Chapter 8 Summary and conclusions

8.1 Introduction and problem statement

The Botswana Kalahari can be characterized as a flat steppe and savanna with rather dense vegetation on a mantle of thick sand cover. Rainfall is concentrated in the hot summer season and is of the order of 400 mm/yr. Infiltration rate is high and almost all rainwater infiltrates and is subsequently removed by evapotranspiration. Surface runoff only occurs very locally in dry valleys in periods of extremely high rainfall.

The question if groundwater is replenished under present day conditions has been a matter of debate for a long time. Research in the eastern fringe of the Kalahari in the 1990s resulted in an average annual recharge figure in the order of 5-10 mm under an average rainfall of 450 mm in an area with a groundwater table between 20 and 100 m (Selaolo, 1998; De Vries et al., 2000). However, there is evidence that the total regional groundwater discharge is less than the total amount of percolate that reaches the groundwater zone, and the question was raised if deep rooting trees could be able to reach the groundwater table and extract groundwater that previously had escaped evapotranspiration from the main root zone in the upper 4 m.

Therefore the present study was initiated with the aims:
(1) To investigate the rooting depth of large trees, to find the horizons from which the trees extract their water and to determine the seasonal water fluxes through their xylem. These problems were approached by the use of applied tracers, environmental tracers and sap flow measurements, at several locations and within different tree species.
(2) To determine rainfall, potential and actual evapotranspiration from micrometeorological observations at different sites, and to analyze the temporal and spatial variability of these important components of the water balance.
To monitor seasonal variations and propagation of soil moisture and to estimate groundwater recharge from a combination of groundwater level fluctuations, rainfall and evapotranspiration data.

8.2 Study area

The investigations were conducted in Serowe area (Chapter 1), which is located at the fringe of the Kalahari, in the Central District of Botswana. The study area of about 2690 km$^2$ straddles two different, but typical Botswana environments that are separated by an escarpment: the sandveld with deep Kalahari sand, to the west, and the hardveld with hard rock at shallow depth, to the east. The climate is semi-arid, with annual potential evapotranspiration (1350-1450 mm/yr) far exceeding annual rainfall (400-500 mm/yr). Groundwater table depths are less than 40 m in the hardveld, and more than 20 m at the sandveld. The study concentrated on the sandveld area.

As a result of the lack of permanent surface water bodies, residents of Serowe village (at the eastern flank of the escarpment) are largely dependent on groundwater resources that are mainly replenished by the scant and erratic rainfall, of which only a small quantity escapes water consumption by the rather dense savanna vegetation.

8.3 Rainfall series

Annual average rainfall in the study area was 437 mm for the observation period 1925-2004, with a minimum of 119 mm and a maximum of 970 mm. Precipitation is largely restricted to the summer period from October to April. Precipitation is mainly of a convective nature and most rainwater comes down during storm events in typical quantities of the order of 20-50 mm.

Chapter 2 focused on rainfall variability within the study area. Based on data from 11 rain gauges (10 installed for the current study and one from the Department of Meteorological Services), it has been shown that within the study area, rainfall is spatially highly variable but that rainfall at un-gauged locations can be reasonably estimated by the observations from the most near gauged location.
8.4 Evapotranspiration assessment

In Chapter 3, potential evapotranspiration (PET) was analysed with the Penman-Monteith equation. Actual evapotranspiration (AET) was estimated with the Bowen ratio surface energy balance (BSEB) and the temperature profile surface energy balance (TSEB) approaches. The calculations were based on microclimatic monitoring data obtained from 11 automated monitoring sites (GS00-10).

The Penman-Monteith PET in the Kalahari indicated large temporal variability, ranging from 0.1 to 6.1 mm/d. The AET obtained with BSEB and TSEB approaches ranged from 0.1 to 3.5 mm/d. On average annual time scale, the calculated actual evapotranspiration exceeds the annual rainfall, and thus the present methods overestimate the evapotranspiration. The overestimation is likely attributed to algorithm problems of the surface energy balance. In addition, direct root extraction from the aquifer at greater depths is likely to be restricted to the deep rooters (such as *B. albitrunca*, *A. erioloba* and *S. longipedunculata*) and also extensive advective-diffusive upward water movement from depths in excess of 70 m is unlikely (Chapter 4). However, it is taken that the obtained PET data are useful as input for water transport modelling and for further analysis of spatial and temporal variability.

In order to analyze PET spatially and to provide input for hydrological models, an attempt was made to derive PET not only at monitoring locations where the complete PET data input was available (e.g. GS00 and GS10), but also at those monitoring sites where wind speed was not recorded. For that purpose, a 10 m high mobile tower was shifted between those locations not equipped with anemometers (GS01-07) and the obtained data was correlated with the wind speed data of permanent stations. The obtained correlations were surprisingly good, due to the homogeneous wind speed characteristic in the Kalahari. These interrelations finally made the estimation of PET distribution possible, which for the same reason as wind speed, turned out to be also spatially homogeneous.
Summary and conclusions

More accurate $AET$ determination methods of practical nature are required because eddy correlation and scintillometry are often too expensive to be justified in regional groundwater projects.

8.5 Tree transpiration assessment

Tree transpiration was monitored in the study area, for a period of more than two years, using TDP tree sap velocity measurements at seven sites (GS01-07), on 5-6 trees at each site. In total 41 measurements were carried out on the selected nine tree species. The individual tree sap flows were temporally variable, with higher flows in wet summer seasons than in dry winter seasons. In order to estimate tree transpirations on plot level scale, the sap flow measurements were upscaled to seven 30x30m plots, surrounding the GS01-07 monitoring sites. Tree plot transpiration was additionally calculated by extrapolation for site GS08, where no sap flow monitoring equipment was installed, using the biometric upscaling functions obtained for each tree species and the average (except for $B. \text{ africana}$ in which a single tree was measured) sap velocity measurements for each species.

The daily plot tree transpiration, varied from nearly zero in the dry season to 0.4 mm/d in the wet season. The annual plot tree transpiration calculated for the eight plots, pointed at low variability of inter-annual tree transpiration, but high spatial variability among the plots, ranging from 3 to 71 mm/yr per plot. Since annual rainfall is of the order of 440 mm, this means that more than 350 mm/yr is lost by transpiration of grass and shrubs as well as from direct evaporation from the upper shallow subsurface layers and from interception. The annual plot level tree transpiration did not show a direct dependency on the yearly rainfall, suggesting that trees mainly use water from much deeper layers instead of soil water from the upper shallow layers. This hypothesis was confirmed by analysis of the depth from which soil water was extracted by the trees, with the help of environmental isotopes ($^2\text{H}$ and $^{18}\text{O}$) (Chapter 6).
8.6 Rooting depth investigation

In Chapter 5, the rooting depths of 19 trees in the Kalahari sandveld and hardveld were investigated in native savanna habitat; groundwater table depths in these areas range from 8 m to more than 70 m. The rooting depths were explored by putting lithium chloride as a tracer in deep boreholes; subsequently, young (immature) leaves of nearby trees were analysed during consecutive days to detect and monitor the uptake of the tracer.

Represented in this experiment were seven variously-aged tree species (*A. erioloba*, *A. fleckii*, *B. albitrunca*, *D. cinerea*, *S. longipedunculata*, *T. sericea* and *Z. mucronata*). The trees were able to absorb the tracer within a few days from varied placement depths, ranging from 8-70 m. This means that the mentioned tree species can develop roots to depths of more than 8-70 m in order to reach deep sources of moisture in water-scarce ecosystems such as the Kalahari desert.

8.7 Determination of water sources used by vegetation

The stable isotopic signature of xylem water for six trees and the associated isotopic composition in soil and groundwater at four sites were investigated in Chapter 6. The objective of the investigation was to identify the depths from which water was extracted by trees, particularly during the dry season. The results show a range of isotopic signatures, indicating that most of the Kalahari trees such as *A. erioloba*, *B. albitrunca* and *S. longipedunculata* made predominantly use of soil water that was extracted from depths of more than 3 m (that is below the main root zone of shrubs and grasses). There is, however, evidence that *A. fleckii*, *A. karoo* and *Z. mucronata* also made use of more shallow water, which in the case of *A. fleckii* meant extraction under suctions that exceeded the permanent wilting point of 1.47 MPa.
8.8 Soil moisture regimes, groundwater level fluctuations and groundwater recharge

Natural groundwater recharge characteristics for the study area have been evaluated in Chapter 7 using rainfall, evapotranspiration, soil moisture and groundwater level observations, acquired by various methods. The sensors used for soil moisture observations were connected to data loggers that also controlled and stored data for evapotranspiration (Chapter 3) and sap flow analysis (Chapter 4).

Soil moisture and matric pressure profiles showed the occurrence of diffuse as well as preferential flow components in rainwater infiltration. The deepest soil profile (76 m) at GS10 indicated that downward soil moisture transport during the period of observation only reached up to 22 m. This might reflect removal of percolate by soil water extraction by deep roots up to 22 m b.g.s. This observation brings into focus the question of how widespread recharge in the Kalahari is. Perhaps it is confined to a few locations where preferential flow is important, such as depressions where rainwater accumulates, and/or areas with high permeability, for instance where fractures in hard rock or duricrust at or near the surface facilitates fast infiltration. The lack of significant variation in soil moisture signals at greater depths can also be explained as residual moisture from earlier major rainfall events, otherwise it could be an artefact of measuring equipment or influence of deep rooting systems.

Groundwater level response to rainfall vary from site to site; the differences in reaction depend mainly on site-specific differences in topographic features, vegetation characteristics, soil physical properties and local aquifer hydraulic characteristics. Groundwater level fluctuations in boreholes in this study were used to assess groundwater recharge. Three recharge estimation approaches were applied: linear reservoir (LINRES), water table fluctuation (WTF) and EARTH lumped parameter model. LINRES and WTF make use of the estimated change in aquifer storage, whereas EARTH is based on a combination of modelling of rainfall, evapotranspiration, moisture transport and groundwater level fluctuations. The EARTH model in
this study was calibrated by estimated model parameters in combination with dry season tree transpiration data, acquired through sap flow measurements, and by groundwater level observations. Soil moisture measurements were not directly used in this modelling exercise because they represent small scale processes that cannot be easily extended to large scale processes.

It is evident that groundwater level fluctuation will be reduced by high attenuation of the seasonal water flux, because the flux will then approach a steady state. Accordingly, the aforementioned methods will under such conditions underestimate the groundwater flux to the water table. On the other hand, a strong reaction of the groundwater table can be the result of local conditions of focused recharge by accumulation of water at the surface and/or preferential flow. Thus regionalized recharge figures based on boreholes which produce a clear reaction on rainfall might be too high.

LINRES and WTF recharge estimates gave comparable results, but EARTH resulted in higher values. The outcome of the recharge calculation ranges between 0 and 150 mm/yr; the latter extreme value is from a location with focused infiltration in an ephemeral stream valley on the hardveld. An overall groundwater recharge average seems to be in the order of 15 mm/yr. Since the overall regional groundwater discharge out of the considered region is estimated at 4 mm/yr, this means that groundwater extraction by deep rooting trees is of the order of 10 mm/yr.

Although the applied methods suffer from a lack of adequate data as well as from conceptual uncertainties, the results are in the order of magnitude which is not much different from previous investigations with chloride mass balances and isotopic tracers, under comparable conditions in the Kalahari, 300 km to the south. In that area groundwater recharge values in the range from 4-12 mm/yr were obtained (Selaolo, 1998; De Vries et al., 2000). It should be noticed that tracer studies normally give, in contrast to the methods used in this study, recharge values that represent average conditions on a longer time scale; in the Kalahari generally tens of years.
8.9 Conclusions

The main conclusion is that this study has proved that several tree species in the Kalahari desert are able to extend their roots to great depths, of more than 70 m locally, and to extract soil water and/or groundwater from such depths. This means that water which has escaped evapotranspiration in the main root zone (the upper 4 m), and has percolated to greater depths or even has reached the groundwater table, can still be subjected to evapotranspiration. These findings are to be taken into consideration in groundwater recharge studies and evaluation of sustainable resources in (semi-)arid areas. Additionally, this shows that a better understanding of moisture dynamics and water consumption in connection with climatic data in general, is essential for a sustainable use of the Kalahari environment and its resources.

8.10 Further research

Future research in the Kalahari should, apart from continuous general recharge investigations and monitoring, focus on water consumption by the various types of vegetation and on the partitioning of transpired water between water that is extracted from different depths of the unsaturated zone and that which originates from the saturated zone. This approach will likely provide important information on groundwater transpiration in areas with a deep groundwater table. Additionally, there is a need to investigate the existence of hydraulic redistribution (hydraulic lift and hydraulic descent\(^4\)) and vapour transport processes, since the role of these features has not yet been taken into consideration in the Botswana Kalahari. The existence and importance of these processes have been indicated by several studies e.g. Burgess et al. (1998), Schulze et al. (1998), Walvoord et al. (2002a, b), Ludwig et al. (2003), Hultine et al. (2004) and Kurz-Besson et al. (2006).

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\(^4\) Hydraulic descent is the vertical transfer of water from wet shallow layers to relatively dry deep layers resulting from root water transport and efflux to the soil.