharge impact groundwater storage, depth to water, and the rate of base flow discharge to surface water (Brutsaert, 2008). This discharge to aquatic ecosystems moderates river/stream flow and alters surface water chemistry and temperature (Hayashi and Rosenberry, 2002). The severity of vegetation response to altered groundwater elevation is influenced by a plant's drought and flooding tolerance and its root system size and water uptake capacity (Naumburg et al., 2005).

Meeting human water needs while sustaining the services that aquatic ecosystems provide is a central research challenge for the 21st century (Palmer and Bernhardt, 2006). Freshwater ecosystems, which are functionally intact and biologically complex, provide economically valuable ecosystem goods and services (potable water, food supply, industrial use, habitat, instream uses as recreation, transportation and waste disposal, and adaptivity to climate change) with intergenerational benefits to society (Jackson et al., 2001; Baron et al., 2002; Richter et al., 2003). Riparian and aquatic ecosystems have been altered or lost in many parts of the world through human-induced groundwater depletion and stream dewatering with particularly strong effects in arid and semiarid regions (Pringle, 2001).

Establishing methodology for scientific ecohydrologic investigation and its application to case studies is an emerging topic of international interest. The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI, 2007) recently released a science plan that identifies "linking the hydrosphere and the biosphere" as the number one challenge in developing a more comprehensive, systematic understanding of continental water dynamics. The EU Water Framework Directive requires that every country introduce measures to improve and sustainably maintain good water quality and ecological status based on the best available scientific information and using an unbiased, independent and logical methodology (Bruen, 2008). It was found by the Internationally Shared Aquifer Resource Management (ISARM) Programme of UNESCO to be considerably more complicated to develop mutually beneficial and sustainable programs for transboundary aquifer development than for surface water, and that multidisciplinary approaches are required (Puri and Aureli, 2005).

Geographic Information Science (GIScience)-based tools and methodology provide a framework for quantitative analysis of the coupling between human and natural systems (Adriaens et al., 2003; Nellis, 2005). Fundamental process understanding of ecohydrology considers interactions operating at a range of spatial and temporal scales (Hannah et al., 2004). This need may be addressed through the rapid improvements in the availability of high-resolution geospatial data, which improves understanding of geomorphic drivers and the contexts of regional vulnerability to land-use change (Poff et al., 2006).

This paper puts forth a GIScience methodology to conceptualize groundwater and its interactions with ecology. The groundwater concepts data model addresses current lack of data interoperability across numerical modeling approaches, data input file formats and shapefile field mapping techniques. Case studies are presented for ecologically important regions in Africa, Europe and North America that identify and utilize GIS data repositories from a variety of sources. These studies develop new understanding to address scientific challenges posed by Newman et al. (2006) for ecohydrology:

1. landscape interactions in the paleodominated and human-dominated ages,
2. vegetation and groundwater recharge, and
3. hydrological change and vegetation.

We examine the impact of human-induced forcings, change in species, and forcings by natural processes on groundwater ecohydrology.

2 Methods

A conceptual view of groundwater ecohydrology processes and important variables are shown in Fig. 1. Recharge is that fraction of precipitation/irrigation that seeps downward past the root zone of plants to the saturated groundwater zone, where voids between soil particles are fully filled with water. Recharged groundwater flows through an aquifer from regions with high groundwater elevation to low groundwater elevation. It re-emerges to the land surface through human induced pumping, phreatophyte groundwater uptake by plant roots or baseflow to surface water. The depth to water (land surface minus groundwater elevation) and the height of the capillary fringe above groundwater in the unsaturated zone controls the proximity of groundwater to phreatophyte root zones.

A mathematical description of groundwater flow is provided by the following three equations. Darcy's Law is a constitutive relationship between the specific discharge vector $\boldsymbol{q}$, which is a measure of the rate of flow, and the head, ϕ, which is a measure

of groundwater elevation (the level to which water would rise in a pipe located at the position (x,y,z),

$$\boldsymbol{q} = -k\boldsymbol{\nabla}\phi \tag{1}$$

where the hydraulic conductivity, k, is a property of the aquifer medium and the fluid. The Dupuit assumption that head is uniform in the vertical z-direction gives a relationship where the discharge per width, $\boldsymbol{Q}=(Q_x, Q_y)$, is equal to the saturated groundwater thickness times the specific discharge, which may be written as follows for unconfined groundwater:

$$Q_x = (\phi - B)q_x\,, \quad Q_y = (\phi - B)q_y \tag{2}$$

where B is the elevation of the base of the aquifer medium. Continuity of flow (conservation of mass) relates the divergence of $\boldsymbol{Q}$ to the change of groundwater elevation over time

$$\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = -S_y\frac{\partial \phi}{\partial t} + R \tag{3}$$

where S_y is the specific yield of the porous medium, R is the recharge rate, and water is assumed incompressible.

Predictive models of groundwater flow utilize these equations, with boundary and initial conditions related to known values of groundwater elevation and flow rates, to forecast existing conditions and future changes to groundwater stores. Three numerical techniques are commonly employed to implement these groundwater equations and boundary/initial conditions in computer models. The Analytic Element Method (AEM) discretizes hydrogeologic features into points, lines and polygons and develops mathematical functions that exactly satisfy the governing equations and reproduces the flow generated by the feature (Strack, 1989). For example, a well has the geometry of a point in two-dimensions and the head is obtained by evaluating the Thiem (1906) or Theis (1935) solution; similar solutions exist for line elements (Steward et al.,

2008) and polygon elements (Strack, 1989). The Finite Difference Method (FDM) discretizes the flow domain into a set of cells (normally rectangular) with grid points used to delineate cells, and utilizes finite differences to develop a set of equations that gives the groundwater elevation at each grid point (Bear and Verruijt, 1987). The head at locations between these points is obtained through interpolation. The Finite Element Method (FEM) discretizes the flow domain into a set of polygons with prescribed geometry and spatial variation of head across each element and develops a set of equations to obtain the head at collocation points on each element (Bear and Verruijt, 1987). The head at points between these collocation points are obtained by evaluating the prescribed shape functions.

Case studies will illustrate results obtained using these techniques with the computer programs:

- AEM: SPLIT (Janković and Barnes, 1999), available at http://www.groundwater.buffalo.edu
- FDM: MODFLOW (McDonald and Harbaugh, 1988), available at http://water.usgs.gov/software
- FEM: FEFLOW (Diersch, 2005), available at http://www.wasy.de

There is a current lack of data interoperability between such groundwater models. The individual numerical techniques lend themselves well to either vector (AEM/FEM) or raster (FDM) data types, which are both important for hydrological investigations (Whiteaker et al., 2007). These differences along with model assumptions lead to organization of input/output file formats that are not well suited for use across all three numerical methods. Individually, these computer models have begun to address this challenge by using vector shapefiles with fields associated with variables pertinent to the particular software needs. Yet still, a need exists in establishing a spatial groundwater data model that supports all models and allows greater flexibility in specifying groundwater properties; a need that is addressed here.

While computer models have difficulty using each other's data files, they are still founded in the same conceptualization of hydrologic properties associated with mass, flux, pathways and residence time (Reckhow et al., 2004). Furthermore, each model uses data related to groundwater ecohydrology that are common across approaches (borehole lithology and hydrogeology, DEM (Digital Elevation Model), surface water quantity and quality, soils, climate, etc.) An existing challenge is to organize data from a variety of sources and resolutions (Zheng et al., 2006) in a format that is conducive to groundwater investigations across a broad range of computational tools.

To address this challenge, a GIScience based framework has been developed to organize conceptual models of groundwater, which contain the hydrogeologic features important for a particular study (Yang et al., 2009). The data model in Fig. 2 is independent from the choice of computational tool. The geological layers are prescribed in AquiferLayer as aquifers and aquitards following Strassberg et al. (2007). Hydrogeology is then subdivided into features associated with the Aquifer (that through which water flows) and the Water (that which drives the flow of water), where features may be raster grids or have the geometry of points, lines, or polygons. This partitions groundwater hydrogeology into objects related to either the AquiferProperty associated with the geologic medium or the WaterProperty associated with the fluid. Each feature is related to the AquiferLayer (aquifer or aquitard) in which it resides. The Units of properties are specified in these tables, and the time at which properties are specified may be set to support transient studies. For example, a WaterLine may be used to represent a river that lies in the AquiferLayer at the land surface and the WaterProperty may be used to specify the head/elevation along the river with Units of meters above mean sea level (m.s.l.). The relationship classes enable a default property value to be associated with each feature and/or additional properties to be specified at points, lines, polygons or rasters.

This data model provides a relational database of data pertinent to groundwater ecohydrology, and a consistent mechanism to gather data and to store a conceptual view of groundwater ecohydrology that is common across and independent from groundwater computer models. This builds upon existing endeavors to establish a consistent data model for vector based data (Steward et al., 2005; Bernard et al., 2005; Steward and Bernard, 2006, 2007; Yang et al., 2009) and extends these studies to incorporate raster data. It is complimentary with existing endeavors to store measurements for observatory level hydrologic data based upon the ArcHydro platform (Maidment, 2002; Strassberg et al., 2007; Horsburgh et al., 2008) and provides a conceptual model of these data. This also provides a platform that may be integrated with the GetValue protocol of OpenMI (Moore and Tindall, 2005; Gregersen et al., 2007) to provide a means of exchanging data across a variety of investigative tools associated with human and natural components of water resources (Steward et al., 2009a).

It should be noted that this data model is not intended to compete with existing Graphical User Interfaces (GUIs) for existing tools, many of which are quite excellent. The data model provides a central storage mechanism to structure and organize datasets for a groundwater conceptual model, making them syntactically similar and ready to integrate for various purposes. With built-in database management capabilities, well-defined domain, relationships, and topological rules, spatial data models improve data storage efficiency and enforce data integrity. For example, data duplication is avoided by storing well locations in a spatial object and defining a relationship to join the wells with their pumping rates and schedule. Rules may be defined to prevent illegal values such as negative well pumping rates and to limit units of hydrological parameters to those with valid dimensions (e.g., m^3/day for pumping rate). Data integrity ensures that, for example, if a well is deleted its associated pumping rates will be deleted also. Topological rules define how points, lines and polygons share geometry, for example, WaterBoundary points that specify values of head along a river must fall on the WaterLine. Once published, the structure of a spatial data model is open and allows any third-party to develop customized tools and interfaces for its specific needs. It also provides a mechanism to archive data from a study for future use.

In summary, the data model in Fig. 2 puts forth a consistent representation for conceptual groundwater models that addresses current lack of data interoperability across models, provides flexibility in management of data and naming conventions, provides enhanced data integrity and a consistent framework to archive data for future use. We next demonstrate the utility of these methods to capture a conceptual groundwater model for studies representative of ecologically and hydrologically important regions of the world. A general procedure for its implementation is followed:

1. Gather pertinent data and make assessable in GIS (scan and georeference maps, load into ArcHydro groundwater model, as appropriate).
2. Add aquifer/aquitards as per conceptualization of geologic media to the AquiferLayer table.
3. Identify important features in conceptualization (geology, surface water, recharge/discharge zones, wells, etc.), and construct those associated with geologic media (AquiferPoint, AquiferLine, AquiferPolygon, AquiferRaster) and the fluid (WaterPoint, WaterLine, WaterPolygon, WaterRaster), and associate with the AquiferLayer in which they reside.
4. Associate appropriate AquiferProperty or WaterProperty with features from information in step 1, and/or model calibration. This may be accomplished by setting a single value of properties important for a feature (e.g., an AquiferLayer may have a single value of Hydraulic conductivity), setting the values at a set of points (e.g., a WaterPoint feature for a well may specify the Discharge for pumping rates) or lines (e.g., An AquiferLine may be used to specify a contour of uniform Base elevation), or setting the values in a raster (e.g., an AquiferRaster may contain the Thickness of a layer obtained from interpolation between borehole data).

The data model for each case study is used within computational models (AEM, FDM, and/or FEM), the conceptualization of important groundwater ecohydrology drivers is refined based upon interpretation of results, and findings are presented. We invite readers interested in more technical details to explore the data model at http://www.growe.ksu.edu.

3 Case studies

The study regions and their soils are identified in Fig. 3. The Ogallala Aquifer lies in the High Plains region of central North America with wind-blown loess soils interspersed with fluvial sands and clays overlying thick sedimentary deposits (Gutentag et al., 1984). This semi-arid grassland ecosystem has been transformed by human-induced groundwater pumping over the past 50 years (Opie, 2000). The Veluwe in the delta region of western Europe contains ice-pushed ridges with soils consisting of glaciofluvial sand, gravel and clay sediments that overlie marine and fluvial sands and clays (Vasak et al., 1981). This region has been transformed from an agriculturally managed grassland to coniferous forest and is planned to be converted to deciduous forest (Gehrels, 1999). The Okavango Delta in the southwestern extension of the East African Rift System of sub-Saharan Africa forms a sedimentary alluvial fan with wind-blown aeolian deposits of Kalahari sands (Wilson and Dincer, 1976). This wetland forms one of the most biologically diverse freshwater ecosystems in the world (Warne, 2004).

In the following sections, we study the groundwater ecohydrology of these regions using the GIScience methods and computational approaches previously described. First, the groundwater ecohydrologic processes and current state of knowledge are reviewed and the ecosystem forcings from human activities, changes in species, and natural processes are identified. A conceptual model is then constructed using GIS data organization supplemented with domain specific understanding from previous groundwater ecohydrology studies to guide this development. A variety of data sources are identified and documented for each case study region; for example, different sources were used to construct the pictures of soils for the three areas in Fig. 3. Numerical models are applied to understand each ecosystem and findings are summarized.

3.1 North America: interrelationships between regional groundwater pumping and phreatophyte distribution over the Ogallala Aquifer

The Ogallala Aquifer is located in the High Plains region of the central United States of America. This region has been transformed with the advent of modern well hydraulics over the past 50 years from the “Great American Desert” in the “Dust Bowl” region into the “Breadbasket of the World”. Groundwater is a common pool resource that has been over appropriated in many regions with withdrawals exceeding the natural rate of recharge. This study examines the relationship between a declining groundwater elevation and the distribution of phyreatophytes in riparian corridors.

3.1.1 Groundwater ecohydrologic processes

The Ogallala Aquifer spans 450 000 km^2 and underlies 27% of the irrigated land in the United States (Dennehy, 2000). This semi-arid grassland ecosystem was classified by Powell (1879) as an arid land lying west of the 100th meridian with a mean annual precipitation less than 500 mm (20 in) that would require irrigation for successful agriculture. This irrigation need is being met through groundwater extraction that provides society with a water supply that is reliable through drought but unsustainable through natural recharge (Custodio, 2002), a pertinent problem occurring in semi-arid regions of the world: e.g. in Africa, Asia, the Middle East and South America (Montaigne, 2002; UNESCO, 2003; Foster and Chilton, 2003). Within the study region, the average water-use over the past 25 years is 175 mm/yr while natural recharge averages 24 mm/yr (Hansen, 1991; Steward et al., 2009b). Attempts to stabilize this imbalance between water input and output include reducing water use, increasing irrigation efficiency, and adopting water-saving land-use practices (Sophocleous, 2005; Bulatewicz et al., 2009).

Groundwater and surface water interact and groundwater depletion leads to reduced baseflow, induced groundwater recharge, and subsequent streamflow depletion (Sophocleous, 2002). Stream depletion is dependent upon the level of pumping induced drawdowns and the properties of the streambed (Butler Jr. et al., 2001) as well as the properties and extent of underlying aquitards that may slow the rate of induced recharge and spread it over a large surface area (Butler Jr. et al., 2007b). Sustaining streamflow in freshwater ecosystems may result in a sustainable yield of an aquifer that is considerably less than recharge if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs and wetlands (Sophocleous, 2000).

Evapotransporation by phreatophytes provides a pathway for most of the 20–50% of total long-term water budget depletions in large river systems that are ascribed to natural vegetation (Cleverly et al., 2006). Within the study region, cottonwoods and salt cedars have both been shown to withdraw groundwater from the capillary fringe that forms in the vadose zone above saturated groundwater (Butler Jr. et al., 2007a). The cumulative effect of diurnal pumping by these phreatophytes results in the capture of groundwater from the upper regions of the aquifer (Steward and Ahring, 2009). This phyreatophyte-induced redistribution of groundwater to drier surface layers significantly increases photosynthesis and evapotranspiration, and establishes a direct link between plant root functioning and global climate (Lee et al., 2005). The two key environmental variables that influence survivorship of wetland and riparian vegetation are depth to groundwater and inundation frequency (Stromberg et al., 1996). Groundwater management practices coupled with drought have led to die-off of phreatophytes and subsequent exotic infestation when drought ended in California (Elmore et al., 2003) and the Ogallala Aquifer region (Butler Jr. et al., 2007a).

3.1.2 Conceptual model and results

The conceptual model of the hydrogeologic features important for this study in Fig. 4 illustrates a drainage network of rivers, pumped wells used primarily for irrigation, and an aquitard situated beneath alluvial deposits of the Arkansas River and above the underlying Ogallala Aquifer. The background 30 m raster National Elevation Dataset shows the gently sloping land surface from west to east incised by river valleys with ephemeral (west) to perennial (east) streams. In predevelopment conditions before wells were

introduced, the groundwater elevation was close to the land surface in the riparian Arkansas River corridor and phreatophytes (cottonwoods) became established. Human forcings through groundwater extraction has contributed to groundwater declines. Currently, this river rarely flows in this region and native cottonwood populations are becoming replaced by exotic salt cedars.

In this study, we demonstrate the capacity of the GIScience methods to address large-scale transient models and datasets. The conceptual model of the Ogallala Aquifer is captured in the GIScience data model presented in Fig. 2 using the data sources and previous studies listed in Table 1. The AquiferLayer table contains the three layers associated with the alluvium of the Arkansas River, the underlying aquitard, and the Ogallala Aquifer. Studies by the United States Geological Survey (USGS) (Gutentag et al., 1984) were augmented by lithology records from boreholes collected by the Kansas Geological Survey (KGS, 2008) to develop AquiferLine features containing contours of bedrock elevation (Macfarlane and Wilson, 2006). These studies also led to AquiferPolygon features used to depict the hydraulic conductivity and specific yield for the three AquiferLayer objects: alluvium in the Arkansas River corridor, underlying aquitard, and the Ogallala Aquifer. The Division of Water Resources in the Kansas Department of Agriculture developed recharge maps (Hansen, 1991) used to develop WaterPolygon features. The DWR also collects annual water-use reports for each point of diversion as mandated by Kansas law (K.S.A. 82a-732) that were used to develop WaterPoint features with WaterProperty of pumping rates. The USGS National Hydrography Dataset was used to construct WaterLine features for rivers and their WaterProperty was assigned water elevation obtained from DEMs and values for the resistance of river beds were obtained from previous studies and model calibration.

The vector features in this data model were used in the FEM based computer model FEFLOW to study the impacts of groundwater pumping. Note that this conceptual model also supports other computer models, e.g., MODFLOW (Yang and Steward, 2009). Thus, a major advantage of utilizing this conceptual data model is that it provides a mechanism to integrate data from existing sources while archiving data in a format that promotes interoperability for future use (e.g., researchers may use the data in their own different model for their specific analysis) and benefit to water-dependent communities.

Results are presented in Fig. 5 that show contours of groundwater elevation and the depth to groundwater obtained by subtracting the DEM raster from the head obtained in the groundwater model. The initial water table elevation was established for predevelopment conditions in 1959 before wells became broadly established, and a transient model was run using these initial conditions to provide groundwater elevations at the end of 2006, the last year of available data. Model results were calibrated against a network of observation wells maintained by the Kansas Geological Survey (Hausberger et al., 1998) and gave a root mean square error of 5.4 m for predevelopment conditions (over 24 observation wells) and 6.1 m for the last year of simulation (over 176 observation wells). Boundary conditions of specified head were established from a surface obtained by kriging yearly values of groundwater elevation across the network of observation wells; this kriging was performed yearly from 1959 to 2006 to provide the transient boundary condition and the WRIS dataset provides annual water use at each well. While most of the wells in the observatory network are used for irrigation with yearly fluctuations to 10 s of meters, measurements were only used for observations taken between 1 December and 31 January when the water level in wells had mostly recovered. The Kansas Department of Agriculture conducted a helicopter survey of salt cedar populations along the Upper Arkansas River in 2005 and classified riparian habitat based upon percentage salt cedar, which is also shown in Fig. 5.

These new model results illustrate that irrigation water used to support crops in the terrestrial ecosystem have led to declines in the groundwater elevation throughout the region. These results also illustrate that the aquitard in the Arkansas River corridor has partially mitigated the groundwater declines and is effectively holding groundwater in the alluvium near land surface. Within this riparian corridor, cottonwood die-offs have been observed as groundwater levels dropped and the helicopter survey illustrates subsequent establishment of relatively deep-rooted salt cedars that continue to

tap groundwater. While irrigated agriculture has sustained economic development in the region for the past half century, change for many western Kansas communities is inevitable (Leatherman et al., 2004). This groundwater ecohydrology model enables forecasts and prediction of the impact of proposed change in water-use practices, feedback to the groundwater due to ecological thresholds like die-off of the riparian vegetation, and provides a scientific basis to inform public policy planning and debate. The data model also facilitates integration of groundwater results with models of human drivers (Steward et al., 2009a).

3.2 Europe: interrelationships between plant species composition and groundwater recharge/discharge zones in the Veluwe

The Veluwe region of The Netherlands is located in the delta region of the international Rhine River system. With formation of the Hoge Veluwe National Park, this region has undergone transition over the first half of the last century from heather vegetation, managed agricultural grassland, bare land and moving sand dunes to a coniferous (spruce, fir) forest that both stabilized sand and provided support wood for the coal mining industry. This change of species has led to decreases in the rate of groundwater recharge with subsequent loss of groundwater fed and biologically diverse fens and wetlands. The EU Water Framework Directive obliges European nations to research and learn how to provide sustainable ecological approaches. This study examines The Netherlands plans to reestablish fens and wetlands by replacing coniferous with deciduous (oak, beech, birch) forests.

3.2.1 Groundwater ecohydrologic processes

The Veluwe is a nutrient poor, sandy area covered by forests, heath lands, drift sand areas and some agricultural fields and constitutes one of the most important nature areas of the Netherlands in terms of both ecological quality and recreation (Turnhout et al., 2004). This temperate maritime climate has an average annual rainfall of 850 mm and evapotranspiration around 550 mm (Gehrels et al., 1994). The hills in this region are the remains of ice-pushed ridges with glacial basins located on their concave eastern and northern sides (van der Meulen et al., 2005). These hills form a groundwater recharge zone with a sandy unsaturated zone of about 40 m in the center that provides baseflow to surface water surrounding the Veluwe where the unsaturated zone is near zero (Vasak et al., 1981; Gehrels et al., 1994). The ice-scoured basins along the edge of the Veluwe form a stacked system of troughs filled with banded material consisting of an ill-sorted mixture of gravels, sands, silts and pebbles with dispersed outsize clasts (Postma et al., 1983). The spring waters that flow into these basins along the eastern and southern Veluwe areas contain high concentrations of NO_3 attributed to enrichment during passage of groundwater through the nitrogen-rich soils (Higler and Verdonschot, 1993).

Fens and fen meadows are rich in endangered species and occur in complex landscape settings where groundwater discharges to low-lying areas, making them sensitive to hydrological changes in the valley and surrounding area (Grootjans et al., 1996). Within the Veluwe area, naturally wet areas have become dessicated (Vermulst and de Lange, 1999) due to landscape changes involving centuries of human use from cutting forests for agriculture to degradation of forest into heath land to grazing and sod cutting leading many heath lands to degrade further into drift sand areas (Turnhout et al., 2004). Dessicated fen mires have become severely eutrophied due to degradation (oxidation) of peat, and watering from other sources usually causes deterioration of the original flora and fauna due to changes in water quality (Best et al., 1993). It is important to study the hydrologic controls in vegetation composition through water and solute cycling and the impacts of water resources management on these regions of species-rich gradients in series of soil and vegetation types that mirror the relief of the landform (Grootjans et al., 1996).

Presently, reforestation of coniferous forests has stabilized most of the drift sand through a succession of vegetation (lichens, mosses, trees) that is increasing biodiversity (Turnhout et al., 2004). The coniferous forests planted as even-aged stands in the

first half of the last century are undergoing conversion into mixed stands with indigenous deciduous tree species in the Veluwe (Kuiters and Slim, 2002). The recharge below a deciduous forest is greater than between a coniferous forest, with rates of interception averaging 10% (winter) to 26% (summer) for deciduous forests and 22–39% for coniferous forests in the Veluwe (Gehrels, 1999). Ecosystem prediction of the implications of such change in landcover and subsequent increase in rates of groundwater recharge and fen/stream baseflow may be facilitated by coupling hydrological and ecological process knowledge using GIS and ecohydrologic models using field data (Grootjans et al., 1996; Boumans et al., 2008). Within the Veluwe region, the dominant causes of changes in groundwater fluctuation are changes in groundwater recharge, large-scale dewatering in polders formed to the north in the former IJsselmeer and groundwater withdrawals by wells (Gehrels et al., 1994).

3.2.2 Conceptual model and results

The conceptual groundwater ecohydrologic model of the Veluwe is illustrated in Fig. 6 by depicting stream networks, inland waterways and wells. The background 25 m Actual Height of the Netherlands dataset shows the ice-pushed hills of the Veluwe and the surrounding valleys along the eastern edge where biologically diverse fens and wetlands are located. The recharge occurring in the Veluwe hills drives groundwater flows through aquifer layers with properties identified from boreholes and knowledge from previous investigations. The baseflow discharge to the aquatic ecosystems is impacted by the rate of recharge in the hilly regions, which is controlled by forest species composition and their relative efficiencies in intercepting/evaporating and transpiring precipitation.

In this study, we demonstrate the capacity of the GIScience methods to provide a data model for the NHI (Netherlands Hydrologic Instrument), an integrated system of models for national water management in The Netherlands. The NHI captures the ecological inputs of vegetation in unsaturated vadose zone models, providing input to this conceptual model and promising better integration with ecohydrologic drivers in the future. The datasets and previous studies are identified in Table 2. The AquiferLayer table contains the four aquifers and three aquitards that exist in the Veluwe region (de Lange, 2006). The TNO-Geological Survey of The Netherlands maintains the REGIS/DINO datasets containing borehole lithography. These AquiferPoint features, together with AquiferPolygon features that depict geological units, have been used to develop AquiferRaster datasets related to hydraulic conductivity and aquifer elevation. TNO datasets also contain water-use information for wells, which is stored in the WaterPoint features with WaterProperty values associated with the pumping rate. WaterLine and WaterPolygon features associated with surface water have been used to develop WaterRaster datasets containing information about surface water properties and recharge. The discharge boundaries providing upward leakage through the less-pervious cover layer in the deep Flevo-polders to the north were specified using cells in the WaterRaster grid along the boundary.

The 250 m×250 m raster datasets in this data model were used in the Finite Difference Method computer model MODFLOW to study the impact of change in tree species in the Veluwe. Note that the groundwater data model also has the capacity to store the complimentary Dutch national groundwater model that uses the AEM (de Lange, 2006), effectively bridging datasets and understanding between these models. New results from this model are presented in Fig. 7 that show the contours of groundwater elevation and the depth to water. This model was exercised by imposing recharge rates throughout the terrestrial ecosystem corresponding to coniferous and to deciduous forests. The results show a groundwater mound beneath the center of the Veluwe that raises from an elevation of 32 m beneath a coniferous forest to 40 m beneath a deciduous forest; this change began in the century before the foresting was completed (1850–1950) and is observed through changes in forest species. Within the lowlands to the east, there is an increase in the upstream portions of the river network that contains shallow depth to water, where fens and wetlands may become reestablished. The depth to water and length of upstream portions of stream bottoms that intersect the water table varies, not just under change in species as examined here,

but also due to non-linear feedbacks associated with climate change and water use.

The NAtional GROundwater Model (NAGROM) was developed to improve understanding of groundwater movement in multiple aquifer systems (de Lange, 2006), and forms a foundation of hydrogeologic understanding for the Netherlands Hydrologic Instrument. This NHI gives national impacts for policy making and to assess possible measures for sustainable ecology. This modeling approach, coupled with the GIScience data model presented here, provides an avenue to research sustainable ecological approaches as required by all European countries in the Water Framework Directive, and to understand feedbacks between the terrestrial ecology of forests, the groundwater hydrology of recharge and baseflow, and the aquatic ecology of fens and wetlands. Thus, the groundwater datamodel promotes future analysis with different modeling concepts to make use and hence show/stress different aspects of the future water system and its interaction/feedback with ecosystems. It also provides a mechanism to promote analysis and comparison of model results across EU countries with different modeling techniques, and more balanced overall conclusions.

3.3 Africa: interrelationships between plant groundwater uptake and salt accumulation and groundwater flow in the Okavango Delta

The Okavango Delta is located in the extreme southwestern extension of the East African Rift Valley. Its transboundary surface water inflows from precipitation occurring during the rainy season in the mountains of Angola and Namibia to arrive months later in northern Botswana during the dry season, providing a biological diverse oasis amidst the sands of the Kalahari Desert. The high evapotranspiration rates of this wetland results in salt accumulation within the delta. This study examines how the regional groundwater flow flushes salts to help sustain this freshwater ecosystem.

3.3.1 Groundwater ecohydrologic processes

The Okavango Delta is an alluvial fan formed by the Okavango River discharging into a graben at the southern extremity of the East African Rift System (McCarthy and Ellery, 1994). This river enters through the panhandle, a tectonic graben 100 km long and 10 km wide, and then spreads atop 300 m of sediment (McCarthy et al., 2005; McCarthy, 2006) to form a wetland with surface area that varies seasonally between 6000–12 000 km^2 (Dincer et al., 1987). The waterborne sediments within the rift valley are bounded by a fault to the south and a parallel fault 15 km from the end that partially redistributes groundwater (Wilson and Dincer, 1976).

The wetlands of the Okavango Delta lie within the Kalahari Desert. While this region receives a mean annual precipitation of 500 mm/yr (Dincer et al., 1987), recharge is small due to grass/tree competition and sands that are of small enough grain size to hold precipitation (de Vries and von Hoyer, 1988). Tree roots have been measured to depths of 68 m (de Vries and von Hoyer, 1988) and it is likely that Acacia trees tap to tens of meters and perched water tables, limiting present recharge of the Kalahari to 1–5 mm/yr (de Vries et al., 2000). Within the wetlands of the Okavango Delta, evapotranspiration exceeds precipitation by a factor of 3–4 (McCarthy and Ellery, 1994; McCarthy, 2006). Inflow in the Okavango River is $10\times10^9\,m^3/yr$ with a net salinity of 30 ppm (major dissolved species consisting of sodium, bicarbonates and silica) and precipitation adds $5\times10^9\,m^3/yr$ (Dincer et al., 1987; Gieske, 1997). Evapotransportion results in a loss of nearly 98% of this influx (Linn et al., 2003), resulting in annual salt accumulation in the delta of 300 000 tons/yr (Dincer et al., 1987; Bauer-Gottwein et al., 2007).

The surface flood inundates the Okavango Delta traveling through an alluvial fan of rivers that traverse the delta and the perennial swamps (Gieske, 1997). Large scale channel avulsions occur in this braided stream network where new channel systems form over tens to hundreds of years as main river channels become blocked by deposition of silts (Ellery et al., 1993b), sediments consisting mostly of fine sand (400 000 m^3

annually) brought to the delta by the Okavango River (Dincer et al., 1987), and blockage formed by papyrus (Gieske, 1997). Within the wetlands, 150 000 vegetated islands have formed on termite mounds (Warne, 2004) and subsurface accumulation of silica and calcite (McCarthy et al., 1993). The islands constitute between 10–20% of the surface area of the perenial swamp with sizes ranging from a few square meters to several hectares (Ellery et al., 1993a; McCarthy et al., 1993). 75% of the total water loss from the wetland is caused by transpiration-driven lateral groundwater flow into the islands, with the remaining 25% lost to evaporation from the open water surface (Wolski and Savenije, 2006).

A zonation in plant species occurs across islands from evergreen trees to deciduous trees and palms to grasses to bare soil in salt pans at island centers (McCarthy and Ellery, 1994). This zonation is not related to depth of groundwater, with seasonal variation of 1.5 m in the panhandle, 20 cm in the central regions of perennial swamps, and 2 m in the lower reaches of the fan (Ellery et al., 1993a). Instead, zonation changes across an island as a carbonate encrusted area free of vegetation forms in the island centers (Ellery et al., 1993a). Salt precipitates preferentially with the most soluble salts found in centers (McCarthy, 2006), where lignin stained (brown) salt water occur with enriched alkali carbonates indicate terminal evaporation of water in the capillary zone around the pans (McCarthy et al., 1991). It is supposed that the vegetation enhanced salt accumulation process takes on the order of 100–200 years to form an area void of vegetation; this process may be interrupted by swamp abandonment leading to accumulation of silica and calcite in the subsurface and leaching of sodium salts to groundwater (McCarthy et al., 1993). Numerical simulation suggests that salts accumulate to densities that, over hundreds to thousands of years, generate density driven fingers that transport high salinity groundwater downward towards the base of the aquifer (Zimmermann et al., 2006). This is supported by electrical soundings carried out on the fringes of the Delta that indicate a marked increase in salinity of the groundwater with depth, with a layer of lower salinity groundwater (50–70 m thick increasing towards permanent swamp) floating on denser saline water (McCarthy, 2006).

3.3.2 Conceptual model and results

The conceptual groundwater ecohydrologic model of the Okavango Delta in Fig. 8 illustrates the regional groundwater system. At the surface, water inflows from the Okavango River in the northwest to an outlet leading towards saltpans in the Kalahari Desert to the southeast. The background 90 m DEM shows ridges surrounding the graben located in the southwestern extension of the East African Rift Valley, as well as the gently sloping land surface within the wetland ecosystem. The region of salt accumulation by phreatophyte driven evapotranspiration of groundwater in the perennial swamp and vegetated islands are averaged over polygons, where tens of thousands of small islands lie within an area of shallow water table. The regional groundwater gradient that flushes salts from beneath the Okavango Delta are driven by surficial flow and recharge depicted by polygons. The connected faults that transport water and the dikes at the southwestern boundary of the Okavango Delta that impede the movement of water are depicted by lines. Groundwater observations have high salt concentrations in areas south of the Okavango Delta, and surficially salts are found in saltpans to the south.

In this study, we illustrate the capacity of the GIScience methods to develop conceptual groundwater ecohydrology models for problems broad in area with relatively sparse data. In such cases, alternative conceptual models may be construcated and the GIS system may be used to help and thus reduce uncertainty and increase robustness. The conceptual model is captured in the GIScience data model using the datasets and previous investigations identified in Table 3. A geological map of Botswana was developed by the Department of Geological Survey and Mines (Hepworth et al., 1973), and a land system map was developed by the Ministry of Agriculture (De Wit et al., 1990). These, together with remote sensed imagery, were used to develop a single AquiferLayer model with AquiferLine features for connected fault systems and AquiferPolygon features for the graben and ridges. The Okavango Delta management plan of the Department of Environmental Affairs (DEA, 2008) was used to develop Aquifer-

Line features for the dikes. WaterLine features for rivers were developed from maps and previous studies and the WaterProperty values for head were obtained from the DEM. The WaterPolygon features for the perennial wetland, areas of high evapotranspiration, and areas of recharge were developed from previous studies and remotely sensed data, and their respective rates of recharge/discharge were specified in the WaterProperty table.

The vector data in this data model was used in the Analytic Element Method based computer model SPLIT to study the steady regional groundwater flow system. The steady assumption is adopted because, while seasonal variation in groundwater elevation fluctuate about a mean elevation immediately beneath the wetlands, the present regional hydraulic gradient is more or less in steady-state (de Vries et al., 2000). The groundwater elevation and depth to water in the Okavango Delta region are shown in Fig. 9. These results compare well with observed values of groundwater elevation and depth to water from both regional (de Vries et al., 2000; Staudt, 2003) and local studies within the Okavango Delta (McCarthy et al., 1998). This model provides new understanding of a low hydraulic gradient in groundwater within the delta extending to the southeast. This groundwater flow provides a mechanism to flush the salts that accumulate within and beneath the wetlands to locations southeast of the Okavango Delta beneath the saltpans in the Kalahari Desert, and thus enable the freshwater zone to continue to exist.

This GIScience data model and groundwater model also enables prediction of the outcome of how future changes in natural forcings or human activities could change this equilibrium between salt accumulation within and groundwater movement away from the Okavango Delta. Driving agents that could change the system dynamics include: climatic changes, geological changes, hydrological changes, vegetational-geomorphological changes, zoological activities, and anthropogenic changes (Ringrose et al., 2005). Human activities such as increased fertilizer application or reservoir construction could result in changes to river flow and plant species composition (Warne, 2004; Murray-Hudson et al., 2006). This model helps establish current conditions and provides a platform to evaluate impacts on regional transport of the salts that accumulate within the Okavango Delta that could result from possible future change of natural and human forcings.

4 Conclusions

Modern society faces challenges in meeting human water needs while maintaining functionally intact freshwater ecosystems that provide goods and services with intergenerational benefits to society. A GIScience methodology is presented here to conceptualize groundwater and its interactions with ecology. Approaches are developed to study the impact of human-induced forcings, change in species, and forcings by natural processes on groundwater ecohydrology.

The GIScience methods for conceptual models and datasets promote a framework to integrate data from existing sources while archiving data in a format that promotes interoperability for future use and benefit to water-dependent communities. International datasets and results from previous studies are organized and archived within the conceptual data model presented in Fig. 2. Hydrogeology is organized about aquifer features (that through which water flows) and water features (that which drives the flow of water). Relationships are developed between vector (point, line, polygon) and raster (grid) data types and their properties. This addresses current lack of interoperability of data across computational groundwater models and provides a platform that is shown to support numerical approaches based upon the Analytic Element Method, the Finite Difference Method, and the Finite Element Method. The data model provides flexibility in management of data and naming conventions and provides rules and topological relationships that enhance data integrity over existing methodology using shapefiles. Further information may be found at http://www.growe.ksu.edu.

Case studies deal with globally important ecosystems in Africa, Europe, and North America. In each study, the groundwater ecology processes and current state of knowledge are reviewed and important ecosystem forcings are identified. We then develop

new conceptual and computational models of each ecosystem to study and understand ecohydrologic processes. In North America, we study interrelationships between groundwater pumping and phreatophyte distribution over the Ogallala Aquifer using the conceptual model in Fig. 4 with data sources and previous studies in Table 1. Results in Fig. 5 illustrate while groundwater pumping has led to regional groundwater declines, the aquitard beneath the alluvium in the Arkansas River corridor holds groundwater near the surface where phreatophytes continue to exist. In Europe, we study interrelationships between forest species composition and groundwater baseflow discharge to biologically diverse fens and wetlands using the conceptual model in Fig. 6 with data sources and previous studies in Table 2. Results in Fig. 7 illustrate the potential for reestablishment of fens as coniferous forest are replaced by deciduous forests with lower interception rates, and the NHI-based groundwater model supports scenario testing to quantify the impacts of these change on baseflow discharge to fens and wetlands. We also demonstrate the capacity of these methods to serve as a computational platform for the National Hydrological Instrument of The Netherlands, and discuss the capacity of this framework to bridge datasets between existing AEM-based national groundwater models and ongoing FDM-based MODFLOW models. In Africa, we study the regional role of groundwater in transport of salts that accumulate in the Okavango Delta region using the conceptual model in Fig. 8 with data sources and previous studies in Table 3. Results in Fig. 9 identify a low gradient in groundwater that contributes to flushing of salts deposited through vegetation enhanced evapotranspiration and enable this freshwater ecosystem to exist.

The grand challenge posed by CUAHSI of linking the hydrosphere and biosphere, and the societal obligation to meet human water needs while sustaining functionally intact and biologically diverse ecosystems, each require new developments in the interdisciplinary science of groundwater ecohydrology. In this paper, we reviewed and documented three important problems that cross this divide. We organized international datasets supplemented by domain specific knowledge gained from previous studies to develop a conceptualization of the groundwater ecohydrology. While a plethora of mechanisms exist to organize this data, we chose to adopt a simple data model to support this process. This approach to conceptualizing groundwater ecohydrology supports a broad range of computational tools to investigate and develop understanding of these ecosystems. This provides a framework to study sustainability, to forecast the impacts of changes in forcings, and to provide a scientific underpinning that informs management and public policy debate.

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Table 1. Data resources for the Ogallala Aquifer region in North America.

Object	Feature	Data Sources
AquiferPoint	Borehole	KGS (2008)
AquiferLine	Bedrock elevation	Gutentag et al. (1984); Cederstrand and Becker (1998a); Macfarlane and Wilson (2006)
AquiferPolygon	Hydraulic conductivity	Dunlap et al. (1985); Gutentag et al. (1984); Cederstrand and Becker (1998c)
AquiferPolygon	Specific yield	Dunlap et al. (1985); Gutentag et al. (1984); Cederstrand and Becker (1998b)
AquiferRaster	Land elevation	USGS (2008a)
WaterPoint	Well	Hausberger et al. (1998); Wilson et al. (2005)
WaterLine	River	Tsou et al. (2006); Goodall et al. (2008); USGS (2008b,a)
WaterPolygon	Recharge	Hansen (1991)

Table 2. Data resources for the Veluwe region in Europe.

Object	Feature	Data Sources
AquiferPoint	Borehole	TNO (2008)
AquiferLine	Fault	Vernes and van Doorn (2006); Goes et al. (2008b)
AquiferPolygon	Geological units	de Lange (2006); Vernes and van Doorn (2006); Goes et al. (2008b)
AquiferRaster	Hydraulic conductivity	Vernes and van Doorn (2006); Goes et al. (2008b)
AquiferRaster	Land elevation	Goes et al. (2008a); Rijkswaterstaat (2008)
AquiferRaster	Layer elevation	Vernes and van Doorn (2006); Goes et al. (2008b)
WaterPoint	Well	Pastoors (2008)
WaterLine	River	de Lange et al. (2008a)
WaterPolygon	Lake, River	de Lange et al. (2008a)
WaterRaster	Recharge	Gehrels et al. (1994); van Bakel and Veldhuizen (2008)
WaterRaster	Surface water properties	Vermulst and de Lange (1999); de Lange et al. (2008b)

Table 3. Data resources for the Okavango Delta region in Africa.

Object	Feature	Data Sources
AquiferLine	Dike	DEA (2008)
AquiferLine	Fault	Hepworth et al. (1973)
AquiferPolygon	Graben	Hepworth et al. (1973); De Wit et al. (1990); Brunner et al. (2007)
AquiferPolygon	Ridge	Hepworth et al. (1973); Staudt (2003)
AquiferRaster	Land elevation	Jarvis et al. (2006)
WaterLine	River	Ellery et al. (1993b); Gieske (1997); Jarvis et al. (2006)
WaterPolygon	Evapotranspiration	Gumbricht et al. (2004); Brunner et al. (2007)
WaterPolygon	Recharge	de Vries et al. (2000); Selaolo et al. (2003)
WaterPolygon	Wetland	De Wit et al. (1990); Bekker et al. (1991); McCarthy et al. (1998)

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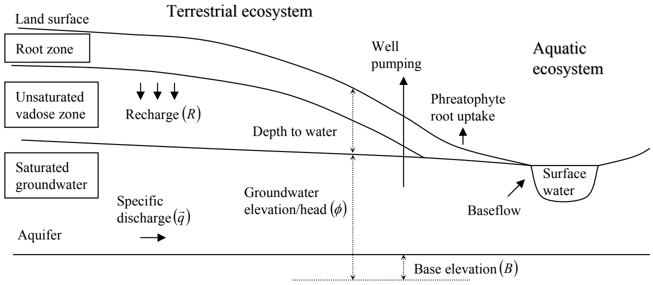
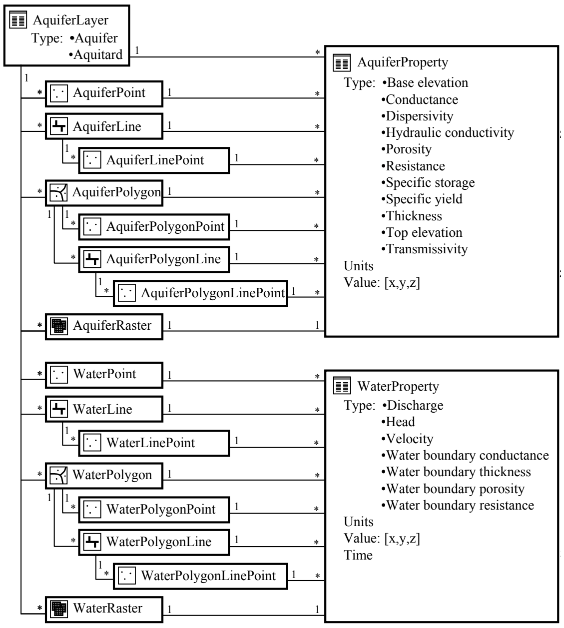


Fig. 1. Conceptual view of groundwater ecology: water that seeps downward past the root zone of the terrestrial ecosystem recharges the groundwater aquifer and eventually discharges to the surface through well pumping, phreatophyte root uptake, or baseflow to surface water in the aquatic ecosystem.



Objects include points, ⊡, lines, ⊞, polygons, ⊠, raster catalogs, ■, and tables, ▥; relationships indicate redundancy (e.g., 1 * relates one-to-many).

Fig. 2. Groundwater concepts data model.

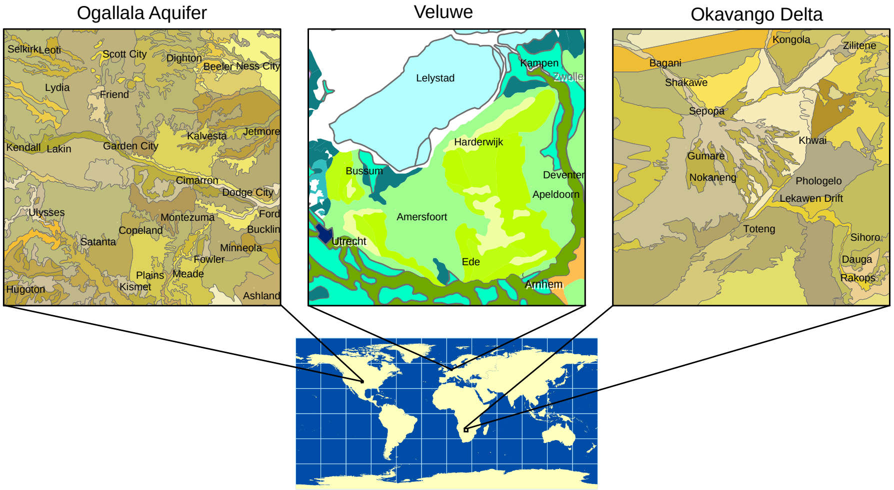


Fig. 3. The three study regions and their soil classifications obtained for the Ogallala Aquifer in the United States of America from the Digital General Soil Map (USDA, 2006), for the Veluwe in The Netherlands from CORINE (UNEP, 1985) and for the Okavango Delta in Botswana from ISRIC (Batjes, 2004). Note that soil classifications and color schemes are used from each of the respective data repositories.

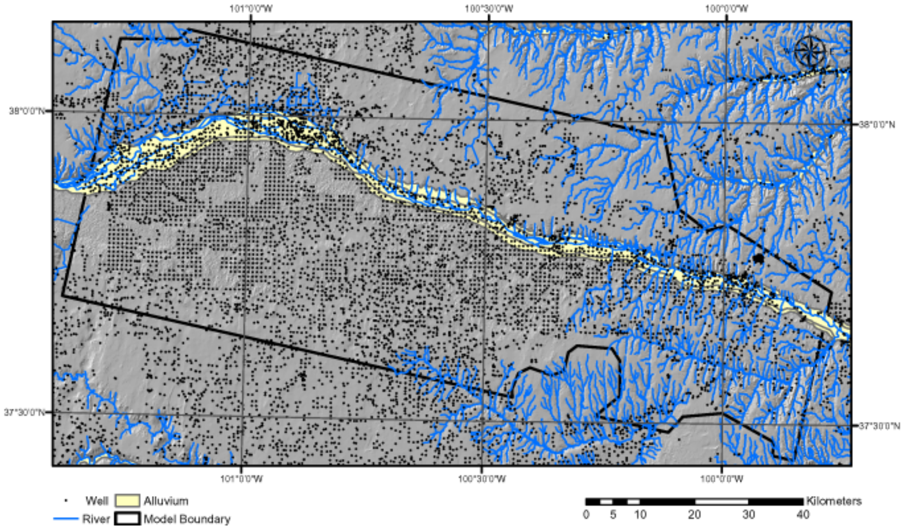


Fig. 4. Conceptual model of the Ogallala Aquifer, western Kansas, USA.

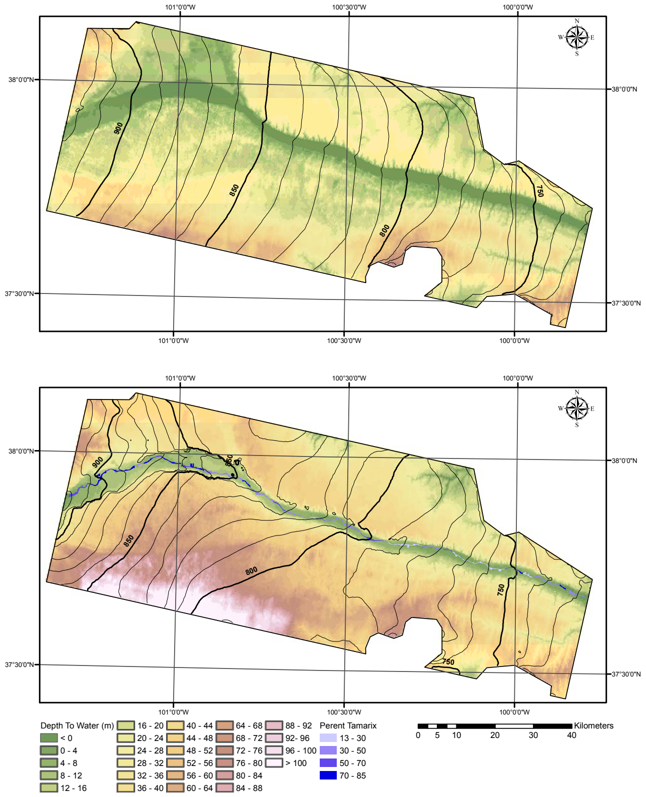


Fig. 5. Groundwater elevation (m above m.s.l.) and depth to groundwater (m) in the Ogallala Aquifer, western Kansas, USA for predevelopment (top) and current (bottom) times.

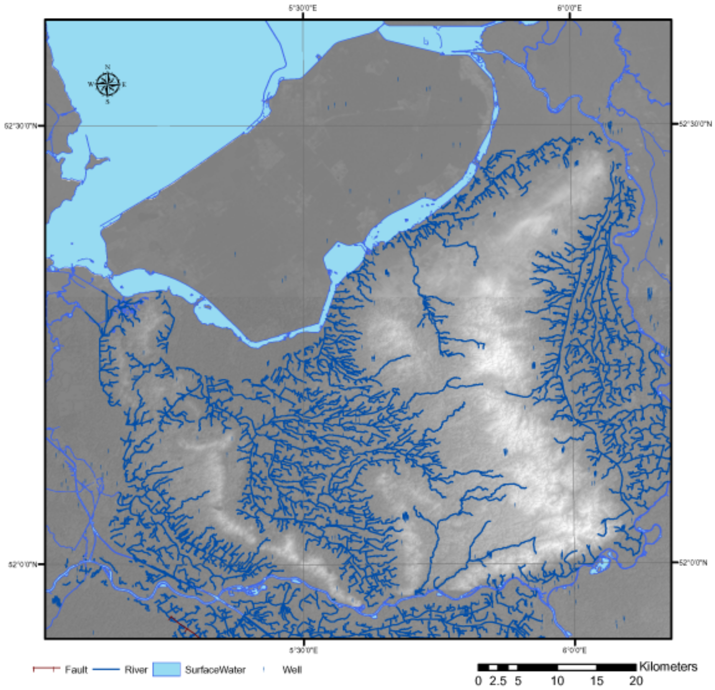


Fig. 6. Conceptual model of the Veluwe, The Netherlands.

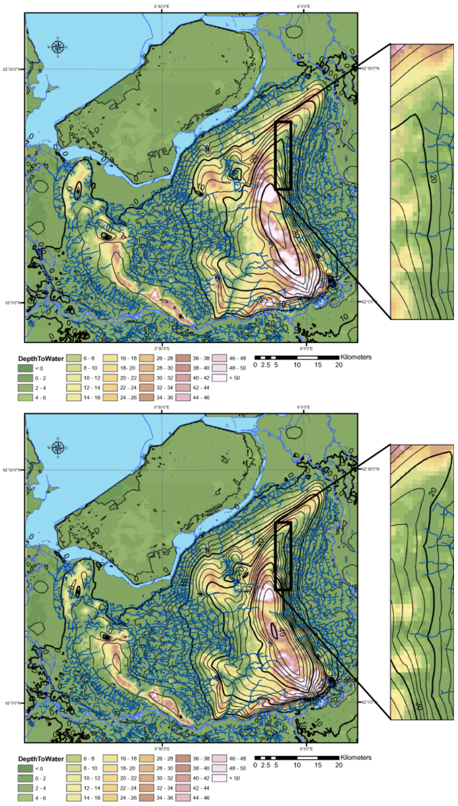


Fig. 7. Groundwater elevation (m above m.s.l.) and depth to groundwater (m) in the Veluwe, The Netherlands with coniferous (top) or deciduous (bottom) forests.

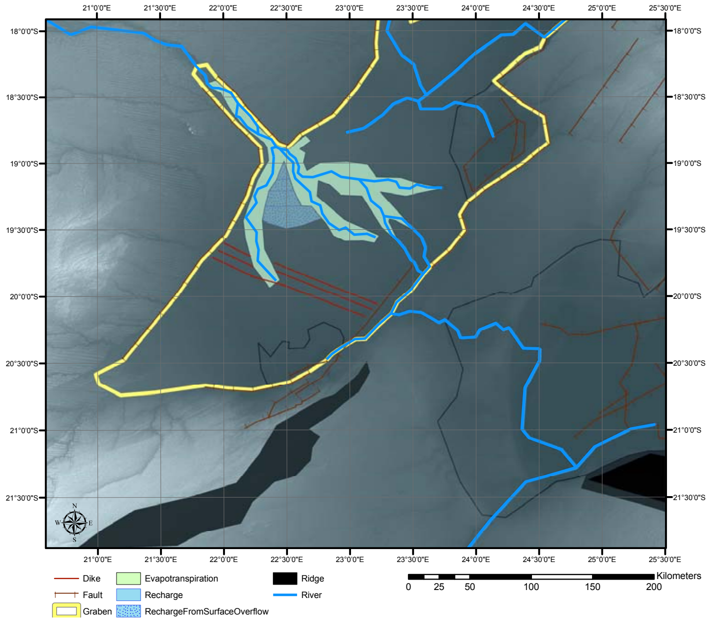


Fig. 8. Conceptual model of the Okavango Delta, Botswana.

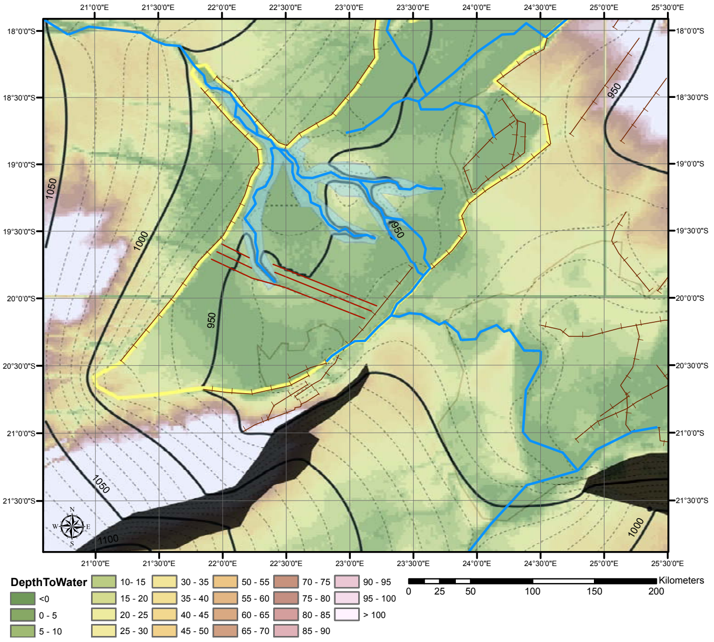


Fig. 9. Groundwater elevation (m above m.s.l.) and depth to water (m) in the Okavango Delta, Botswana.