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Wechselwirkung von Galeriewäldern und alluvialen Aquiferen

Interaction between riparian phreatophytes and alluvial aquifers

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Hiermit erkläre ich, dass diese Diplomarbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

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Zusammenfassung

Im Rahmen dieser Diplomarbeit werden die Auswirkungen von Grundwasser zehrender Vegetation auf den Wasserhaushalt in semiariden, ephemeren Einzugsgebieten untersucht. Die Fragestellung enstand im Zuge aktueller Forschungsarbeiten im EU-Projekt WADE. Die Validierung ermittelter Grundwasserneubildungsraten, anhand eines Grundwassermodells, führte zu Problemen bei der Kalibrierung. Selbst bei der kleinsten angenommenen Neubildungsrate konnte das System nicht genügend Wasser abführen. Die aus dem Modell resultierenden Wasserstände lagen für einen Großteil der Alluviumsflche über der Geländeoberkante.
Der nicht berücksichtigte Wasserverbrauch von tief wurzelnden Pflanzen könnte eine mögliche Erklärung für die zu hohen Wasserstände darstellen.

Um den Einfluss der Vegetation auf den Wasserhaushalt zu quantifizieren, ist es notwendig, die Verdunstung aus dem Grundwasser detailliert zu bestimmen. Zu diesem Zweck wird die Methodik der multi-Agenten basierten Modellierung verwendet. Dieser für die hydrologische Modellierung neue Ansatz erlaubt es, die Vegetation als ein aus Einzelindividuen bestehendes System zu beschreiben. Somit können Regelmechanismen definiert werden, die den einzelnen Individuen erlauben, sich an das bestehende Wasserangebot anzupassen.

Im theoretische Teil werden die Mechanismen der Wassernutzung von Pflanzen untersucht. Außerdem wird auf die Auswirkungen der Vegetation, auf die Prozesse und den Haushalt des Wasserkreislaufes, eingegangen. Für Trockengebiete gilt, dass die Vegetation der Grundwasserneubildung entgegen wirkt und dass im Falle einer Verbindung mit der gesättigten Zone ein erheblicher Anteil des Grundwassers verdunstet werden kann.
Des Weiteren werden die Grundlagen der Agenten-basierten und der Individuen-basierten Modellierung erläutert und ein Pflanzenagent abstrahiert.

Im zweiten Teil der Arbeit wird ein gekoppeltes Grundwasser – Vegetationsmodell entwickelt und angewendet. Das bisherige Grundwassermodel aus dem Untersuchungsgebiet des Buffelsrivier Einzugsgebietes wird dazu mit einem Multiagentenmodell kombiniert. Die Implementierung erfolgt in REPAST.

Da die hydraulische Leitfähigkeit für das Untersuchungsgebiet nur in grobem Maße abgeschätzt werden konnte (10^{-7} m/s bis 10^{-8} m/s), wird für die beiden Grenzbereiche je ein Modelllauf durchgeführt. Die Ergebnisse zeigen, dass das gekoppelte System nur unter Verwendung der geringeren Leitfähigkeit interagiert.

Die quantitative Auswertung der Grundwassermodellierung lässt darauf schließen, dass für das untersuchte Teilgebiet am Buffelsrivier Oberlauf, die Wiederverdunstung aus der gesättigten Zone des Alluviums die Neubildungsrate im Mittel übersteigt und somit auch unterirdisch zufließendes Wasser aus den angrenzenden Gebieten verbraucht wird.

Schlüsselwörter

Vegetation-Grundwasser Interaktion; Multi-Agenten Modellierung; Individuen-basierte Modellierung; Buffelsrivier Südafrika; EU-Projekt WADE; Multi-Agenten Systeme; Grundwassermodellierung; Pflanzenagenten;

Summary

Within this thesis the influence of groundwater dependent vegetation, on the water balance of semi-arid, ephemeral river basins is treated. The topic emerged from recent investigations within the EU research project WADE.
The validation of determined groundwater recharge rates, using a groundwater model, resulted with calibration problems. Even the smallest measured recharge rate caused an overflow of the groundwater system. The results were calculated water tables that exceeded the top ground surface. An explanation for the observed pattern could eventually be the groundwater withdrawal by deep rooting plans.

Determining the influence of vegetation on the water balance makes it necessary to estimate the transpiration spatially and temporally in a detailed way. To achieve this, multi-agent based modeling will be used. This approach, that is new in hydrological modeling, makes it possible to define vegetation as a system of singular individuals. Hence, rules and controlling mechanisms can be specified that allow an adaptation of the individuals to the actual supply of water.

The theoretical part of this thesis addresses the mechanisms of wateruse by vegetation. Furthermore, the impact that plants have on hydrological processes is dealt with. For drylands it can be stated that vegetation decreases the amount groundwater recharge. In case a direct connection between plants and groundwater exists, a significant part of the shallow aquifers water can be lost by transpiration.

Within the second part of this work, a coupled vegetation-groundwater model is developed and applied. The former groundwater model from the study area at the Buffelsrivier catchment is combined with a multi-agent model. The implementation was realized using the REPAST modeling toolkit.

In order to take into account the uncertainty within the estimation of hydraulic conductivities for the model area, that range between 10^{-7} m/s and 10^{-8} m/s, two separate simulation runs were carried out. The results show that an interplay between the two systems was only achieved if lower conductivities were chosen.

The analysis of the water balance of the groundwater model leads to the conclusion that, for the investigation area at the upper Buffelsrivier, the re-evapotranspiration from the unsaturated zone of the alluvium exceeds the groundwater recharge amount. Hence, additionally, inflowing water from adjacent areas is needed to clear the water balance.

Keywords

Vegetation-groundwater interaction; multi-agent modeling; individual-base modeling; Buffelsrivier South Africa; EU-project WADE; multi-agent systems; groundwater modeling; plant-agents;

1 Introduction

More than 33% of earth's land surface is affected by aridity. The bigger part of these zones is located in developing countries. There is little available water for both, humans and biota. In many regions, water is taken from fossile sources. Recently recharged occurrences are mostly overused.

Today, hydrological processes in arid and semiarid catchments are still a matter of research. One important question is to determine whether a system is balanced or overused. Ephemeral streams, which are typical representatives of dryland catchments, often show richly developed riparian gallery forests. Many of the plant species that form such communities are phreatophytes that are able to withdraw water from the saturated zone. Hence, they become seasonally independent. In summer, the transpiration by phreatic vegetation can cause major water losses to the tapped aquifers.

The impact that deep rooting plants have on dryland alluvial aquifers has been widely underestimated in water balance modeling. For the Kuiseb river in Namibia, most research is being done on infiltration processes and the role of floods although 6/7 of the water budget is attributed to evapotranspiration (Külls, 2006).

One problem in modeling transpiration effects on aquifers is that vegetation occurs spatially distributed and temporally variable. Such inhomogeneous settings could hardly be implemented within the common groundwater modeling approaches.

Within the last years, a new type of modeling came up. Agent-based or individual-based models allow us to define autonomously acting entities that can be freely placed within the model area. Hence, plants can be positioned within an investigation area to represent individual groundwater users.

Such a plant-agent-groundwater approach does not exist in the literature. Hence, this work is a basic step towards the integration of agent-based modeling into hydrology.

For practical reasons, the Buffelsrivier catchment, located in South Africa, was chosen. The Buffelsrivier is an ephemeral stream that is being researched within the WADE - project of the European Union.

The investigations that have been carried out so far, substantiate the assumption that phreatic plants have a significant impact on the hydrological processes and on the water balance of the study area.

The aim of this work is to study the influence of phreatophytes at a subarea of the Buffelsrivier catchment. This will be done by implementing a coupled model that includes both the groundwater system and the phreatic vegetation.

2 Motivation and Objectives

This work is part of the European Union project WADE, which is integrated in the Sixth EU Framework Programme "Global Change and Ecosystems". WADE means "Flood**W**ater Recharge of Alluvial **A**quifers in **D**ryland **E**nvironments". The project aims to asses the long term water resources of four semiarid to hyperarid catchments, located in Israel, Namibia, Spain and South Africa. Specific attention is turned on the role of groundwater within the water balance. Thus a major concern is to understand and quantify the mechanisms of groundwater genesis and depletion.

It is assumed that the soil evaporation and the transpiration of riparian vegetation have significant influence on the groundwater balance.

A previous thesis by Wachtler (2006), investigated the average annual groundwater recharge at different places of the catchment. Several methods had been used in order to eliminate errors and to achieve accurate values. The recharge activities mainly occurred at the river alluvium. This had been found out by isotopic methods. The estimated values, resulting from 0.7 to 5 mm per annum for the overall catchment, were put into a numerical groundwater model (VisualModflow) for validation (Wachtler, 2006).

The application of the groundwater model showed that different recharge rates resulted in a similar model output (Wachtler, 2006). The boundary conditions allowed inflow from one edge, only. An assumed inflow from three boundaries, for a given recharge rate of 1 mm/a on the tributary areas, would have led to overflow of the aquifer and thus to surface runoff. The outcome lead to the conclusion that the increased water use by phreatic vegetation could be responsible for the problems that came up with the groundwater model calibration (Külls, 2006).

To determine the impact that phreatophytes have on the water balance of the model area that was described by Wachtler (2006), the following objectives for this thesis were defined:

- the investigation of the mechanisms of vegetation and groundwater interaction, especially by riparian phreatophytes, based on a literature review,
- the development of a groundwater-vegetation model by using agents to represent the groundwater using plants,
- the application of the model to the study area within the Buffelsrivier catchment,
- and the assessment of a quantitative water balance.

3 Vegetation and the hydrological cycle

A single tree evaporates up to several hundred liters per day during the vegetation period. Drawn down on the captured surface the number seems much smaller. Under humid conditions vegetation is mainly influenced by available space and the presence of nutrients. Usually, in humid climes, the replenishment of water lies above the demand of the consumers. This keeps the rivers flowing and the groundwater levels high. From another point of view, the supply of water determines how the dependents develop or behave. A change in climate or in human landuse naturally has an effect on flora and fauna.

3.1 Impacts of vegetation on hydrological processes

In Hydrology and Meteorology vegetation is usually associated with interception and transpiration, first. Plants prevent precipitation from reaching the ground. Contrarily, they enforce infiltration by retaining the throughfall from surface runoff. At this point it is not just the constitution of the soil that defines the amount of percolation. It is also the vegetation's current demand that has an influence.Hence, pertaining to the meso-scale, it can be conjectured that without biota, transmissions towards the aquifer and the river channel would be certainly different.

However, the influence of plants on aquifers and river channels on the short-scale is difficult to determine and quantify. This is because of the inhomogeneous distribution of type and age, the complex interplay of individuals and communities and the small quantity in the whole system. From a measured hydrograph the vegetation's influence cannot be quantified although the information should logically be contained within it. One way of exploring the control factors of a system or a system's output is to analyze the complexity or information content of measured timeseries.

Hauhs *et al.* (2005) compared measured and modeled runoff timeseries with daily resolution, using methods of information theory. The results showed that artificial time series, generated by deterministic or stochastic approaches, never reached a similar level of information content and complexity. Hence, it can be conjectured that some unaccounted nonlinear factors exist. Complex interactions as the biota's competition for water and nutrients could cause such nonlinear interactions.

Vegetation influences climate on different scales. For instance, an increase in vegetation is negatively linked to albedo and temperature. Lower temperatures at constant radiation input are the effect of increased evapotranspiration. Higher evapotranspiration again leads to a surplus in air humidity and thus results in enhanced precipitation. And accordingly, a plus in precipitation betters the conditions for vegetation (Phillips, 1993; Ripley, 1976).

The ways, that vegetation interacts with hydrological processes are numerous. In the following, the focus is on riparian vegetation and phreatic plants in semiarid and arid environments.

Riparian vegetation

At ephemeral streams, the riparian vegetation has to cope with several contrarious circumstances. The plants face irregular flow, ranging from drought to flood. For accommodation,

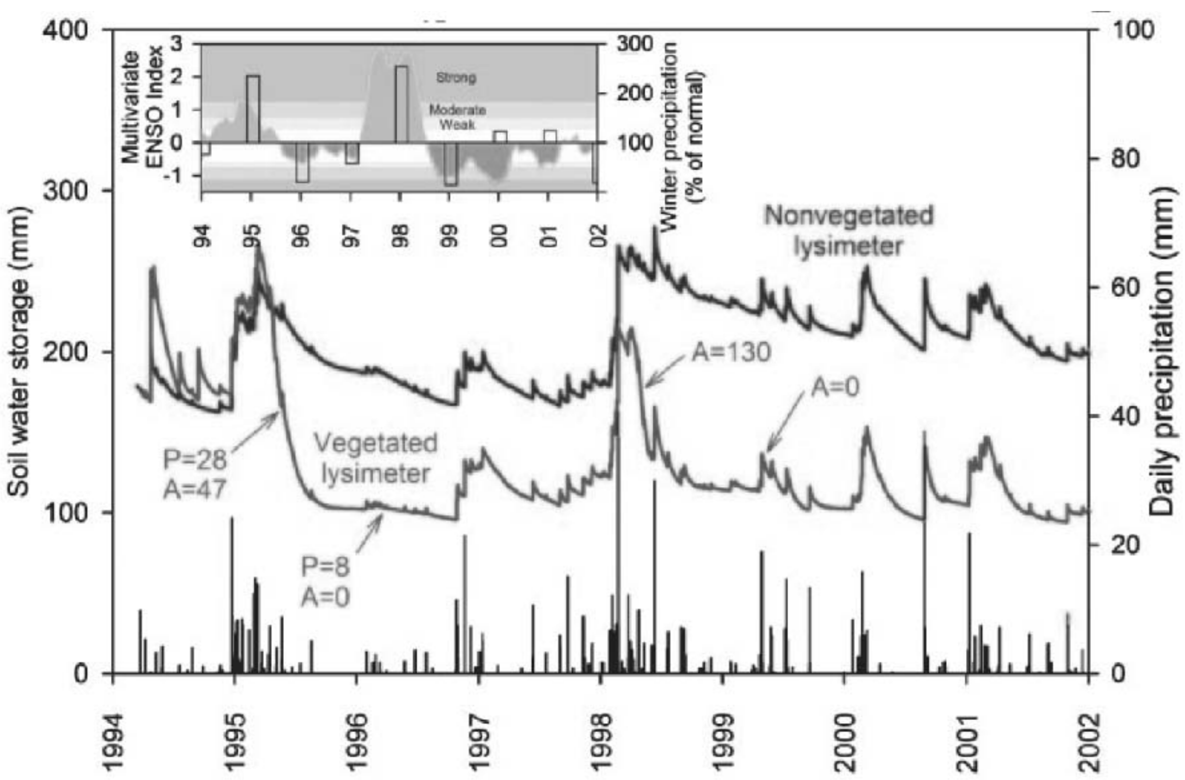

Figure 3.1: Influence of vegetation on soil moisture in deserts (Scanlon *et al.*, 2005).

species developed individual strategies to survive. Access to groundwater is an advantage here. Taproots of trees like *acacia* are able to reach depths of 60 meters. Additionally, some shrub species tap shallow aquifers but also live on soil water from infiltration and capillar fringe. According to Le Maitre *et al.* (1999), deep root systems play a significant role in South Africa's ecosystems.

The establishment of plant communities along the river channels has substantial influence on soil water processes. The root channels can cause preferential flow. Because of transpirational water use, the amount of percolating water is reduced. Evaporative discharge from the saturated zone can lower the piezometric surface (Le Maitre *et al.*, 1999). If runoff occurs, more water is likely to infiltrate due to increased surface roughness. In contrast, as Scanlon *et al.* (2005) discovered (see also next paragraph), vegetated soils in dry environments retard water from percolation and thus decrease the amount of groundwater recharge. Bowie *et al.* (1968) showed that the eradication of riparian vegetation significantly "reduced water losses that resulted from evapotranspiration".

Vegetation in arid environments

Scanlon *et al.* (2005) compared the water contents of vegetated and non-vegetated soils in deserts. The results, shown in figure 3.1, indicate that vegetated soils in deserts have a generally lower soil water content than nonvegetated. Even strong winter precipitation of El Niño in 1998 could not fill the water storage to an extent similar to the areas with no vegetation. This behavior implicates a reduced tendency of percolation. For the first years of the times series, the values are quite similar. This is because the plants were newly cropped and thus roots were not developed well. From the middle of 1995 the influence becomes obvious. The subsurface flow is now regulated by the vegetation. The process of controlling subsurface water flux has been noticed for booth, point and regional scale. Soil water storage and vegetation have a feedback relationship. The soil water content is as well a function of vegetation composition as vegetation is a function of soil moisture.

3.2 Water use by plants and regulating factors

Physiology of water uptake

As for almost every living creature, water is the substantial element for the existence and persistence of plants. It holds the solved nutrients for the cells and donates protons during photosynthesis. Additionally, the exchange of water is substantial for the temperature balance (Sitte *et al.*, 1998).

Water uptake into cells is generally driven by diffusion. In dry or dead parts of plants only the gradient caused by hydration of dipoles is crucial. Vital cells balance their water demand by osmosis through a semipermeable membrane. The cormophytes observed here (higher plants with stem and root system) draw their water from the soil or groundwater, predominantly.

To withdraw water from the underground, the osmotic potential of the roots must exceed the soil matrix potential. The osmotic potential increases with elevating solute concentrations of cells. If a plant cannot compensate the matrix potential, it reaches its wilting point. In order to minimize the effort needed for water uptake, the roots grow in the direction of better conditions. In some cases, roots can return water to the soil. This effect, where water from deep wet layers is transported to drier areas, is termed *hydraulic lift* (Sitte *et al.*, 1998).

The upward transport of water is induced by a large gradient between the soil water potential and the vapor pressure deficit of the air. Cormophytes use this transpirational pull to lead the water stream through their bodies. No metabolic effort by the plants is required. For a rapid fluxion, the stream is channeled through the cells of the xylem. These sclerotic cells are open at two sides and thus well interconnected. The water flux is unhindered and the water column is always connected. If the connection of such a vascular bundle is interrupted once, it cannot be restored(Sitte *et al.*, 1998).

The release of water or water vapor into the atmosphere is termed as transpiration. Transpiration occurs at all outside cells. Usually, the higher plants have a low transpiration through stem and leaf surface. Stomata and lenticells are specially developed cells that control the transpiration, depending on a plant's actual demand (Sitte *et al.*, 1998). Over 90 percent of total transpiration is accounted to stomata, less than 10 percent to cuticles. The limiting effect of stomata aperture on transpiration intensity is only potent at strong airflow (Schopfer & Brennicke, 1999).

During the day the amount of water uptake and release can differ. Usually, by day more water is used than replenished. By night the storage is then refilled. Under scarce conditions the balance becomes negative. The plant has to compensate the lack of water by increasing the uptake from the soil or by reducing the transpiration through the stomata. This state is referred to as water stress (Sitte *et al.*, 1998). About 10 percent of the water taken up from soil are effectively used. 25 percent are emitted by guttation. The remaining water is subject to transpiration (Schopfer & Brennicke, 1999).

Water use dependencies

Soil moisture, and therewith water availability, is a basic control factor of transpiration. If the atmosphere's vapor pressure deficit becomes equal to the matrix water potential, the transpirational pull between soil and air will become zero.

The amount of transpiration is also associated with the morphology of a plant or species. Leaf surface, that is a function of age and root configuration are positively linked with the amount of water used.

The effect of air temperature on transpiration is twofold. On the one hand, higher air temperatures lead to a stronger vapor pressure deficit and thus increase the intensity of the transpirational pull and with it the possible water flux, presumed a sufficient supply. On the other hand, increased temperature can lead to water stress and therefore cause faster wilting of plants which will generally reduce transpiration.

Other factors that influence the intensity of transpirational water use are windspeed and radiation.

Water use by riparian vegetation

Only a few percents of riparian plant water uptake are likely to come from direct interception. The major part is taken from soil moisure and groundwater. (Tabacchi *et al.*, 2000). In riparian ecosystems, where streams are ephemeral and the soil is wetted irregularly, older trees can be exclusively linked to groundwater (Dawson & Ehleringer, 1991).

According to Penka (1991), about 10 percent of riparian potential evapotranspiration belongs to the shrub layer. Trees account up to 90 percent of PET.

Schmidt (2003) analyzed what factors influenced wateruse of *Tamarix spp.* (saltcedar), a common riparian halophyte shrub. The study showed that an increase in "depth to the water table was the major factor that decreased saltcedar growth and water use" for the seasonal scale. Increasing salinity only slightly reduced water uptake. The timing of the diurnal rhythm of transpiration "seems to be site and season specific".

Response of vegetation to changes in water supply

For the majority of riparian fauna groundwater is the essential source of water supply. Hence, these ecosystems are strongly sensitive to diminishing water levels. A study in the semiarid floodplane of San Pedro River, Arizona showed that increased depth to groundwater is likely to result in partial desertification and in the decline of biodiversity (Stromberg *et al.*, 1996).

Species that are able to cope with South Africa's dry conditions usually have deep root systems. Even three year old *Eucalyptus grandis* trees had sinker roots of eight meters length. Although, a significant portion of water is taken from the vadose zone, the plants

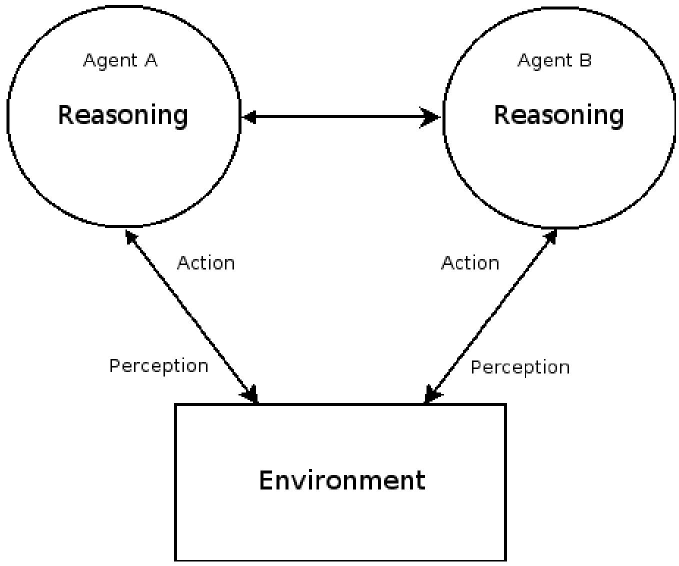

Figure 3.2: Scheme of two agents and their interactions (after Jannsen (2005)).

could not survive without groundwater, even if the upper layer had enough water content. Phreatophytes (plants that use water from the saturated zone) are well adapted to fluctuations of water tables. Only if the hydraulic heads drop faster than the plants can follow with their roots, the species become sensitive to dry conditions. Sudden changes in water levels may cause partial or complete mortality of riparian trees. Therefore, "deep root systems are pervasive and play key roles in ecosystem functioning and in water and nutrient fluxes. "In turn, "[...] changes in vegetation alter both recharge rates and water-table depths. "Le Maitre *et al.* (1999).

3.3 Modeling vegetation aquifer interaction

As a conclusion of the above, the system vegetation - soil - groundwater is complex and interconnected. Plants are, unless in human monocultures, spatial variable. Hence, modeling riparian phreatophytes means to take into account their inhomogeneity and their dependencies on water availability.
Within the last years, a new approach in modeling is gaining popularity. Agent-based or individually based modeling offers the possibility of applying rules, that describe individual behavior, on single entities that act autonomous in a modeling framework. In the following paragraphs, the agent-based approach is introduced and concretized for plant agents.

3.3.1 Multi-Agent models in hydrology

Basics of Multi-Agent models
In the context of model theory the term *agent* has been used for various different meanings. Gunkel (2005) gives an overview of common approaches and definitions. As pointed out by Ferber (1999) "an agent is a physical or virtual entity, that is capable of acting in an environment" and that is "driven by a set of tendencies" or needs. The agent's "behavior

tends towards satisfying its objectives"or needs by implicating the momentary state of its environment. And so, it is "capable of perceiving its environment" , "possesses skills" and "resources of its own". Figure 3.2 shows the organization diagram of two agents in an environment.

A physical entity, for example, might be a human being in a social network or a robot in a factory. Software agents, like search engines in the internet are referred to as virtual entities (Gunkel, 2005).

After Wooldridge (2002), agents distinguish from objects by autonomous and flexible behavior. Also, they have one or multiple threads of control.
During their lifetime, agents continuously adapt to the actual state in trying to meet their objectives. Every agent decides by itself, without a third person's intervention, whether it should become active or not.

As the name implies, Multi-Agent Systems (MAS) are composed of a number of mutual self-acting agents. Every entity follows its goals. Therefore, it has to negotiate with and to compete against other entities. The system's behavior, if the model includes enough elements of unpredictability, is then a result of emergence and cannot be related to the functioning of a single agent (Gunkel, 2005).

Software implementation of multi-agent systems
From the view of implementation, agents can be seen as a kind of software abstraction like objects, methods and functions in object orientated programming.
The history of agent-based modeling reaches back to the time when artificial intelligence was introduced. The first programs came up by the middle of the 1980s. From the 1990s on, with the dispersion of object orientated programming, the application of MAS gained importance. This led to the development of a number of different implementations (Gunkel, 2005).

As visualized in figure 3.3, a typical approach of agent modeling tools is to put the agents on either a 2D grid or a continuous map. As the simulation begins, the agents start acting on the model space. For every timestep, they process their built in control structures. They can move around, explore, use and share or deal with resources after predefined rules. For the modeling result, several factors can be of interest. For example this can be the state or distribution of resources, the convenience of agents and so on. Practically, a model implementation usually consists of a minimum of three classes. One general class for controlling the model, a model space class that describes the model world and a class that defines the behavior of the agents.

The ***Re****coursive* ***P****orous* ***A****gent* ***S****imulation* ***T****oolkit* (Repast) is commonly used in multi-agent modeling. The open source software is hosted on sourceforge. The tool is recommended by Gunkel (2005) because of its flexibility to various problems and because it is actively developed. Hence, Repast was chosen as the modeling tool, used for the plant-agent model, developed within this thesis.

Use of Multi-Agent models in water sciences
For water resources research, the usefulness of multi-agent approaches has been evidenced

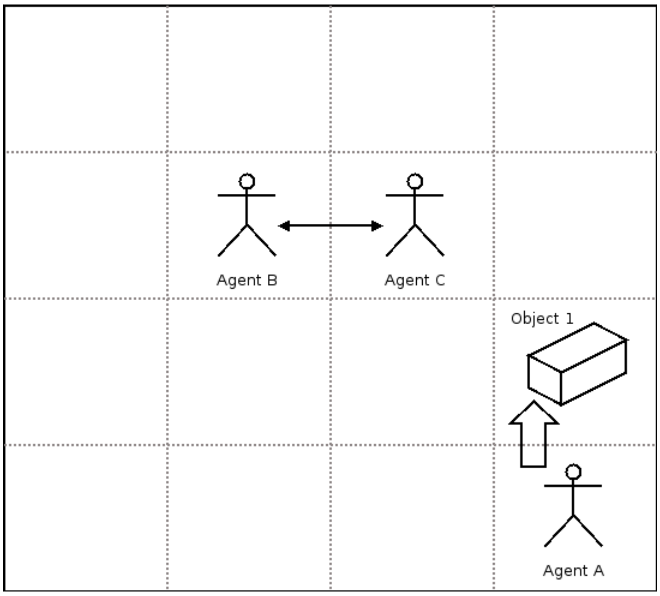

Figure 3.3: Typical multi-agent model setup. The agents are situated on a two-dimensional grid that represents the modeled world.

by numerous publications. Agents, that emulate water users or decision makers are used to represent social and socio-economic networks and patterns of actions. Urban water management, integrated natural resources management or integrated watershed management are typical fields of application where multi-agent systems can be used for decision support (Gunkel, 2005).

According to Gunkel (2005), the use of multi-agent models in hydrology is very sparse. The RIVAGE project (Servat *et al.*, 1999), is aimed at coupling runoff dynamics, infiltration and erosion by using a particle-based approach. Servat (2002) showed, that aboveground hydrological processes can be described as multi-agent systems of autonomous *waterballs* that move on a surface according to inclination and friction. Furthermore, multiple agents (waterballs) form joint entities. For example, in a local depression, the waterballs regroup in a pond. The same procedure exists for water streams. If necessary, the joined entities can be reconfigured into their waterball structure.

Unfortunately, this is the only approach to agent-based modeling of hydrological processes that can be found in the literature. There are no new publications, concerning the RIVAGE project.

A more common way of using multi-agent models in hydrology is to combine hydrological and multi-agent models. Thereby, an environment is built with the results of a hydrological model and agents are placed into this world. For every timestep the environment variables are recomputed. Hence the agents are situated in a realistic and changing world.

Within this thesis, a coupled approach is developed, using agents that emulate the riparian vegetation and a traditional groundwater model representing the environment for the plants.

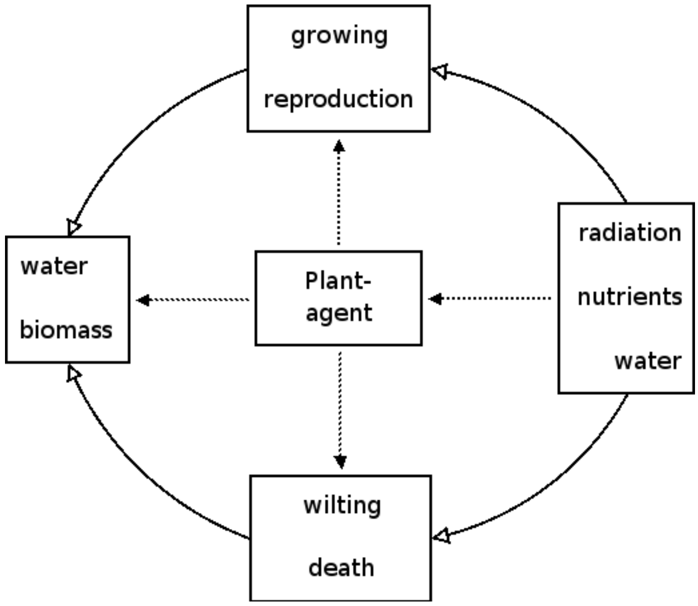

Figure 3.4: Scheme of a virtual plant-agent and the environmental variables that determine its state and behavior.

3.3.2 Individual-based models (IBMs) in ecology

Ecological systems can be understood as collections of unique individuals. Therefore, the characteristics of a system accrue from the properties and behaviors of its individuals. Different from entities, e.g. atoms or molecules, individuals are living organisms that grow, develop, change, reproduce and die. Usually, a system exists much longer than its single individuals (Grimm & Railsback, 2005).

Every individual is driven by the objective of successfully passing their genes to future generations. However, they only consider their own concerns and not the traits of the whole population. The adaptive characteristics of the single entities result in complex adaptive systems (CAS) in which emergent properties arise from the circular causalities of entities and from the condition of the environment (Grimm & Railsback, 2005).

The classical approach of modeling ecosystems, e.g. population levels, is to find differential equations that describe a system's behavior. However, even if the system could be reproduced well, there was no connection between individual properties and system characteristics. The individual-based modeling approach focuses on the coherence of individual traits and system dynamics (Grimm & Railsback, 2005).

From the theoretical point of view, individual-based models force a new paradigm that challenges the classical theory of population ecology. Pragmatically considered, "IBMs simply add a new tool to the toolbox of ecological modeling" (Grimm, 1999).

Plant-agent systems

Humans, animals and plants are likewise related to the resource water, although different concepts of taping exist. Because of their immobility the latter are reliant on a locally available source. Human and animals depend on water in varying but regular intervals.

Plants, given that they are well adapted to their environment, are able to survive over long periods of drought. Plants like humans are capable of exploiting subsurface resources. Animals, beside those living in soils or groundwater, depend on surface access to water.

Therefore, a plant can be described as a water consumer with the restriction of being unable to move directly. Movement or expansion is only possible indirectly, for example by reproduction. As illustrated in figure 3.4, a plant agent can be constructed as a consumer that takes up water and nutrients from the ground. Depending on the balance of matter and the supply of radiation energy , it produces, keeps or reduces biomass and emits water to the atmosphere.

Individual-based models of plants are generally simpler than models concerning animals or human beings. Plants are situated in a certain environment. Adaptation, for them, means coping with disturbances, soil conditions, weather extremes or water availability. The key concept in individual-based plant ecology refers to local competitive interaction. Animals, in contrast, have the ability to move. This results in completely different decision patterns and modes of adaptation (Grimm & Railsback, 2005).

Several plant IBMs have been developed in the past. For instance, forest models focus on long term species composition or the mechanisms of gap-filling in the canopy. Growth-yield models are used to manage e.g. timber production. Neighborhood models analyze the emergent properties of competition between individual plants and their surrounding opponents. (Grimm & Railsback, 2005).

Models that use plant-agents in combination with a groundwater model are lacking in literature. The impact of riparian vegetation on groundwater was ususally quantified by using water balance models (e.g. Bate & Walker (1991) and Bowie *et al.* (1968)) or field studies (e.g. Schmidt (2003)).

3.4 Conclusion

The influence of vegetation on the hydrological cycle is composed of many processes that lead to a highly complex interplay. Present hydrological models use general assumptions like evaporation and interception in order to describe the fauna's influence on water balance. As Hauhs *et al.* (2005) suggested, the use of agent based modeling could lead to a better involvement of vegetation's complex behavior into hydrological models.

Normally, in dry environments, vegetation has the strongest impact on the water balance. Plants that take their water from unsaturated soils retard water from percolation and keep the soil water storage at an elevated level compared to unvegetated soils. Phreatophytes, especially trees affect groundwater levels and sometimes salinity by their transpirational demand.

Plant species, morphology and age as well as temperature, humidity, wind, soil moisture or depth to groundwater are determining factors for the quantity of water that is used or needed by vegetation. A change in only one of these components can lead to significant changes in transpiration amounts.

Riparian vegetation rarely experiences water stress due to the accessibility of stream- or groundwater. Hence, the actual evapotranspiration mostly corresponds with the potential.

For the long-term, decreasing groundwater levels are a major threat to riparian ecosystems. In contrast, eradication of vegetation results in higher groundwater levels.

Agent-based or individual-based models are a novel way to deal with discrete consumers in the hydrological cycle. The approach of defining a framework, consisting of similar entities that follow all the same rules, provides an alternative way of bottom-up modeling that uses easily comprehensible assumptions.
Over the last ten years, this approach has gained popularity and its theoretical foundation was markedly strengthened (Grimm, 1999; Grimm & Railsback, 2005). Plant-agents can be seen as a logical consequence of real world settings.

In order to simulate the impact that riparian vegetation has at ephemeral streams, the agent-based approach seems to be a sophisticated way to emulate the adaptive traits of plants and their variability in space and time.

The method of combining a plant-agent model with a groundwater model has not been mentioned in the literature so far. Hence, no materials exist that could be useful for developing a coupled plant-agent-groundwater model.

4 Study area

4.1 Buffelsrivier South Africa

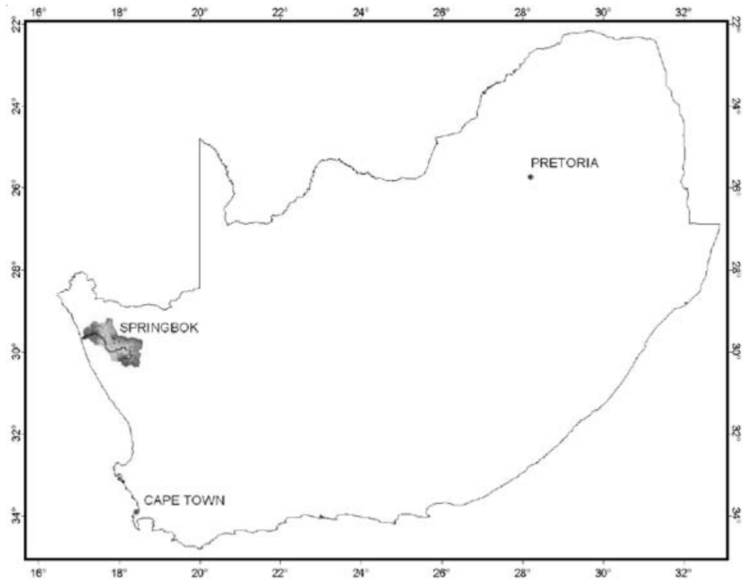

Figure 4.1: The Buffelsrivier catchment in South Africa (Wachtler, 2006).

The Buffelsrivier is one of the largest rivers in the northwest of South Africa. Ita catchment is located in the region of Namaqualand. It drains an area of over 9000 km^2 while it's elevation ranges from sea level to over 1000 meters height. The climate is generally semi-arid with rainfall occurring mainly in winter (May to August). Precipitation in the lower parts of the catchment lies around 90 mm/a. The mountainous upper part has up to 300 mm of annual rainfall, due to orographic effects (Wachtler, 2006; Titus *et al.*, 2002).
Figures 4.2 and 4.3 show the precipitation characteristics at the station Springbok that is located in the center of the catchment. The mean annual precipitation is 213 mm for the period from 1878 to 2003.

4.2 Geology, soils and aquifers

The catchments geology is dominated by crystalline bedrock and its weathering products. Beside the two dominating rock formations of granite and gneiss there are some sediments in the coastal area and a few locations of limestone and schist in the northern parts of the catchment. Figure 4.4 shows the different geologic zones. A more detailed overview on geological structures can be gleaned from Titus *et al.* (2002) and Adams *et al.* (2004).

Soils are nonexisting to shallow, in general sandy and in a few places they consist of loamy sands. River beds contain a variety of sandy and loamy substrates, ranging from coarse to fine.

The aquifers in the Namaqualand area can be subdivided into three, usually well connected, systems. Basement aquifers consist of fractured bedrock or weathered material (e.g.

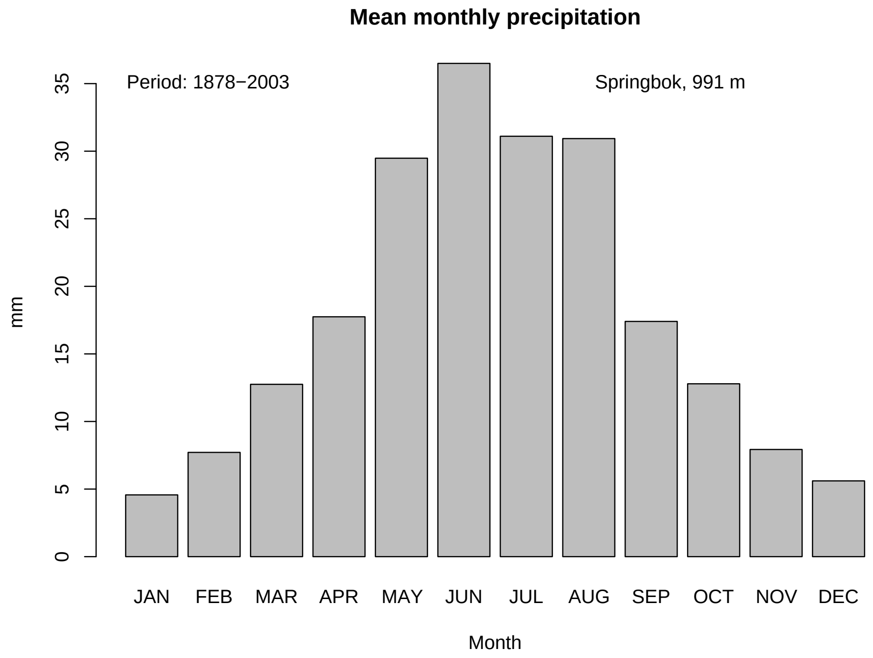

Figure 4.2: Mean monthly precipitation measured at the station Springbok. The measured period is 1878-2003.

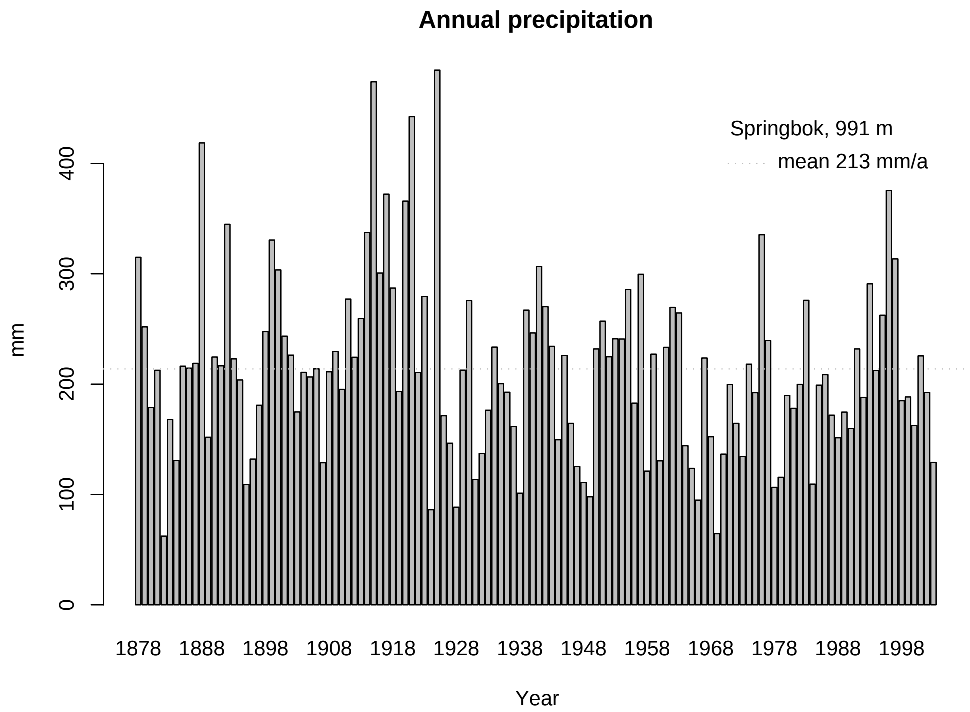

Figure 4.3: Annual precipitation recorded at the station Springbok.

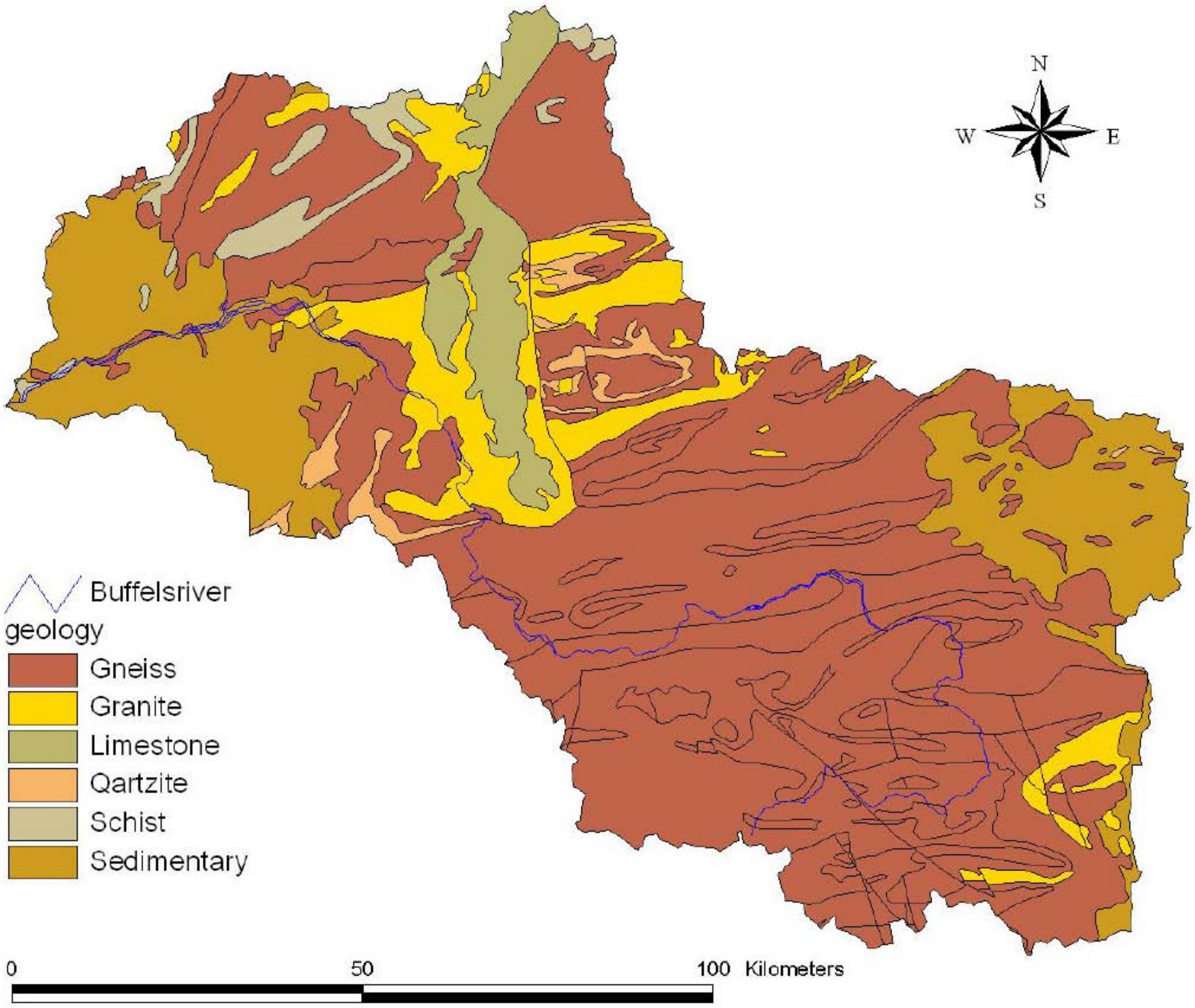

Figure 4.4: Geology of the Buffelsrivier catchment (Wachtler, 2006).

regolith). Normally, they are hydraulically interlinked, except from where extensive clay formations act as a barrier. The weathered zone aquifers have a high storage potential and thus are the donators for the recharge of the bedrock layer. Alluvial aquifers occur on coastal plains, along ephemeral rivers and at paleochannel sites. Usually the thickness ranges from 1-15 meters. During rainy periods they are efficiently recharged and under suitable conditions, percolation into deeper layers takes place. In the dry season, the groundwater draws back from the alluvium into the river channel banks (Adams *et al.*, 2004).

4.3 Groundwater system

The groundwater flow is generally orientated in a south north direction. Streaming velocities are low, approximately 0.5-3 meters per annum Adams *et al.* (2004). With increasing depths, the basement aquifers are supposed to become less conducting Külls (2006).
The mechanism of groundwater recharge is complex for this catchment, because of the altering surface conditions (geology, soils, topography, vegetation), the stratigraphy of the underground and the sporadic occurrence of precipitation. Wachtler (2006) investigated tritium concentrations of alluvial water samples. The data showed that the alluvial aquifer is mainly recharged by transmission losses from flood events. However, only some samples showed recent tritium values. A certain amount of tritium concentration was below recent levels, indicating an admixing of older water from deeper layers. Samples from the coastal plain and inactive reaches mostly lacked tritium. Thus, for those areas direct recharge is not assumed. The net recharge rate found for the catchment was 1 mm/a (Wachtler, 2006). The ratio between recharge and precipitation is very small because of high interception or evaporation losses and because of the bedrock structure of the catchment. Small amounts of rainfall will be evaporated. Greater quantities are likely to produce surface runoff as infiltration capacities of the bedrock are low. During runoff events water infiltrates into the river alluvium (transmission loss). Usually, at flood events, the alluvium is speedily filled up and no more water infiltrates. Thus, recharge rates are low, even if flooding takes place.
Figure 4.5 outlines the different zones in a typical cross section of the alluvial zone. The main river channel consist of sands, the adjacent overbanks are composed of deposited silt. Surface evaporation is limited to the amount replenished by capillary rise. Inspection in the field showed that capillary action occurs only to an extent of 20 cm in the sandy substrate and 150 cm in the silty overbanks (Külls, 2006). Hence, after flood events, the surface evaporation quickly decreases at the alluvium and evaporation in controlled by phreatophytes only.
As aerial photographs prove, phreatic vegetation typically occurs before riverbed constrictions due to backed up water and thicker deposits. Hence, most of the transpiration is narrowed to certain zones.

Although the potential evaporation is high, the actual evapotranspiration is low because of the sparse vegetation and the insufficient replenishment by capillary action. The low conductivity rates avoid an effective draining of groundwater. Hence, the water tables remain close under the alluvial surface and the system is considered to be almost saturated. Thus, minor precipitation events cause surface runoff. A complete removal of phreatic

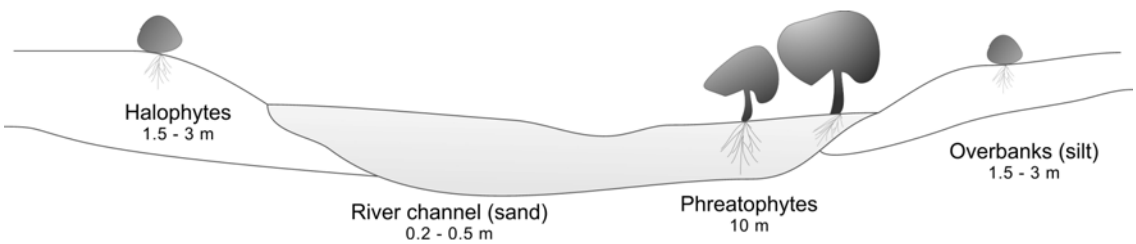

Figure 4.5: Maximum evaporation depths at the alluvium of the alluvium of the model area.

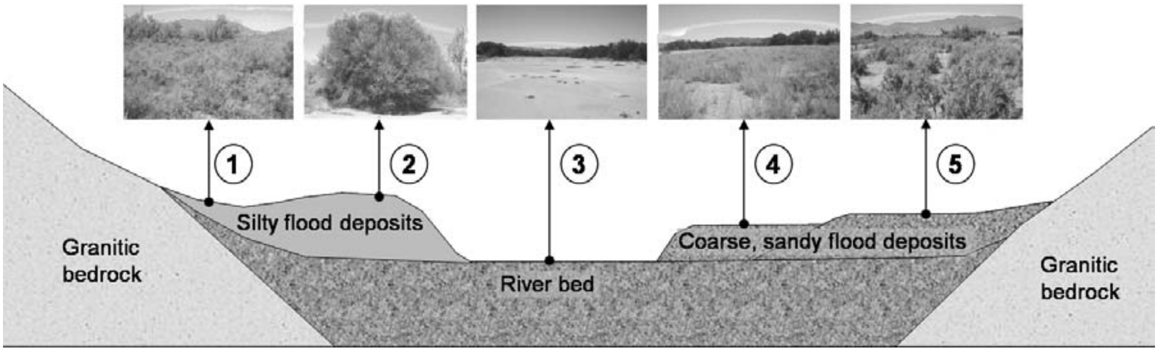

Figure 4.6: Habitats for different plant species at the alluvium of Buffelsrivier. (1) *Suaeda fruticosa, Tamarix usneoides*, (2) *Acacia karroo*, (3) *stream bed perennials*, (4) *Stipagrostis namaquensis*, (5) *Salsola aphylla.*

vegetation could lead to a raise in water levels and consequently to more frequent runoff events in the riverbed (Külls, 2006).
Photographic records from the beginning ot the 20th century revealed that soils were wetter in earlier times, so that wheat-cultivation was possible without irrigation (Külls, 2006). This also complies with the precipitation records displayed in figure 4.3, where, around the year 1918, a series of increased precipitation occurred.

4.4 Riparian vegetation

To a large extent, the riparian vegetation consists of five major species *Acacia karroo*, *tamarix usneoides*, *suaeda fruticosa*, *stipagrostis namaquensis* and *salsola aphylla*. *Acacia karroo*, that belongs to Mimosoideae, is the dominant tree in the area and forms large gallery forests at the river banks (Todd, 2005). It is fast growing (up to 15 m in height), frost- and drought-resistant. Because of its massive thorns it can't be used for grazing. Flowering is likely to occur several times during summer (Palgrave Coates, 1977). Defoliation has not been noted at the Buffelsrivier catchment. Another species that is able to reach groundwater is *tamarix usneoides*. Its size ranges from shrubs to medium sized trees, that are up to 10 meters in height. The plant usually grows on silty often hyper-saline flood deposits (Todd, 2005). Likewise, *suaeda fruticosa* is a common halophyte on saline soils. But usually, *suaeda f.* is not connected with the groundwater. *Stipagrostis namaquensis* and *salsola aphylla* prefer recently deposited, coarse sand banks. These species are dependent on soil moisture and are likely to become eroded during floods. Only a few plants are able to exist in the riverbed . Most of them are herbaceous annuals (Todd, 2005). Figure 4.6 introduces the important species that populate the alluvium of the Buffelsrivier and makes clear, where the different species settle.

The riparian phreatophytes don't vary much in age and size. Seedlings are rare. Hence, it seems that the riparian ecosystem develops slowly and that spreading of plants occurs only under certain conditions (Todd, 2005)..

Figures 4.7 and 4.8 give the mean diurnal water level variations in the alluvium of Buffelsrivier, at intensely vegetated areas. The records were made between December 2005 and

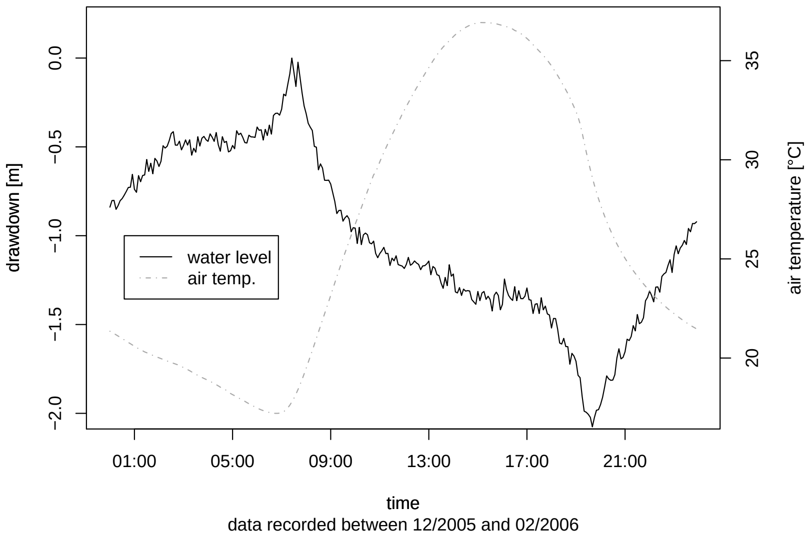

Figure 4.7: Mean diurnal relative water level changes at a vegetated site near the commune of Buffelsrivier.

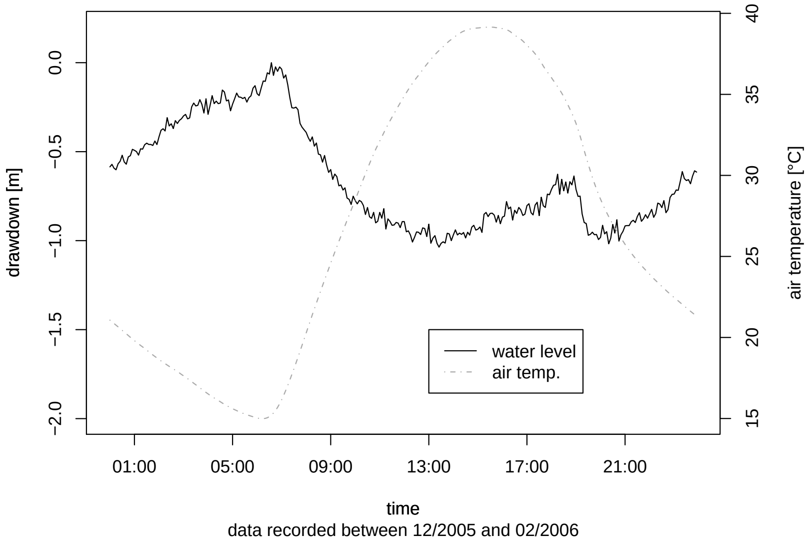

Figure 4.8: Mean diurnal relative water level changes at a vegetated site near the commune of Rooifontein.

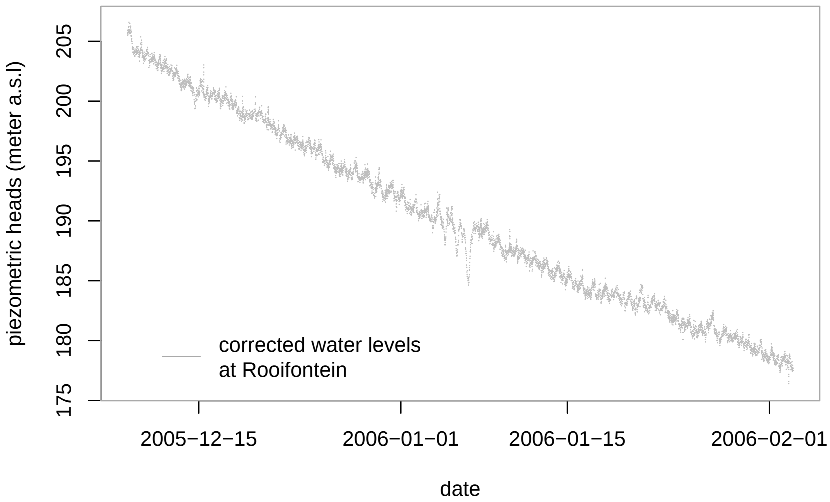

Figure 4.9: Absolute water level changes at a vegetated site near the commune of Rooifontein.

February 2006. Both graphics show remarkable changes during the day. However, it is not sure whether evapotranspiration is solely responsible for the amplitudes of level change. Especially the strong drawdown that can be recognized in figure 4.7 at 8pm, could be attributed to pumping for irrigation, as plants do not transpirate much at this time of the day. For both areas, the amplitude is about one meter.

The groundwater replenishment is delayed and takes place at night, predominantly. The relative drawdown varies for the two locations. This could be because of different aquifer properties (e.g. hydraulic conductivity or thickness of the alluvium). To demonstrate the amplitude of water level change the data have been detrended. Effectively, over the considered time period, the mean water level continuously decreased. This can be seen in figure 4.9. Due to the small storage capacity of the alluvial layer and because of the crystalline geology with low hydraulic conductivities and low flow rates, the water used by vegetation and pumping is not refilled promptly.
During the observation period, at Rooifontein, the water level decreased about 25-30 meters. As daily oscillations remain almost constant, no change in hydraulic conductivity is assumed. Hence, the water table should be located within the basement aquifer. The low effective porosity of the basement aquifer could be an explanation for the measured amplitudes and the long term trend, because a minor withdrawal of water leads to significant head changes. But all in all, the missing information on pumping activities prevents a clear conclusion.

4.5 Landuse

Most of the area of the Buffelsrivier catchment is used for farming and livestock breeding. Additionally, two natural reserves exist. The land around greater residential areas belongs to the communes (Wachtler, 2006).

4.6 Conclusion

The Buffelsrivier catchment has semiarid conditions with an inhomogeneous distribution of rainfall and thus groundwater recharge. Its geology is mainly composed of crystalline rock. The alluvium consists of mainly sands and silty deposits. The aquifers can be subdivided into the three major zones: alluvium, weathered zone and bedrock. Most notably, groundwater recharge takes place in the riverbed and river alluvium. Surface evaporation is restricted to an amount that can be replenished by capillary rise. Plants have a much higher potential for vertical discharge of groundwater, because they can withdraw it from the whole thickness of the alluvial layer and sometimes even from the basement aquifer. Phreatophytes are principally restricted to the alluvial zone. Within this zone, they appear mainly at certain spots that correlate mostly with geological or morphological factors. The remaining catchment areas are vegetated with shallow rooting plants that usually don't use groundwater.

Hence, to simulate the water use by phreatophytes, the configuration of the alluvium, the deep rooting plants pertaining to it and the behavior of the saturated zone must be taken into account. For this reason, a coupled approach has been developed, bringing together a vegetation and a groundwater model. In the following section, the modeling approach will be described.

5 Vegetation-aquifer model Buffelsrivier

5.1 Modeling concept

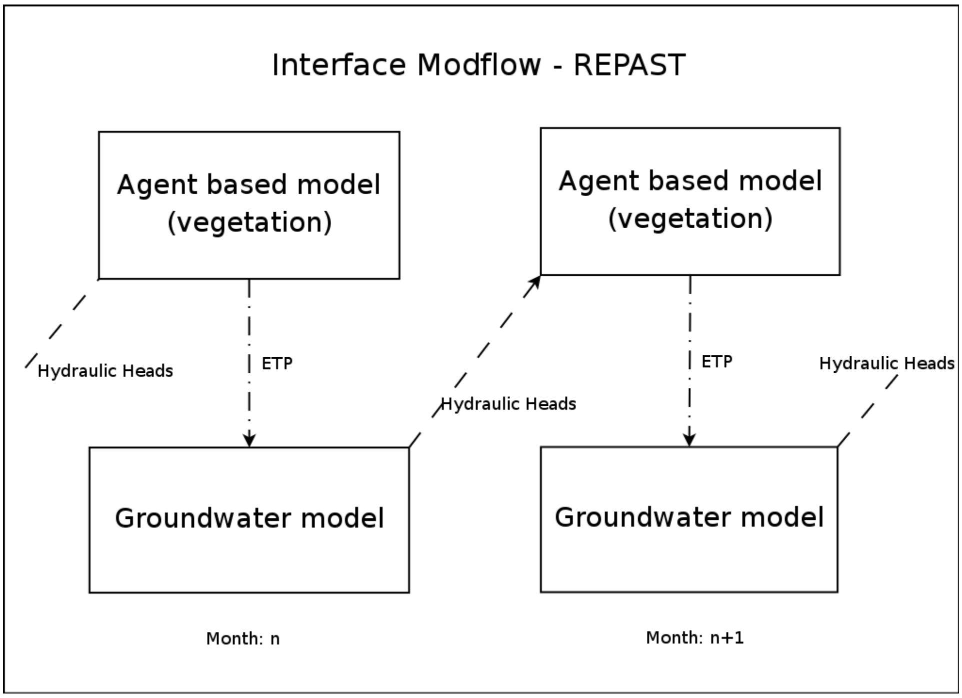

Figure 5.1: Conceptual model of the riparian vegetation-groundwater system.

The model, developed in the course of this thesis, is aimed at assessing the amount of riparian-induced evapotranspiration, taking effect on the groundwater system in a semiarid environment. To achieve an appropriate simulation of the interacting system, groundwater and vegetation were considered and realized as single systems, oppositely depending. The groundwater flow and the water levels of the aquifer was patterned using the standard finite elements model of the USGS, Modflow96 (Mc Donald & Harbaugh, 1988).
The model of the phreatic vegetation was set up as a multi agent system within REPAST (North *et al.*, 2006), a multi agent modeling tool. This allows the definition of the plant parameters in a bottom up way and thus the use of simple rules for describing the vegetation. A detailed description of the two models can be found below.

Figure 5.1 shows the conceptual model of how the two systems interact. The hydraulic heads influence the water uptake by the phreatophytes. The water, transpirated by the phreatic vegetation, is directly being taken from the bottom of the alluvial aquifer, causing a decrease in water tables. Modeling the vegetation with the spatially heterogeneous multi agent approach leads to an detailed and differentiated estimation of evapotranspiration parameters for the groundwater model. In turn, the groundwater model is used for computing the hydraulic heads.

Riparian ecosystems have a rather complex composition of different vegetation types. Some plants are connected to the ground water, others withdraw water from soils, only. The

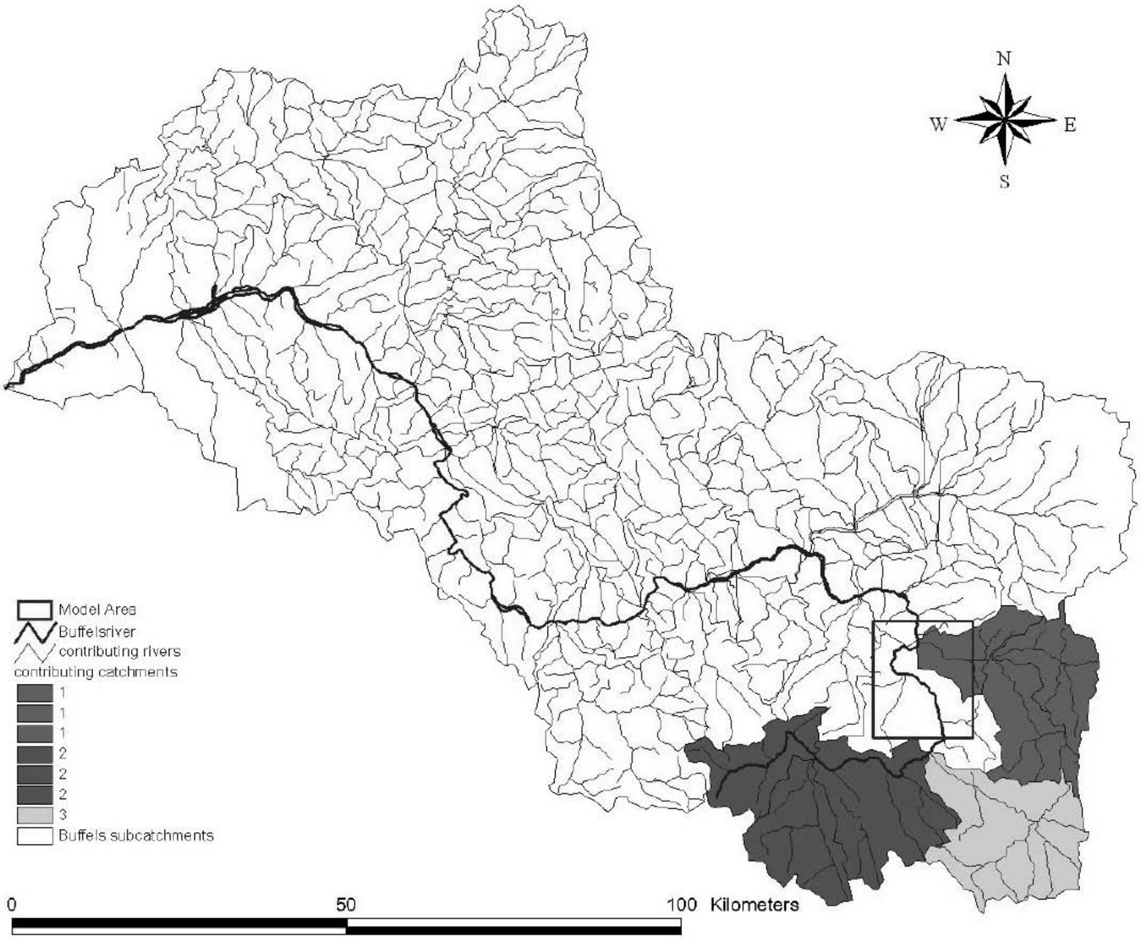

Figure 5.2: Location of the model area within the Buffelsrivier catchment (Wachtler, 2006).

latter are considered of being important to the process of groundwater recharge. However, depletion of underground water ressources is only affected by phreatophytes and by humans. The above-mentioned, measured net groundwater recharge rates already include the water use of soil water using plants. Hence, for understanding the budget of the groundwater system, only the deep tapping vegetation is relevant. For this reason, the model excludes the processes of the unsaturated zone. Intrinsically, it is not the total evapotranspiration that is examined within this thesis. Only the re-evaporation or re-evapotranspiration of already regenerated groundwater is considered here. Thus, the term evaporation (evapotranspiration) is tantamount to re-evaporation (re-evapotranspiration), henceforth.

The modeling area (figure 5.2) is located in the upper part of the Buffelsrivier catchment and had been chosen in dependence on the groundwater model, realized by Wachtler (2006). Several properties have been adopted. Therefore, the model has a dimension of 12.44 km x 16.92 km (210 km^2), which is approximately two percent of the whole catchment's area. Located within are the two communes of Kammassies and Roifontain, that are small farming villages.

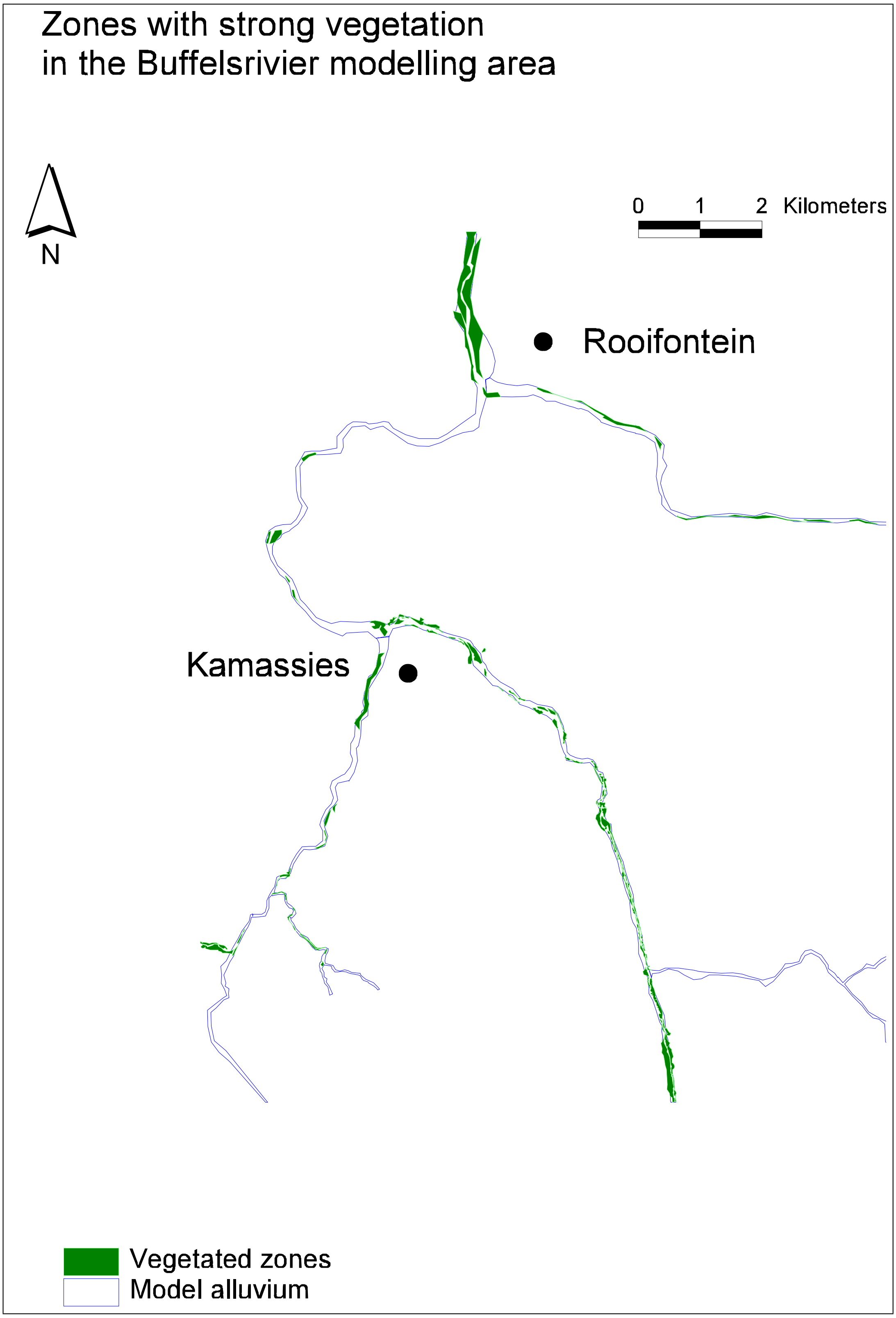

Figure 5.3: River alluvium and vegetated zones of the model area.

5.2 Groundwater model

General settings
A previous groundwater model had been set up by Wachtler (2006). It was used to verify groundwater recharge rates determined by various methods. Problems occurred during the model's calibration. Several parameter combinations resulted in a successful model run, although some of them were unrealistic. When the estimated groundwater recharge rate of 1 mm/a was used the evapotranspiration (ETP) parameter became less sensitive.

The extended groundwater model adopts the principal structure and some initial parameters as grid size, number of layers, hydraulic conductivity and recharge rates. Changes were made on boundary conditions and the spatial distribution of recharge and ETP rates. For a better usability the model was set up using Processing Modflow for Windows (PMWIN 5.3.0) (Wen-Hsing & Kinzelbach, 2005). In comparison to Waterloo's Visual Modflow (3.1) where settings are stored in nested zipfiles, with PMWIN it was easier to manually change parameters of single cells or cell groups. The input files used by this software are in pure ASCII format and thus easily editable.

Figure 5.3 gives an overview of the model area. For simulation, it is split up into two layers of different properties. Both of them contain 311x423 squared cells of 40 meters edge length. Thus the model area has 210.5 km^3, 12,440 m in width and 16,920 m in length (flow direction). The upper layer (layer 1) represents riverbed and alluvium, consisting of sandy deposits. The underlying layer (layer 2) is configured as solid rock consisting of a low permeable granite. For the model, the thickness of the aquifer has been narrowed to approximately 300 meters. For both layers, the underground is assumed to be homogeneous and isotropic. Physically based parameters like hydraulic conductivity, porosity and storage coefficient had been taken from Titus *et al.* (2002) and are listed in table 5.2.
Table 5.1 specifies the volumes of the two layers in the model area and their maximum storage capacity. As the values show, the basement aquifer contains only five times more water than the alluvial aquifer, although it's extent is 1400 times larger. In case of withdrawal the water table is supposed to drop rapidly, since lateral influx is inhibited because of the low hydraulic conductivities.

The fact that the model area is not a self-contained subbasin makes it necessary to define surrounding boundary conditions. In order to achieve an appropriate solution of the numerical equations, at least one boundary should be fixed. The lower (northern) boundary at the outlet is defined as constant head, meaning that the water level is predefined and thus not calculated by Modflow. The remaining three sides are defined by general head boundaries. Here, the water flux is dependent on the gradient between the calculated hydraulic head of a cell and a point of known distance and water level outside the model space.
For recharge an annual amount of 1 mm was assumed, according to Wachtler (2006). Field

Table 5.1: Aquifer volumes and absolute water contents in m^3 for the model area.

alluvium	water alluvium	basement	water basement
47,266,900	11,816,700	65,140,350,600	65,140,300

Table 5.2: Parameters of the steady-state groundwater model.

parameter	bottom layer	top layer	river alluvium	unit
horizontal hydraulic conductivity	$1.014 \cdot 10^{-7}$	$1.014 \cdot 10^{-7}$	$0.5 \cdot 10^{-05}$	m/s
vertical hydraulic conductivity	$1.014 \cdot 10^{-7}$	$1.014 \cdot 10^{-7}$	$0.5 \cdot 10^{-05}$	m/s
storage coefficient	0.01	0.01	0.25	%
recharge	0.359	0.359	25.8	mm/a
evapotranspiration (evt)	-	-	31	mm/a
evt extinction depth	-	-	1.2	m
evt surface	-	-	0.5	
well Kamassis	-40	-	-	m^3/d
well Roifontain	-30	-	-	m^3/d

investigations (Adams *et al.*, 2004; Titus *et al.*, 2002; Wachtler, 2006) showed that recharge primarily occurs at the river alluvium during flooding. Hence, the total recharge rate is split up on / over the alluvium and the remaining model area by a certain ratio.
Surface evaporation is generally low for the alluvium because of the low extinction depth and the lack of the bedrock surface layers. Transpirational losses rely mainly on phreatic vegetation that is able to withdraw water from greater depths. On that account, the phreatophytes were mapped from air photographs and parametrized using the agent model. A detailed matrix of maximum evapotranspiration, extinction depth and evaporation surface, depending on surface and vegetation compositions, provides the values for the individual cells of the groundwater model.
At the model area, two pumping wells are used for water supply. One belongs to the commune of Kamassies and the other to Roifontain, respectively. The daily pumping rates average 30 to 40 m^3.

Steady-state calibration

As the coupled model is set up in a transient mode it needs appropriate starting hydraulic heads. Therefore, Modflow96 is configured in steady-state mode. Table 5.2 contains the parameters used for the model.
For calibration the estimated amount of 1mm recharge per year, found by Wachtler (2006),

Table 5.3: Water balance of the calibrated steady-state groundwater model in m^3/a.

parameter	recharge	evt	ghb	constant head	wells	sum
input m^3	209545	0	49636	0	0	259181
output m^3	0	164325	12	69276	25568	259181

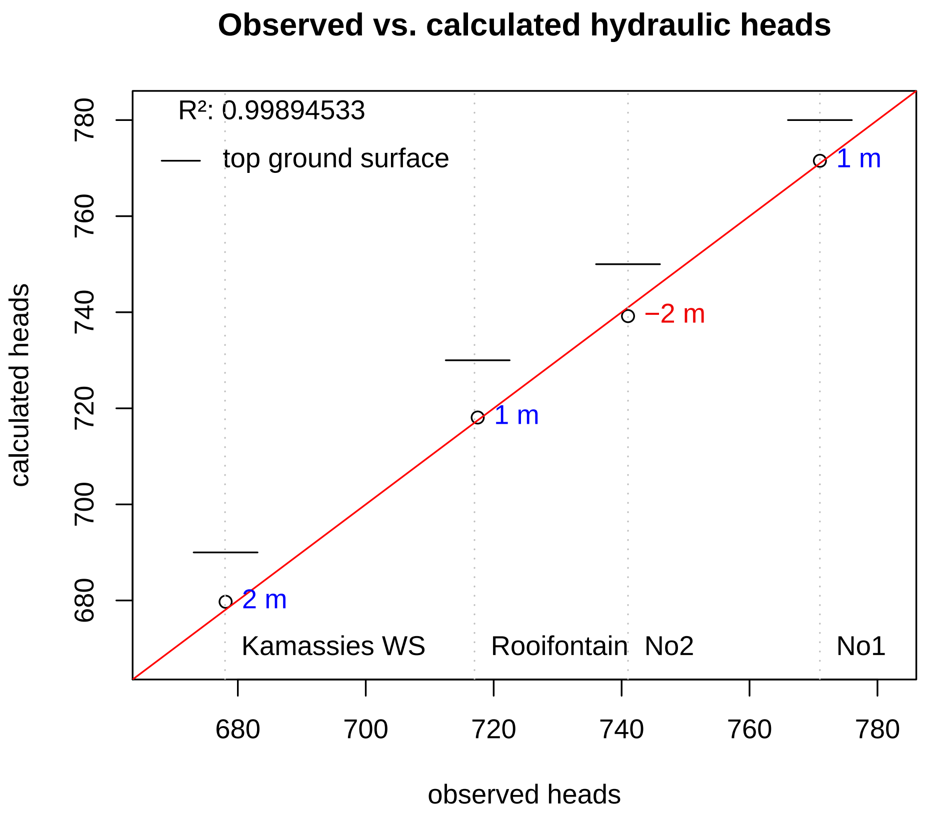

Figure 5.4: Calibration results, observed versus calculated hydraulic heads.

was distributed among alluvium (65%) and the remaining area (35%).
The attempt to draw evaporation from the alluvium of the top layer was unsuccessful. Above a certain maximum evaporation rate the alluvial cells became dry during Modflow's solving process. Thereby, the water replenishment by the underlying cells was cut off and the water table of the bottom layer rose over the surface elevation level of the top layer. This problem is reasoned in the architecture of Modflow. Cells that became dry during an iteration in the solving process cannot be wetted again and thus remain dry for the whole stress period. Within Modflow96 the Wetting Capability Package can be used to evade this problem. The package defines a threshold (water table) above which a cell will be re-wetted within the iteration process. However, the application of a Wetting Capability failed for the here described model because the solver didn't converge. Hence, in order to obtain a coherent model balance, evaporation is drawn from the second layer. Logically, evaporation from the second layer can be reasoned by assuming phreatic plants to be the consumers. Of course, for the transient model application where evaporation is distributed among surface and plants, the surface evaporation must be restricted to a certain upper limit.

The evaporation (maximum evaporation) and recharge ratio (alluvium/field) parameters were varied until the lowest discrepancy, compared to observed water levels, was achieved. Figure 5.4 contains the goodness of fit between the measured and the modeled (calculated)

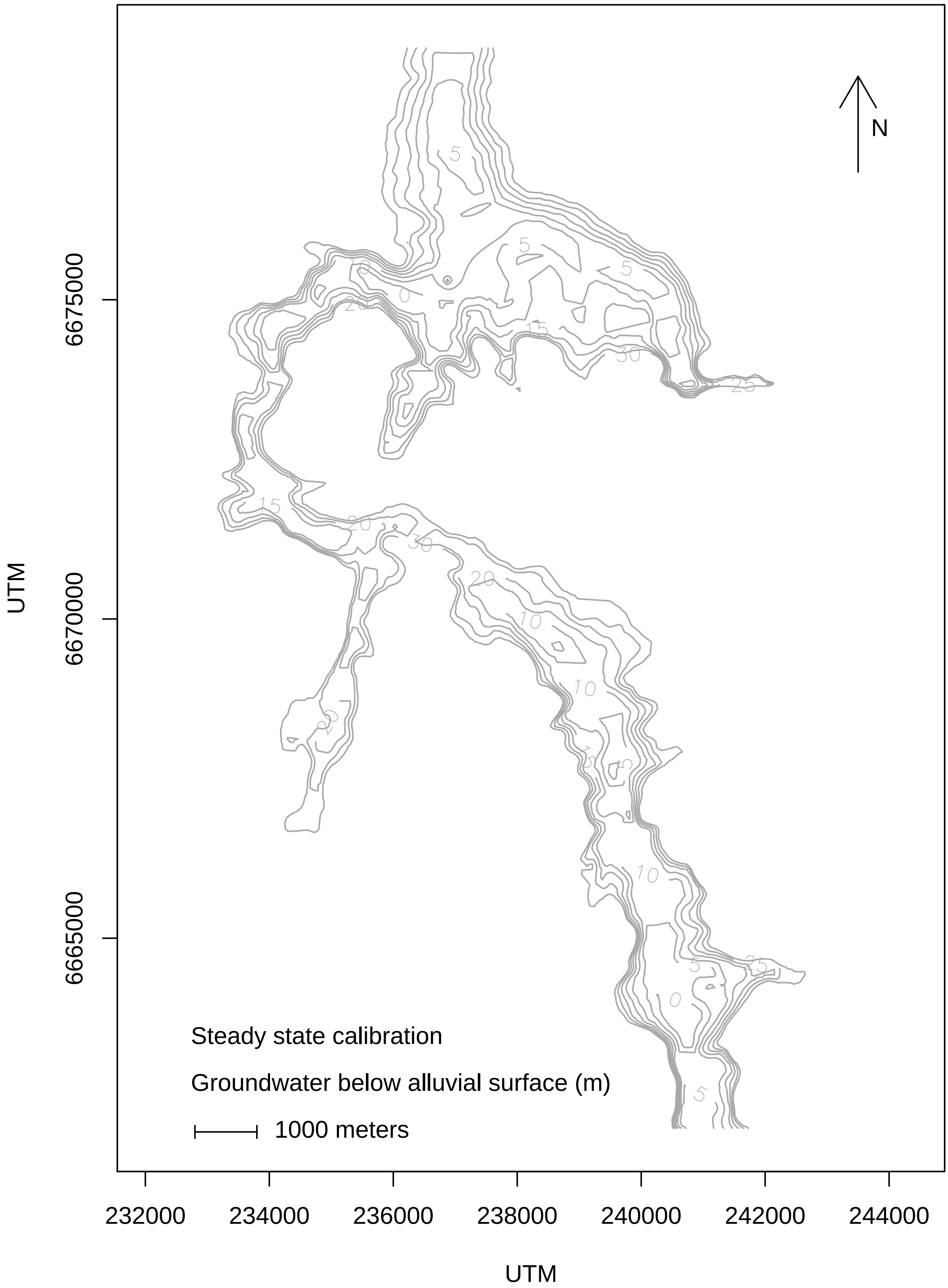

Figure 5.5: Distance between top level surface and groundwater table for the alluvium of the model area.

hydraulic heads. Regrettably, only four values were available for calibration.
The model budget is listed in table 5.3. The input of the model is dominated by recharge. The output by evaporation. Inflow at the upper and outflow at the lower boundary have virtually the same size. Only a minor part of recharge leaves the model area through the aquifer. The major part is re-evaporated.
Considering Darcy's law for calculating laminar flow in a porous unconfined aquifer (equation 1), the amount of throughput between the model boundaries is in sound dimensions. For $k_f = 1.014 \cdot 10^{-7}$ m/s, A = 12440 m · 200 m and i = 0.01, the resulting discharge is approximately 79,000 m^3/a compared to the constant head boundary outflow of 69276 m^3/a.

$$Q = k_f * A * i \tag{1}$$

Q	rate of flow(m^3/s)
k_f	hydraulic conductivity (m/s)
A	flow area (m^2)
i	slope / hydraulic potential (-)

The steady state calibration represents mean annual conditions for the modeling area. The horizontal bars in figure 5.4 describe the top ground surface at the respective boreholes. The annual variation of the groundwater table is assumed to range between a few meters under the surface and several meters under the calibrated state.

For the river alluvium, figure 5.5 shows the depths to the groundwater table, as calculated by the initial run. The graph nicely reveals the assumed pool and riffle structure of the carved river channel in the upper model area, where groundwater depths range between five and ten meters. The area northerly from UTM 6675000 has rather low depths to the water table. In this region, phreatic vegetation is strongly present. The pumping well from the commune Roifontain is located here, too. In the middle section of figure 5.5, ahead of the curvature of the riverbed, relatively high distances to the water level occur. The fact, that this area is well vegetated leads to the assumption, that the calibration does not match the real situation. It could be that the alluvial layer is actually deeper than the hypothesized ten meters, so that plants can withdraw water from depths of 30 meters. Another possibility to cause the difficulty could be a change in the hydraulic conductivity of the basement aquifer, resulting in increasing water tables. Altogether, the contours in figure 5.5 comply with the course of the main river bed of the Buffelsrivier. Therefore, and in reference to the graph in figure 5.4 it is assumed that the steady state calibrated model has the capability to simulate the model in an appropriate way.

Transient model configuration
As above-mentioned, groundwater recharge mainly depends on infiltration during flood events at the Buffelsrivier catchment. On an average, the river channel carries water once in three years. The runoff periods usually last from a few days to a couple of weeks. Sometimes, continuous flow over several months is possible.
In transient mode, the groundwater model includes the aquifer storage as sink and source term. Thus, as in reality, an overplus of input results in a rise of water tables and therefore

Table 5.4: Parameters needed for the groundwater model in transient mode.

parameter	bedrock	river alluvium	unit
specific storage	10^{-6}	10^{-4}	1/m
specific yield	10^{-3}	0.25	%
storage coefficient	10^{-4}	0.025	%?

in filling up the storage. In turn, if input is smaller than output, the system compensates this by decreasing hydraulic heads. A transient groundwater model calculates the changes in water levels depending on time variant parameters like evaporation, recharge or pumping rates.
To compute the storage term, a set of additional parameters is needed. The specific storage describes the amount of water that is released from an aquifer when the groundwater level drops one unit, assuming that the aquifer remains saturated. The freeing of water happens due to the compressibility of the aquifer material and the water itself. Values for the specific storage are usually small, about 10^{-6}/m. For a homogeneous and anisotropic aquifer, the product of specific storage and aquifer thickness results in the dimensionless term of storativity. Storativity is considered as the averaged specific storage value for an aquifer.
The ratio between the volume of water an aquifer yields if it is totally drained and the aquifer volume is termed specific yield. The values can be equal or smaller than the effective porosity.
In table 5.4 the parameters for the transient groundwater model are itemized. The values used were estimated after Adams *et al.* (2004) and Titus *et al.* (2002).

In transient mode, Modflow computes head changes for consecutive timesteps termed stress periods. For every stress period, several parameters can be redefined. Within this model, evapotranspiration and recharge are altered. The obtained hydraulic heads of a stress period are taken as input for the next. For the first stress period, the values derived from the steady state model are used.

5.3 Plant-agent model

The plant-agent model adopts the grid structure from the groundwater model. Hence, all calculations made are based on cells of 40 X 40 meters. Every cell can be occupied by one plant agent. At initialization, the model space becomes allocated with information, describing the environment. The values considered are top surface elevation, hydraulic heads and depth to groundwater. In the next step, the agents are assigned to the model area. For this purpose, the vegetated areas, consisting of phreatophytes, had been mapped from air photographs (see figure 5.3). As the model is started, evapotranspiration and recharge values are determined for every cell and the groundwater model becomes executed. After that, the newly computed hydraulic head values are read. This is repeated for every timestep.

The approach used to determine evapotranspiration and the input function used for recharge estimation is described in the next section (model application).

Table 5.5: Names of Modflow96 input files for steady state and transient configuration.

MF package	basic (BAS)	evaporation (EVT)	recharge (RCH)	wells (WEL)
Steady state	bas.dat	evt.dat	rch.dat	wel.dat
Transient	basM0000.dat	etpM0000.dat	rchM0000.dat	welM0000.dat

5.4 Coupled model

File exchange

The main issue in coupling the agent model with USGS Modflow96 was to generate appropriate input files for Modflow96 on the one hand, and to pass the obtained output of hydraulic heads to the agent model on the other hand. Figure 5.6 shows the final concept of how the coupling between Repast and Modflow96 has been realized.
First of all, the system has to be set in an initial state, because hydraulic heads are needed for assessing the evapotranspiration by the plant agent-model and also for the transient groundwater model as starting values. For the calibration run of Modflow96 the evaporation and recharge parameters have to be estimated and some starting heads have to be defined. The outcome is an array of hydraulic head values.

After the initial state has been computed, the proper coupled model is started and, within the plant-agent model, four Modflow input files are generated (evt, rch, wel and bas).
With the evt-file the evapotranspiration parameters are handled over. It consists of four arrays, describing the maximum evaporation, the maximum depth of evaporation (extinction depth, where evaporation becomes zero) and the evaporation surface (below which evaporation decreases with depth). The decrease of evaporation with depth is linear between evaporation surface and extinction depth (Mc Donald & Harbaugh, 1988). The fourth array is the layer indicator array that defines the layer from which evaporation is taken.
The rch-file contains the values of recharge for every model cell. This value can be changed manually for every timestep within the plant-agent model.
As the pumping rates of Kamassis and Roifontain are considered to be constant throughout the years, this parameter is only changeable when the agent model is started. Hence, an alteration was not implemented within the model yet.
The remaining input file belongs to the basic package (BAS). Within this file, the starting heads for Modflow are defined.

Modflow is started in batch-mode from within the plant-agent model. Batch mode means that the input files are specified in a namefile. For the reason of mistaking the steady state parameter files for the transient two namefiles exist. buffelsrivier.nam is the name of the steady state namefile and bumod.nam is used for the transient runs. Table 5.5 shows the names of the input files used within the different name files. circular After a completed groundwater model run the calculated hydraulic heads are saved in a file named heads.asc. This file is again read by the agent model. Exceptionally, after the initial run, the heads must be saved manually, using PMWIN's results extractor.

At the end of a modelrun, the graphs and the data values, recorded during the simulation, are saved in png format and ASCII, respectively. The output directory is defined in the

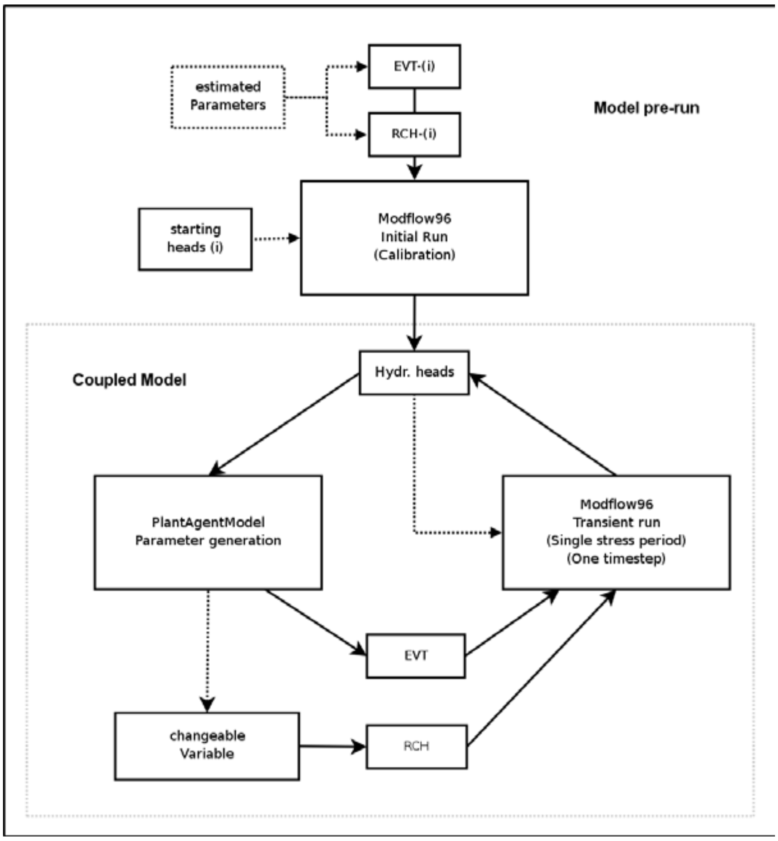

Figure 5.6: The coupled model, pre-run and circular model.

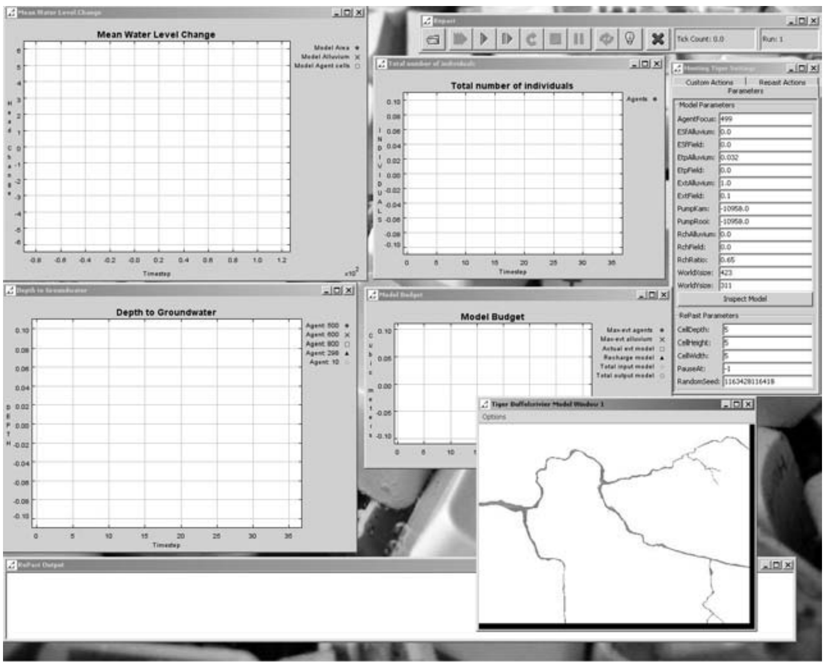

Figure 5.7: Screenshot of the running plant-agent model's graphical user interface.

sourcecode. The files are saved into a subdirectory that is created when the model is initialized. The name of this folder is deduced from the CMOS time at model start.

The graphical user interface

The Recursive Porous Agent Simulation Toolkit (REPAST) (North *et al.*, 2006), where the plant-agent model has been developed. It comes with a graphical user interface (GUI). Figure 5.7 shows a screenshot of the plant-agent model implementation's graphical surface. The GUI contains a control and a parameter panel plus the output console, a map of the model area and four graphs, showing the results of a modeling period. The control panel has several buttons. The button with a single curve initializes the model. The button located to the left of it starts a single timestep of the model. The play button to the left of their latter starts a continuous run of the model, lasting until the stop button (square) is pressed. The red X exits the model. The button with the two curved arrows should restart the model. This function has not been implemented for this model, hence the program will hang after the button is pressed. The folder button can be used to load a model.

The parameter panel contains all user-editable parameters. The values can be edited only before a modelrun is started. Afterwards, the fields become inactive.

Within the Repast output window information on a modelrun (e.g. groundwater budget or created input files) is printed to the console. The map window shows the different cell types of the model. Grey is the color of alluvium cells. Plant cells are colored depending on if they are growing (green), stagnating (orange) or experiencing stress (red).

The four graphic windows plot the developing of certain values from the modelrun.
Mean water level change is calculated between an actual and its antecedent step using equation 2. The mean level change is recorded for agent cells (turquoise) for alluvium cells (blue) and for the whole model area (red). The black line demonstrates the absolute level change since the model has been started.

$$\Delta h = \frac{\sum_{j=1}^{n}(h_{j,t} - h_{j,(t-1)})}{n} \tag{2}$$

Δh	mean water level change (m)
h_t	actual hydraulic head (m)
h_{t-1}	previous hydraulic head (m)
n	number of cells of specified type (-)

The water balance of the groundwater model is visualized in the model budget graph. The maximum amount of evapotranspiration is computed for agents (red) and the alluvium (blue). These values are passed to Modflow. Actual evapotranspiration (turquoise squares), recharge (black) total input (yellow) and total output (turquoise circles) are the results from the groundwater model. The total in- and output values do not consider Modflow's storage term, otherwise both terms would be similar, because Modflow compensates a change in water level with an in- or outflow from the aquifer's storage.
The plot, showing the number of individuals stands for the adaptation activity of the agents. The number of individuals rises if conditions are good. If agents experience stress, the number of individuals decreases and therewith evapotranspiration.

The remaining graph displays the distance between alluvium surface and groundwater table at the coordinates of certain agents. Ordinate values increase with lowering water tables.

6 Model application

6.1 Adaption scenario

The scenario is used to investigate whether a stable system can be created using a periodic recharge input function and agents that transpirate water in dependence on the distance to the water table, at their location. It is assumed that transpiration decreases with lowering piezometric heads. The simulation is started from the initial state, after the steady state groundwater model calibration. The maximum depth from where water can be withdrawn is supposed to be limited by the depth of the roots. If the system becomes stable, the water tables will oscillate around a certain mean value. The phreatic vegetation is initialized as it had been mapped from air photographs (see figure 5.3).

In order to cover the range of hydraulic conductivity uncertainty, two seperate runs are performed using 10^{-7} m/s and 10^{-8} m/s respectively, for the conductivity parameter.

6.2 Agent design

In the model, every agent describes a container that holds a certain configuration of vegetation. It is characterized by the parameters root depth and number of individuals. The term individuals is used to illustrate growing, seedling and wilting of plants. Speaking of transpiration capabilities or leaf area index would be another possibility, referring more to increase and decrease in green biomass and thus in water demand.
For this scenario, root depth is assumed to be constant. The number of individuals is variable and different for every agent and timestep. Hence, the agents have the ability to adapt to the amount of available water by changing the quantity of their individuals. The parameter is checked for every timestep. If an agent has less than the maximum number of individuals and if water supply is sufficient an individual is added. In turn, if the agent experiences stress over more than one timestep, the number of individuals is reduced.

The source code, given in listing 1, shows the method that is used to compute the transpiration rates for the agents. It is assumed that the rates depend on groundwater depth. Hence, the variable *depthfactor* is introduced (line 8). *depthfactor* ranges from one (full transpiration) to zero (no transpiration). The water table is expected to remain above the root depth. If it does not, the value of *depthfactor* is set to zero to avoid negative results (line 9). *depth2GW* has negative values if the water table rises above surface elevation. In this case, *depthfactor* is set to one (line 10).
Within the following if-statements, the transpiration rate is calculated for different conditions. Agents are assumed to grow if the number of individuals is greater than zero and the agent has no water stress. Degradation will occur if the number of individuals is greater zero but the agent experiences water stress. For the case that no individuals exist, a minimal evaporation is defined (lines 25-28) .The remaining lines of code ensure that no negative values occur. This becomes necessary, because negative evapotranspiration values are interpreted as water input to the model, by Modflow.

Surface evaporation is only applied to cells that are not occupied by agents. Surface evaporation also decreases with depth. The value is calculated with equation 3:

Listing 1: Method used for calculating the agent transpiration

```java
public double calculateActET() {

    double actEt = 0;
    double depthfactor; //reduction factor

    // calculation of depthfactor:
    if (depth2GW >= 0) {
        depthfactor = (rootDepth - depth2GW)/rootDepth;
        if (depthfactor < 0) depthfactor = 0; // avoid values < 0
    } else depthfactor = 1;

    // transpiration rate of growing plants:
    if ((individuals > 0) && (agentComfort == true)) {
        actEt = (0.05 * individuals * depthfactor);

    // transpiration rate if stress occurs
    } else if ((individuals > 0) && (agentComfort == false)) {
        actEt = (0.001 * individuals * depthfactor);

    // transpiration rate if vegetation died
    } else if ((individuals == 0) && (agentComfort == false)) {
        actEt = 0.001;
        if (actEt < 0.001) actEt = 0.001;

    // transpiration rate for anything else
    } else {
            actEt = 0.0005;
    }

    if (actEt < 0) actEt = 0; // avoid values < 0
        return actEt;

}
```

$$evt = m * d \tag{3}$$

evt	surface evaporation rate (mm/a)
m	maximum surface evaporation rate of the alluvium (mm/a)
d	depthfactor (-) value between 0 and 1

6.3 Results

6.3.1 Run 1 - hydraulic conductivity 10^{-7} m/s

Because of a memory overflow error, only 110 timesteps (months) were calculated. The results are visualized in figures 6.1, 6.2, 6.3 and 6.4.

The first graph in figure 6.1 shows the development of groundwater depths at five different agent locations in the model area. For all curves, the depths to the groundwater table increase with time. Agent 10 and agent 298 represent the lower part from the model, close to the outflow boundary. The agents 500, 600 and 800 stand for the upper part around Kamassies and upstream from there.
The graph demonstrates that water levels drop with elapsing time. Only at the location of agent 298, the value levels off between seven and eight meters. All curves, except for agent 10, show a periodic course, according to the seasonal variation of recharge.
Altogether, the lowering of water tables is more intense for the upper part of the model area. Close to the lower boundary, piezometric heads remain almost stable.

The second graph in figure 6.1 plots the water balance, derived from the groundwater model, (actual evt model, recharge model, total input and total output) and the amounts of evapotranspiration, estimated by the plant agent model (max evt agents, max evt alluvium). Surface evaporation drops after modelstart and increases slightly afterwards. In turn, transpiration from plant-agents increases first and descends then, fluctuating between 6960 and 13800 m^3 per month. The evapotranspiration rates, calculated by the groundwater model (actual evt), are slightly lower than the estimations made with the plant-agent model.
The mean recharge rate (16860 m^3/m) lies above the mean evapotranspiration (13884 m^3/m). But the total input to the model (recharge, boundaries) is below the total output (evapotranspiration, boundaries, wells). The difference is about 19800 m^3/m. Hence, the groundwater levels are supposed to fall.

The first graph in figure 6.2 describes the changes in transpiration effort (number of individuals) for the plant-agents. At the beginning of the modelrun, the transpiration capacities increase until a maximum is reached and the curve descends. After the peak is passed, the course begins to oscillate. This is the point when the model starts acting in an adaptive manner, but all in all the transpiration effort decreases with time and analog to dropping water levels.

As already assumed, the tendency of falling water levels, is also observed in figure 6.2 (second graph), where the mean changes in water levels for different cell types are plotted. The values were computed separately for agent, alluvium and total model area cells, using equation 2. The curves also oscillate in correlation to the recharge input function. The amplitude

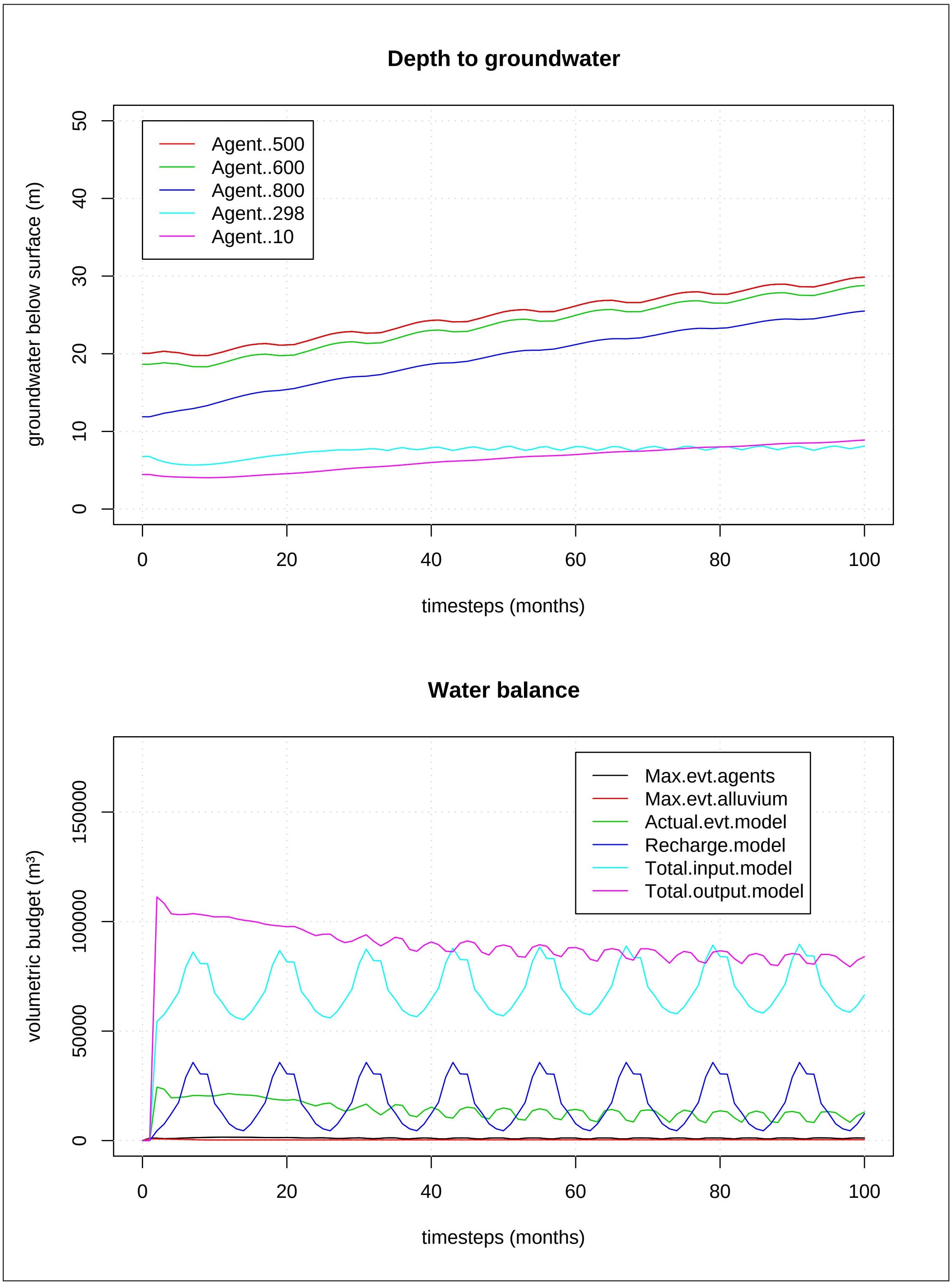

Figure 6.1: Results from the first simulation run.
Top: depth to groundwater for the different plant-agents.
Bottom: water balance of the groundwater model.

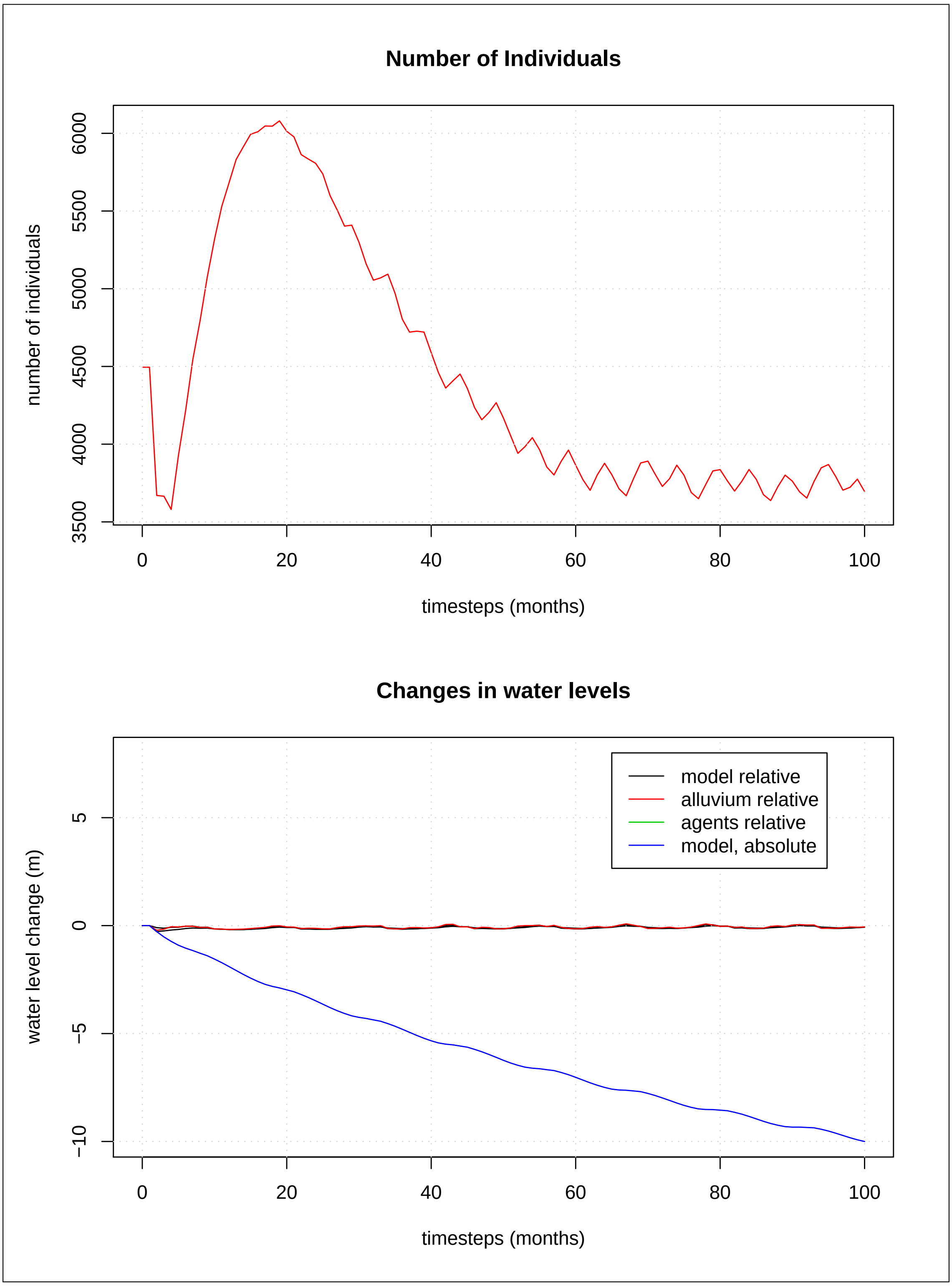

Figure 6.2: Results from the first simulation run.
Top: number of individuals.
Bottom: water level changes for the model area.

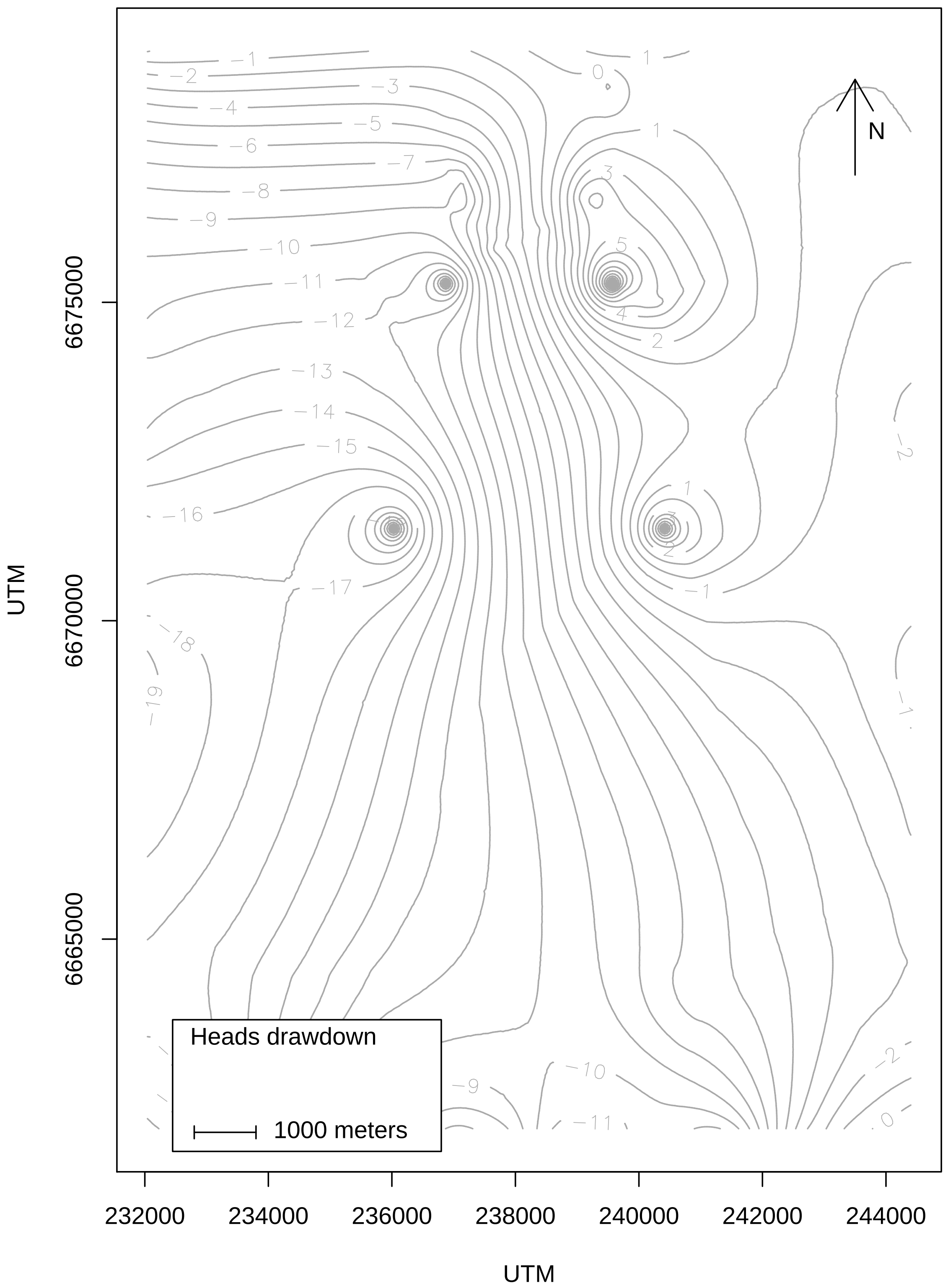

Figure 6.3: Water level drawdowns between timestep 100 of the first model run and the model start.

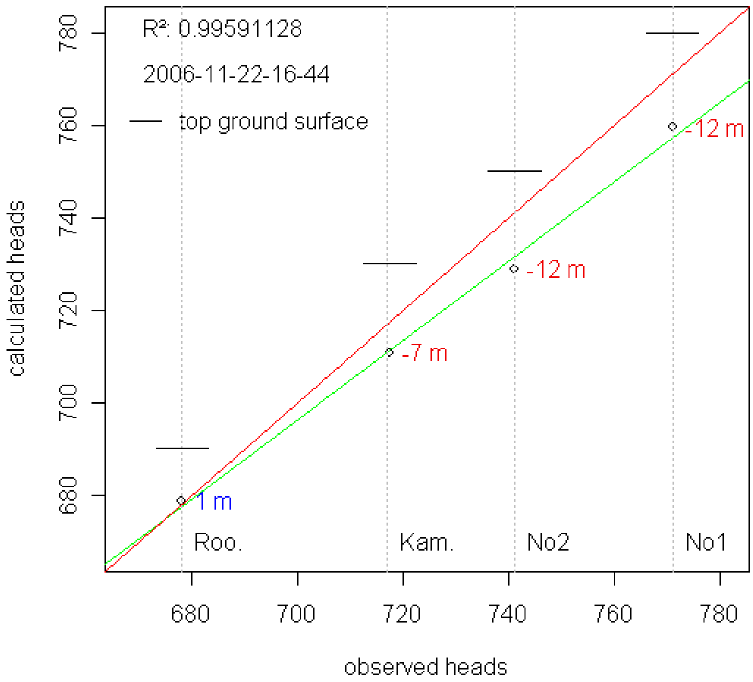

Figure 6.4: Piezometric heads at the observation wells at timestep 100 of the first model run. The values beside the data points quantify the deviation from measured water levels.

is different for the cell types, meaning that agent cells have the strongest variations and alluvium and model cells are affected by it. The perspective of the graph doesn't reveal the variations between the different cell types because of the cumulative curve widens the scale. Throughout the model run, level changes are negative. The blue line (model, absolute) shows the cumulative values for the whole model area. The head's drawdown is far below plausible values and a reversal of trend is not to be expected.

Figure 6.3 shows the changes in water levels between first and last modeling step. Within the left half of the model area, the water levels drop. The water levels in the right half are almost similar to the initial state or even exceed it. Hence, in general, the hydraulic heads decrease with a north-east south-west gradient. It seems that the groundwater becomes dislocated to the north-eastern part of the model area.
This tendency is also reflected by the water levels of the observation wells. Figure 6.4 shows that water levels drop increasingly with distance from the northern model boundary.
Figure 6.3 also reveals four spots of elevated activity. Two of them are caused by decreasing water levels. The remaining two are caused by increasing water levels. The points of water depression fit together with the locations of the pumping wells. For the other two points there is no explanation as yet.

The water balance of simulation run 1 is shown in table 6.1. An equilibrium of input and output is not achieved. The major part of the water leaves the model area at the constant head boundary (~ 600,000 m^3/a). More water, than the evaporative discharge amounts (~ 156,000 m^3/a), is withdrawn by pumping (~ 252,000 m^3/a). For the observed period the mean evapotranspiration rate is below the input of recharge. Drawn on the alluvial area, the annual evapotranspiration rate is 26 mm. The corresponding recharge rate is 40 mm. The evapotranspiration rate observed from the steady state groundwater model amounts to 31 mm/a.

6.3.2 Run 2 - hydraulic conductivity 10^{-8} m/s

For the second model run, the hydraulic conductivity had been changed to 10^{-8} m/s. The results are visualized in figures 6.5, 6.6, 6.7 and 6.8.

As figure 6.5 (top) shows, the water levels oscillate for all agent locations, except for agent 10, from the very beginning. For the whole modeling period, the mean levels remain almost constant. At the location of agent 10, the hydraulic heads drop until timestep 100 is reached. Then the curve follows the one from agent 298, but without oscillation.

The model's water balance, plotted in figure 6.5 (bottom), is less divergent than in the first model run. The rate of total input exceeds the total output term. Again as already obtained by the previous run, the evaporation rate, calculated by the groundwater model, is below the rate that had been determined by the plant-agent model. With elapsing time, the water output from the model rises. This is caused by the increasing evaporation term. After timestep 200, the mean water balance seems to become constant.
In table 6.2, the water balance for the last year of the simulation is listed. All in all, the difference of total input and output is positive (~ 99,711 m^3/a), which means that the water balance is not closed. The annual amount of evapotranspiration lies about two times higher than the recharge input. For the area of the alluvium, the annual recharge and evapotranspiration rates are 39 mm and 78 mm, respectively.

The number of individuals, shown in figure 6.6 drops from an initial value to a minimum of 1000, before it increases constantly until a level of approximately 13000 is reached.

In contrast to the results from the first model run, the water level changes, drawn in figure 6.6 (bottom) are predominantly positive. The relative changes at the alluvium show a distinctive response to the recharge input function. For the whole model area, the mean cumulated water level change converges to a value between 14 and 15 meters.

At timestep 300, the detailed changes in water levels, drawn in figure 6.7, show two distinct tendencies. For the alluvial zone, water levels remain constant or decrease within some spots. For the rest of the model area, hydraulic heads increase with closeness to the inflow boundaries (south, west, east). Again, as observed by the first model run, the area near the northern model boundary has almost constant water levels. Furthermore, the four points with strong hydraulic gradient occur also in the actual model run. However, the changes are not as intense as in the first run.

The water levels at the observation wells, shown in figure 6.8, remain under the top ground surface. In comparison to the initial state (see figure 5.4), levels drop lightly at Rooifontein and rise at the upper parts of the model area. The strongest increase is noted at the well

Table 6.1: Water balance of the groundwater model in m^3 per timestep(s). Results from the first model run with $k_f = 10^{-7}$ m/s.

parameter	recharge in	evt out	total input	total output	difference
timestep 86	4,488	12,696	58,272	84,420	-26,151
timestep 87	7,548	8,712	61,368	80,352	-18,973
timestep 88	12,300	8,244	66,168	79,920	-13,746
timestep 89	17,412	12,912	71,304	84,696	-13,389
timestep 90	28,968	13,320	82,872	85,404	-2,522
timestep 91	35,688	12,624	89,616	84,948	4,664
timestep 92	30,456	8,724	84,396	81,012	3,380
timestep 93	30,324	8,244	84,264	80,556	3,708
timestep 94	16,932	13,008	70,896	84,984	-14,086
timestep 95	12,648	13,272	66,648	84,996	-18,352
timestep 96	7,680	12,780	61,728	84,216	-22,484
timestep 97	5,376	10,440	59,460	81,612	-22,151
timesteps 86-97	209,816	138,022	856,643	1,000,914	-144,271

Table 6.2: Water balance of the groundwater model in m^3 per timestep(s). Results from the second model run with $k_f = 10^{-8}$ m/s.

parameter	recharge in	evt out	total input	total output	difference
timestep 289	4,487	30,788	38,567	39,215	-648
timestep 290	7,546	36,992	41,633	45,407	-3,774
timestep 291	12,302	34,626	46,395	43,072	3,322
timestep 292	17,404	30,847	51,496	39,354	12,143
timestep 293	28,959	27,435	63,037	36,089	26,948
timestep 294	35,687	33,003	69,746	41,801	27,945
timestep 295	30,453	39,944	64,500	48,770	15,731
timestep 296	30,315	40,751	64,351	49,608	14,742
timestep 297	16,926	38,256	50,961	47,004	3,957
timestep 298	12,642	35,987	46,680	44,650	2,030
timestep 299	7,683	31,541	41,730	40,108	1,622
timestep 300	5,371	30,907	39,429	39,396	33
timesteps 289-300	209,775	415,204	618,338	518,627	99,711

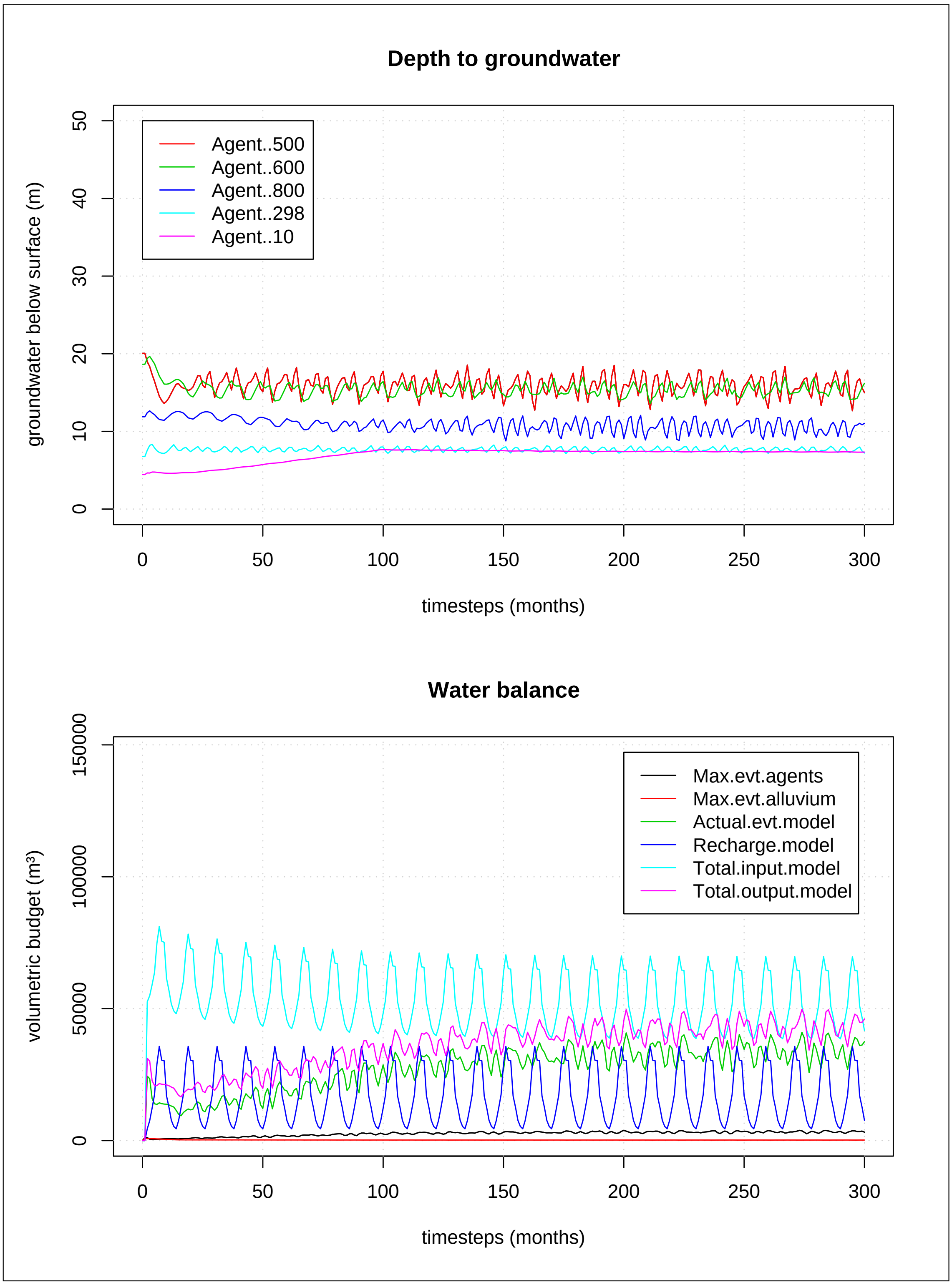

Figure 6.5: Results from the second simulation run.
Top: depth to groundwater for the different plant-agents.
Bottom: water balance of the groundwater model.

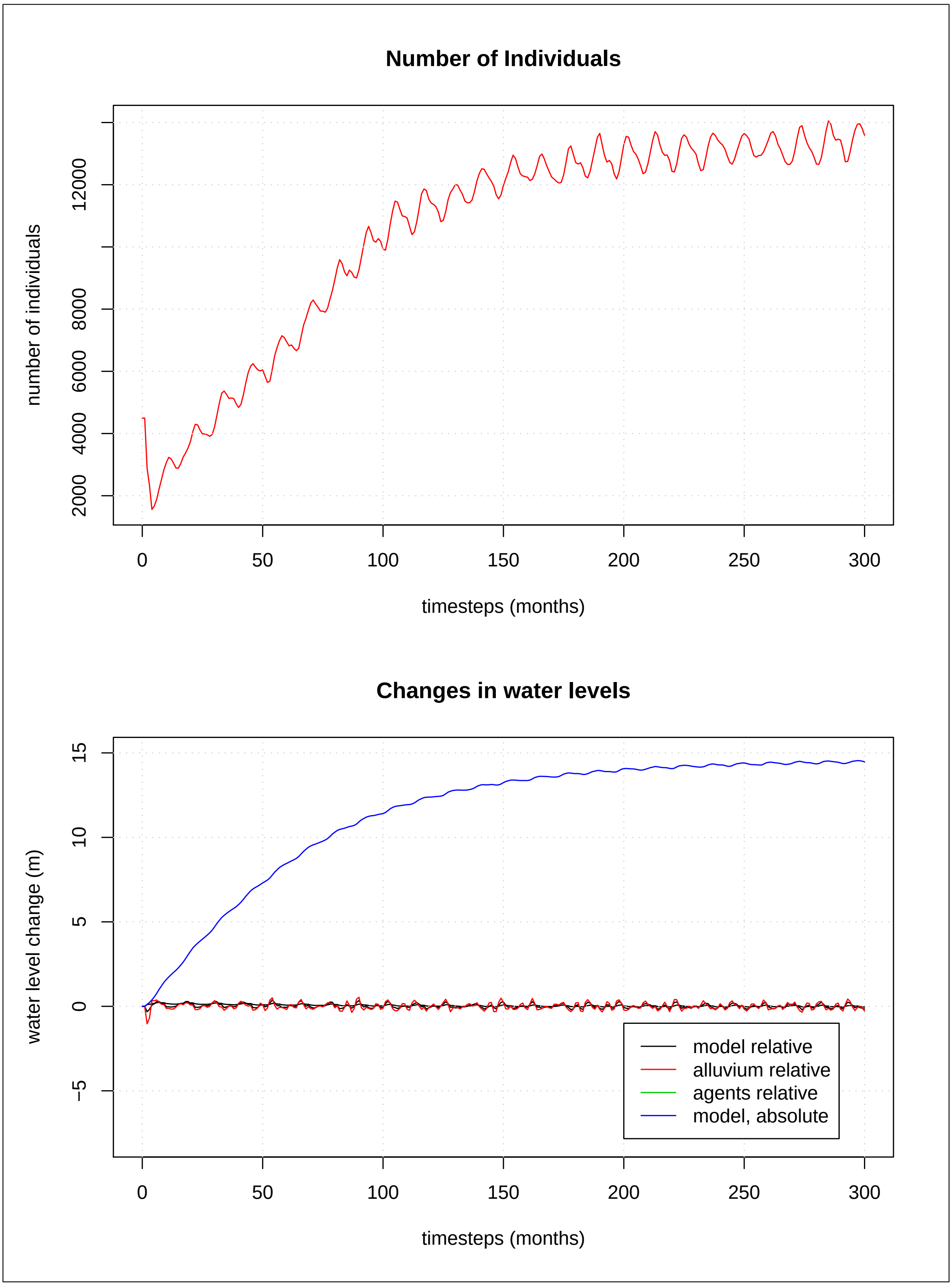

Figure 6.6: Results from the second simulation run.
Top: number of individuals.
Bottom: water level changes for the model area.

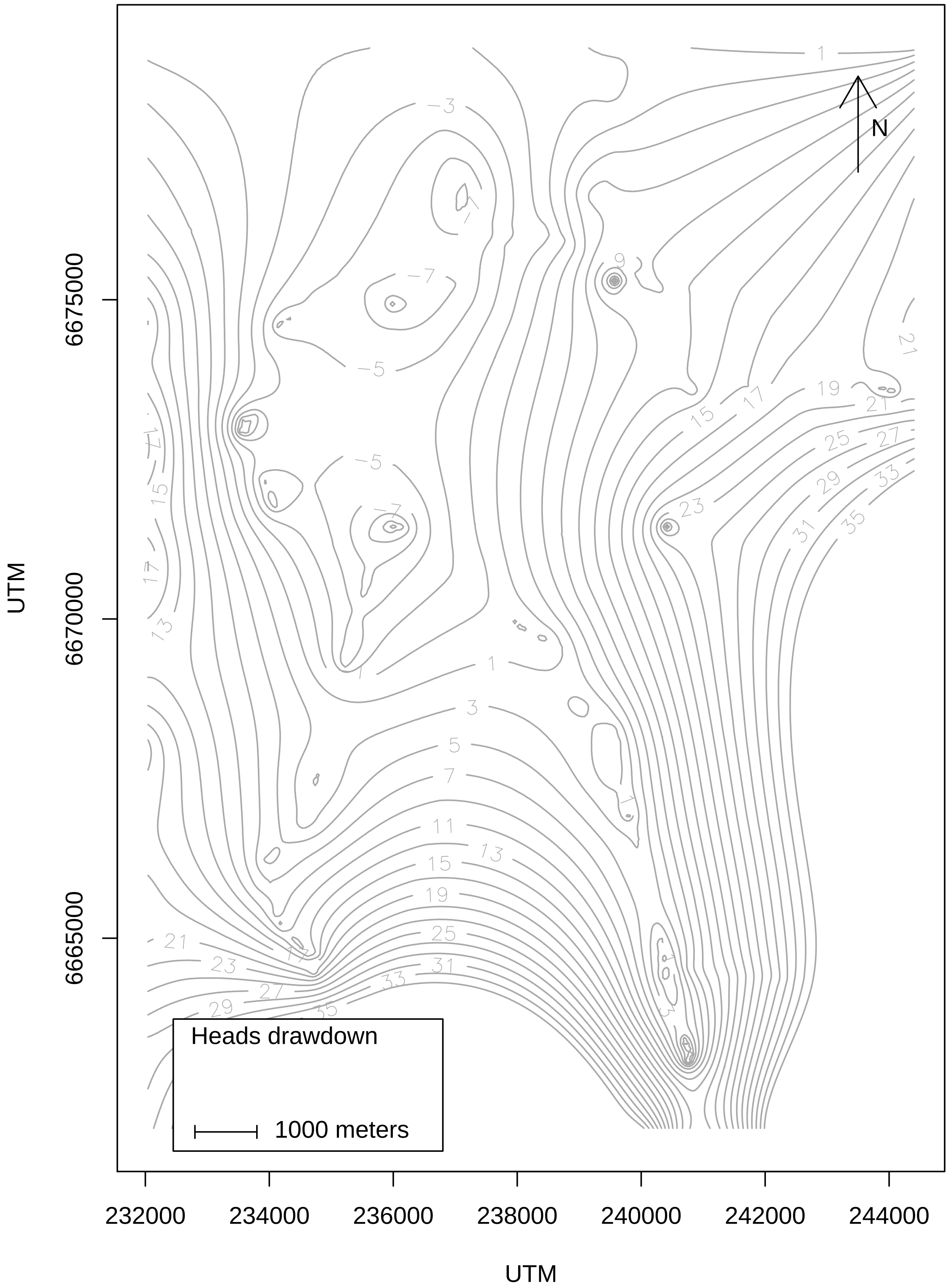

Figure 6.7: Water level drawdowns between timestep 300 of the second model run and the model start.

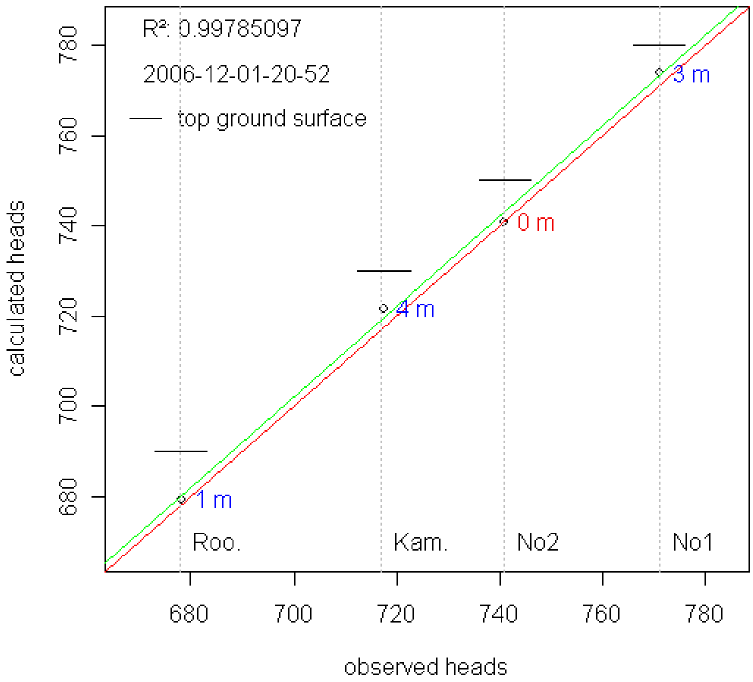

Figure 6.8: Piezometric heads at the observation wells at timestep 300 of the second model run. The values beside the data points quantify the deviation from measured water levels.

of Kamassies.

6.4 Discussion

The two model runs represent the range of system response in dependence on the hydraulic conductivities. Although the steady state groundwater model could be successfully calibrated for both extremes, the two transient model runs show a strong variation within their results.

Run 1

The results from the first model run indicate that the groundwater system drains the groundwater too quickly. Hence, the water flows to the lower parts of the model area. In turn, this leads to falling water levels in the upper area. The fact that the gradient of level changes crosses the area diagonally and not in the direction of the river alluvium (south-north) could be because of the geometry of the groundwater model.

The number of individuals (figure 6.2) remains above 3500, but only a small group of plant agents in the region of Rooifontein are still able to reach the groundwater. This leads to the conclusion that those agents transpirate the water that comes from the upper parts of the model area.

Unfortunately, the model run was interrupted by a memory error and only 100 timesteps have been calculated. However, the water budget (figure 6.1) and the individuals diagram (figure 6.2) indicate that the output functions are likely to continue oscillating around constant mean values. Considering the depths to groundwater in figure 6.1 and the water level changes in figure 6.2, once could assume that the groundwater tables will drop until the aquifer is emptied.

The water balance of the groundwater model quantifies the amount of water that is lost from the storage of the system with every timestep. The values show that recharge exceeds evapotranspiration and hence groundwater recharge would take place.

Alltogether, with the chosen hydraulic conductivity of the first simulation run, the interaction between the groundwater model and the plant-agent system fails. The water levels drops to quickly and are below the influence of the vegetation. Hence, most plants would die, except for a few in the lower part of the model area, where water accumulates. The pattern of vegetation that has been mapped from air photographs (figure 5.3), cannot be reproduced with the chosen configuration model.

Run 2

The output of the second model run shows a different interplay between the two systems. For the agent locations the mean water levels remain stable. Only for agent 10 a different behavior was recorded. It seems that this area is influenced by the constant head boundary condition. Hence, the water table drops to a certain level that marks the lower limit. This behavior is caused by the numerical solving process of the groundwater model. At the constant head boundary no inflow occurred.

The number of individuals correlates with the absolute change in water levels (figure 6.6). Both curves converge to a maximum value. Hence, it can be deduced that the simulated vegetation is capable of adapting to the amount of supplied water. This is underlined by the distribution of head changes shown in figure 6.7. In comparison to the simulation start, at timestep 300, the water levels in the river alluvium remained equal or decreased within some areas.

The change in hydraulic conductivity resulted in lower flow velocities for the basement aquifer. Recharge, applied to the river alluvium, could not be drained as quickly as within the previous model. Thus, the water levels of the lower model area were not increased significantly. Consequently, the outflow at the constant head boundary was smaller than within the first run. In turn, this has led to elevated groundwater tables.

Within this simulation, the plant-agents were able to use the groundwater for transpiration, because their roots reached down to the water table. The low conductivity and the recharge input function resulted in rising water levels. For the alluvium area, this surplus has been fully absorbed by the transpiration activity of the agents.

The water balance, plotted in figure 6.5, reveals the same adaptation mechanism that is caused by evapotranspiration. The curve of evapotranspiration, and with it the curve of total water output, converges to a level above the recharge input function. Hence, the simulation results predict that re-evapotranspiration exceeds recharge by a factor minimum two (see table 6.2). Consequently, for the model area, effective groundwater recharge does not take place. Even water that comes from outside (inflow boundaries) is used for transpiration. The amplitude of water level changes, simulated at the agent locations (figure 6.5) is small, compared to the measurements made at the location of Rooifontein (see also figure 4.9). Assuming larger drawdonws than the ones modeled, for the water balance, means an increment of the evapotranspiration term. Hence, within this simulation, transpiration could be underestimated.

The strongly increasing water levels beside the alluvium could be an artifact from the general head boundary condition. Possibly, the chosen gradient is too high and hence too much water comes from outside of the model area. The two spots with decreasing hydraulic heads can be connected with the locations of the pumping wells. However, the two spots that show a level change in the opposite direction cannot be explained, for both simulation runs.

6.5 Conclusion

With the second model run, the aim of simulating a stable adaptive system has been achieved. The transpiration rates obtained, are the result of the independent behavior of individual plant-agents. The simulation outcome indicates that with the given recharge input function, the occurance of adaptation is based on a slow reacting groundwater system that keeps the water resource within the reach of the phreatic vegetation. Clearly, the first run showed that the hydraulic conductivity had been underestimated. After the parameter had been decreased one order of magnitude, the system changed from oppositional to interactive.

The calibration of the steady state groundwater mode with a hydraulic conductivity of 10^{-8} m/s failed, because water levels were always above the surface of the alluvium. The water levels, computed within the second model run, remain below the model's surface, although the same conductivity had been applied.

The results from the quantitative water balance can only be cautiously interpreted. The fact, that re-evapotranspiration exceeds the amount of recharge, potentiates the assumption that the vegetation is capable of detaining the full amount of recharge from the basement aquifer. Hence, the outcome of the simulation proves the theory of phreatic plants controlling vertical water fluxes in regions with dry conditions. The comparison of measured and simulated water level changes leads to the assumption that the impact of riparian vegetation could be stronger than obtained by the developed model.

7 Overall conclusion and recommendations

Phreatic riparian vegetation
The literature review showed that for dryland ecosystems, most notably at ephemeral river sites, riparian phreatophytes have a severe impact on the hydrological processes. They control evaporative discharge from the alluvium and hence, affect the recharge of the underlying groundwater layers. The vegetation's capability of adaptation assures an efficient use of the momentarily available resources. Riparian phreatophytes possess the ability to cope with long lasting periods of drought as long as their roots reach the saturated zone. Quickly dropping water levels can cause the destruction of entire forests. Therefore, it is important to investigate the edge conditions that allow the survival of riparian ecosystems and to research the effects climatic variations will have in the future. For this reason, modeling the vegetation-groundwater interaction as attempted within this thesis, is necessary in order to find meaningful results.

Study area
For the investigated area, the modeling results indicate that more water is used by evapotranspiration than replenished by recharge. The assumption is underlined by the high chloride concentrations that have been measured at the model area. The estimated evapotranspiration rates for the alluvium range between 30 mm/a (steady state groundwater model) and 78 mm/a (transient vegetation-groundwater model). The corresponding recharge rate is 25 mm/a. Taking into account that vegetation occurs only at a small part of the alluvial area (899 agent cells of 3315 alluvium cells), underlines the importance of spots with phreatic vegetation for the water balance of the whole catchment.

Vegetation-aquifer model
With this thesis, an adaptive model of vegetation-groundwater interactions had been successfully implemented. The spatially distributed definition of the evapotranspiration term led to plausible results. For the second model run the water table remains under the top ground surface. With the primary groundwater model such results could not be achieved. The model was intentionally held simple. Only one regulation factor has been used for the adaptation mechanism.
Admittedly, the two performed simulation runs showed that the model suffers from different uncertainties. A major problem is caused by the nonnatural boundaries. The definition of artificial boundary conditions for all of the four fringes is error-prone. Another drawback is the lack of measured data. For the whole model area ($\sim$ 210 km^2) only four observation wells exist and all of them are located within the river alluvium. Hence, no estimations can be made for the areas besides the river bed.

In order to extend the model, it is recommended to switch to another investigation area where more data is available and boundary conditions are given by the geographical or geological borders of the basin or subbasin.

Further development of the model
The approach followed within this thesis was to use plant-agents as a tool for modeling vegetation that shows adaptive behavior to environmental conditions. The only restriction

that controlled adaption was the depth at which groundwater was available. The influence of vegetation on groundwater levels could then be used for comparison with observations from reality.

However, other important factors had been ignored for the ease of a simple, comprehensible, adaptive model. For climatic conditions, only the annual variability of recharge has been taken into account. But evapotranspiration also has a seasonal dependence. At the time when recharge intensities are highest, evapotranspiration is reduced by a lack of radiation and higher air humidity. This effect can be implicated by deducing the actual evapotranspiration from potential evaporation.

Another point of interest would be the development of plants with time. Transpiration can be seen as a function of climate, plant type, leaf biomass and water availability. This could be easily implemented in the plant-agent model if the ratio of transpiration and leaf area or green biomass is known. Such coherence had been used by Bate & Walker (1991) for modeling the water use of phreatic vegetation at the banks of the Kuiseb river in Namibia. The influence of developing plants on the groundwater system can be simulated if the function of plant age and the corresponding green biomass (that is important for transpiration) is known. Additionally, reproduction can be taken into account, by implementing seedlings to the model. Of course this would imply a mechanism for dying plants. Defining a maximum age for plants and a maximum dry stress tolerance would be a plausible approach.

Taking into account the above-mentioned points could lead to a new type of eco-hydrologic model where the traits of phreatic vegetation that interfere with the mechanisms of groundwater recharge and transport, are included in a comprehensible way, but still individual and differentiated for space and time. As the model is considered from the other, the groundwater side, changing the climatic conditions as recharge or photosynthetic active radiation would be another interesting question to the model.

Furthermore, the recharge process can be described in greater detail. Adding a flood routing routine could simulate both, runoff generated by surface discharge of groundwater, and infiltration by transmission losses during flood events.
An extension that calculates a chloride balance would provide another mean for validation with measured values.

Agent-based models in hydrology
Most of the agent- or individual based models that deal with water or include hydrological processes are aimed at describing biotic ecosystems or economic problems. Looking at the perspective from a hydrologist's point of view was a major intention of this work. The combination of well understood groundwater models with distributed ecological or biological approaches offers new possibilities and perceptions for both sides. The approach that was developed within this thesis is just one step on the path of agent-based modeling in hydrology towards a better comprehension of the interactions between biota and subsurface water. The results of this thesis suggest that more work should be done on multi-agent systems in the hydrological cycle. Yet, the potential of agent-based modeling in hydrology is still not exhausted.

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Appendix

A Java classes from the agent model

Below, the important classes and methods from the multi-agent model are explained. The detailed Model API is provided in standard JavaDoc format (HTML) with the enclosed CD.

A.1 BuffelsrivierModel

Main class of the agent model. Includes the inherited methods from the REPAST tool.

setup() initializes the parameters that are needed to start the model (e.g. schedule, BuffelsModelArea, hydraulic heads) and sets up the display. This method is called when the button with the two curved arrows is pressed or a new instance of the model is started.

begin() is called when the initialize bottom from the panel is invoked. The method starts buildSchedule(), buildDisplay() and prints the created displays to the screen.

getInitParam() is a method inherited from the interface uchicago.src.sim.engine.SimModel. It initializes the parameters that can be edited in the control panel. In order to change a parameter, a setter method is needed, as the parameters are declared as private.

The method registrateNewAgents() assigns the agents, read from the file agents.dat, to bmArea (instance of BuffelsModelArea) and to agentList (instance of ArrayList that contains a list of parameters for every agent).

rchMatrix() calculates the amount of recharge for every cell, using the recharge parameter from BuffelsParamIterator and the recharge factor (recharge alluvium / recharge field).

updateAgents() updates the agent parameters (e.g age, comfort status, bad conditions counter ...)

A.2 BuffelsModelArea

The class BuffelsModelArea is used for managing the spatial model parameters like elevation, hydraulic heads, depth to groundwater, agent distribution or alluvial cells.

The method updateAfterModflowRun() refreshes the hydraulic head and depth to groundwater values.

A.3 BuffelsPlantAgent

With this class agents are represented in the model. The rules of agent behavior and their individual parameters (e.g. age, position, root depth, transpiration) are defined here.

calculateActEvt() is the key method of this class, that returns the amount of water an agent uses from a model cell.

A.4 BuffelsParamIterator

This class is used to alter certain parameters during the model run. So far only recharge is considered here.

A.5 BuffelsEvtAssembler

Simple class that produces three parameter arrays for evapotranspiration needed for the Modflow input file (evaporation surface, extinction depth, max value of evaporation).

A.6 BuffelsDataMan

BuffelsDataMan (data manager) contains the methods needed for reading data from or writing ASCII data to files. It is needed at the model initialization in order to read hydraulic head values (getMF96StartingHeads()) and after each timestep to update the heads (getMF96HydraulicHeadsAscii()) and for writing a data input file towards GNU-R.
The class also reads the groundwater model's water balance (getMF96ModelBudget()). The values are stored in an one dimensional array with the following values:

Table 1.1: Values from the groundwater model's budget and the corresponding indexes of the one dimensional array

value	**index input**	**index output**
storage	0	7
constant head boundary	1	8
wells	2	9
evapotranspiration	3	10
general head boundaries	4	11
recharge	5	12
total	6	13

A.7 BuffelsModflowOut

BuffelsModflowOut is used for writing the different input files for Modflow96. createBASFile() produces the base-package (BAS) input file. createETPFile() creates the evaporation-package (EVT) input file. createRechargeFile() generates the recharge-package (RCH) input file and createWells() is used for the well-package (WEL).

A.8 ModflowStarter and R

Both classes are used for program execution. ModflowStarter executes Modflow and R executes a GNU-R script.

B Manual for using the model

B.1 Required software and files

In order to run the model developed within this thesis five programs must be available:

- *Java, version 1.5.07 SDK* from *SUN Microsystems* (www.sun.com)
- *eclipse, version 3.1.2* from *The Eclipse Foundation* (www.eclipse.org)
- *REPAST, version 3.0* from North *et al.* (2006) (http://repast.sf.net)
- *Processing Modflow for Windows, version 5.3* from Wen-Hsing & Kinzelbach (2005) (www.pmwin.net).
- *GNU-R, version 2.4.0* (www.r-project.org).

All software tools are freeware or open source and can be downloaded from the specified websites.
The following installation paths should be used:

program	path
java	optional
eclipse	optional
REPAST	c:\program files\repast
PMWIN	optional
GNU-R	standard

optional means the directory can be freely chosen, standard means to adopt the path proposed by the installation program.
The best way to meet all file dependencies is to put the *nemo_lokal* tree with all its subdirectories into the root directory of drive D:\. Of course any another directory can be used, but in this case, all paths within the source code and configuration files must be adjusted. Write access must be granted to the whole data tree.

B.2 Initial calibration

The first step in the modeling process is to create the steady state groundwater model using PMWIN. The procedure can be found in Wen-Hsing & Kinzelbach (2005). If a new model is created, the project file should be saved in the .*modflow_buffelsrivier*\\ directory. After the model has been successfully calibrated, the hydraulic heads must be saved in ASCII format (do not choose the wrapped format). The read path for the heads file is specified in BuffelsModelArea.java.

B.3 Transient model run

Before the plant-agent model can be executed, the time parameter within PMWIN must be set from steady state to transient and the hydraulic heads, obtained by the calibration run must be copied to the initial hydraulic heads matrix. Also the modflow namefile *bumod.nam* must be checked whether paths are correct.
Now the *repast* model can be started by the execution of *eclipse*. Within eclipse it is important to choose the right workspace directory, usually this would be
d:\nemo_lokal\MAGMA\buffelRepastModel.
The main class for starting the model is BuffelsrivierModel.java. If no unresolved dependencies exist, the model starts without error messages. The simulation is started using the play button from the panel window. The model can be stopped by pressing the stop (square) button. After the button had been pressed the simulation ends when the computation of the running timestep has been completed. Then the input fields of the parameter window become white. The output data has now been written into the output directory (modflow_buffelsrivier\output\run_data).

B.4 Changeable parameters

At model start, several parameters can be adjusted. The following table gives an overview:

parameter	**meaning**
AgentFocus	here an agent can be chosen, its environmental variables will be printed to the standard output window and it will appear in the depth to groundwater result graph
ESfAlluvium	modflow: evaporation surface of the alluvium
EsFField	modflow: evaporation surface of the remaining model area
EtpAlluvium	modflow: maximum evaporation for the alluvium
EtpField	modflow: maximum evaporation for the remaining model area
ExtAlluvium	modflow: extinction depth at the alluvium
ExtField	modflow: extinction depth at the remaining model area
MaxTimeSteps	length of the simulation run (number of timesteps to be computed)
PumpKam	modflow: pumping rate at Kamassies
PumpRooi	modflow: pumping rate for Rooifontein
RchAlluvium	don't change refer to the BuffelsParamIterator class instead
RchField	don't change refer to the BuffelsParamIterator class instead
RchRatio	number between 0 and 1, percent of recharge that will be put on the river alluvium

Further changes are only possible within the source code. Please refer to the JavaDoc API documentation and to the comments in the source code. Both are available on the CD, that is enclosed with this work.