University of Potsdam, Institute of Earth and Environmental Science

Analysis and management of low flows in small catchments of Brandenburg, Germany

Dissertation submitted to the Faculty of Mathematics and Natural Sciences at the University of Potsdam, Germany, for the degree of Doctor of Natural Sciences (Dr. rer. nat.) in Geoecology/Hydrology

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Abstract

Water management and environmental protection is vulnerable to extreme low flows during streamflow droughts. During the last decades, in most rivers of Central Europe summer runoff and low flows have decreased. Discharge projections agree that future decrease in runoff is likely for catchments in Brandenburg, Germany. Depending on the first-order controls on low flows, different adaption measures are expected to be appropriate. Small catchments were analyzed because they are expected to be more vulnerable to a changing climate than larger rivers. They are mainly headwater catchments with smaller ground water storage. Local characteristics are more important at this scale and can increase vulnerability.

This thesis mutually evaluates potential adaption measures to sustain minimum runoff in small catchments of Brandenburg, Germany, and similarities of these catchments regarding low flows. The following guiding questions are addressed: (i) Which first-order controls on low flows and related time scales exist? (ii) Which are the differences between small catchments regarding low flow vulnerability? (iii) Which adaption measures to sustain minimum runoff in small catchments of Brandenburg are appropriate considering regional low flow patterns?

Potential adaption measures to sustain minimum runoff during periods of low flows can be classified into three categories: (i) increase of groundwater recharge and subsequent baseflow by land use change, land management and artificial ground water recharge, (ii) increase of water storage with regulated outflow by reservoirs, lakes and wetland water management and (iii) regional low flow patterns have to be considered during planning of measures with multiple purposes (urban water management, waste water recycling and inter-basin water transfer). The question remained whether water management of areas with shallow groundwater tables can efficiently sustain minimum runoff. Exemplary, water management scenarios of a ditch irrigated area were evaluated using the model Hydrus-2D. Increasing antecedent water levels and stopping ditch irrigation during periods of low flows increased fluxes from the pasture to the stream, but storage was depleted faster during the summer months due to higher evapotranspiration. Fluxes from this approx. 1 km long pasture with an area of approx. 13 ha ranged from 0.3 to 0.7 ls^{-1} depending on scenario. This demonstrates that numerous of such small decentralized measures are necessary to sustain minimum runoff in meso-scale catchments.

Differences in the low flow risk of catchments and meteorological low flow predictors were analyzed. A principal component analysis was applied on daily discharge of 37 catchments between 1991 and 2006. Flows decreased more in Southeast Brandenburg according to meteorological forcing. Low flow risk was highest in a region east of Berlin because of intersection of a more continental climate and the specific geohydrology. In these catchments, flows decreased faster during summer and the low flow period was prolonged. A non-linear support vector machine regression was applied to iteratively select meteorological predictors for annual 30-day minimum runoff in 16 catchments between 1965 and 2006. The potential evapotranspiration sum of the previous 48 months was the most important predictor ($r^2 = 0.28$). The potential evapotranspiration of the previous 3 months and the precipitation of the previous 3 months and last year increased model performance ($r^2 = 0.49$, including all four predictors). Model performance was higher for catchments with low yield and more damped runoff. In catchments with high low flow risk, explanatory power of long term potential evapotranspiration was high.

Catchments with a high low flow risk as well as catchments with a considerable decrease in flows in southeast Brandenburg have the highest demand for adaption. Measures increasing groundwater recharge are to be preferred. Catchments with high low flow risk showed relatively deep and decreasing groundwater heads allowing increased groundwater recharge at recharge areas with higher altitude away from the streams. Low flows are expected to stay low or decrease even further because long term potential evapotranspiration was the most important low flow predictor and is projected to increase during climate change. Differences in low flow risk and runoff dynamics between catchments have to be considered for management and planning of measures which do not only have the task to sustain minimum runoff.

Zusammenfassung

Sowohl Gewässermanagement als auch die Gewässerökologie können durch extreme Niedrigwasserereignisse stark betroffen sein. In den letzten Jahrzehnten haben sowohl der Abfluss während der Sommermonate als auch die Niedrigwasserabflüsse in den meisten Flüssen Zentraleuropas abgenommen. Projektionen des zukünftigen Abflusses lassen einen weiteren Rückgang der Abflüsse aus Einzugsgebieten Brandenburgs erwarten. Anpassungsmaßnahmen zur Stützung von Niedrigwasserabflüssen müssen den hydrologischen Prozessen gerecht werden. In dieser Arbeit werden kleine Einzugsgebiete betrachtet, weil sie anfälliger gegenüber dem Klimawandel erscheinen als größere. Es handelt sich hierbei hauptsächlich um Kopfeinzugsgebiete mit kleineren Grundwasserspeichern. Lokale Gegebenheiten können darüber hinaus ihre Vulnerabilität erhöhen.

In dieser Arbeit werden Ergebnisse über die Ähnlichkeit von kleinen Einzugsgebieten verwendet, um geeignete Anpassungsmaßnahmen zur Stützung von Niedrigwasserabflüssen herauszuarbeiten. Folgende Leitfragen werden bearbeitet: (i) Was sind die maßgeblichen Prozesse und Zeitskalen, die zu Niedrigwasserabflüssen führen? (ii) Wie unterscheiden sich die Einzugsgebiete bezüglich ihrer Vulnerabilität? (iii) Was sind geeignete Anpassungsmaßnahmen unter Berücksichtigung der vorherrschenden Prozesse und ihrer räumlichen Muster?

Mögliche Anpassungsmaßnahmen können in drei Kategorien unterteilt werden: (i) Landnutzungsänderungen, Änderungen der Feldbewirtschaftung und künstliche Grundwasseranreicherung führen zur Erhöhung der Grundwasserneubildung und somit des Basisabflusses. (ii) Talsperren, Seen, Teiche und ein entsprechendes Wassermanagement in Feuchtgebieten eignen sich zur Wasserspeicherung und regulierten Wasserabgabe. (iii) Maßnahmen bei deren Planung Wissen über Niedrigwasserabflüsse einfließen muss, aber die Stützung von Niedrigwasserabflüssen nicht die einzige Aufgabe ist (Siedlungswassermanagement, Abwassermanagement und Wasserüberleitungen zwischen Einzugsgebieten). Darüber hinaus wurde die Effektivität ufernaher Grundwasseranreicherung durch bestehende Bewässerungsgräben explizit an einem Standort unter Verwendung des Models Hydrus-2D quantifiziert. Hohe Wasserstände in den Gräben und das Unterbrechen der Wassereinleitung führten zu einer Niedrigwasseraufhöhung. Im Sommer wurde der Wasserspeicher wegen der Verdunstung schneller verbraucht. Je nach Szenario betrug die Niedrigwasseraufhöhung,die von der ca. 1 km langen und 13 ha großen Fläche ausging, zwischen 0.3 und 0.7 ls^{-1}. Eine Vielzahl solcher dezentraler Maßnahmen wären für eine deutliche Stützung der Niedrigwasserabflüsse in mesoskaligen Einzugsgebieten notwendig.

Das Niedrigwasserrisiko sowie meteorologische Niedrigwasserprädiktoren wurden vergleichend analysiert. Der tägliche Abfluss aus 37 Einzugsgebieten zwischen 1991 und 2006 wurde mittels einer Hauptkomponentenanalyse ausgewertet. Der Abfluss in Südost Brandenburg ging klimabedingt stärker zurück. Das Niedrigwasserrisiko war in der Region östlich Berlins als Folge des kontinentaleren Klimas und der lokalen geohydrologischen Verhältnisse am größten. Diese Einzugsgebiete zeigten einen relativ schnellen Abflussrückgang während der Sommermonate und eine längere Niedrigwasserperiode. Darüber hinaus wurde eine nichtlineare Support Vektor Machine Regression zur iterativen Bestimmung der meteorologischen Prädiktoren für den jährlichen Niedrigwasserabfluss im 30-Tage Mittel in 16 Einzugsgebieten zwischen 1965 und 2006 durchgeführt. Die potentielle Verdunstungshöhe der vorhergegangenen 48 Monate war der wichtigste Prädiktor ($r^2 = 0.28$). Die potentielle Verdunstungshöhe der vorhergegangenen 3 Monate sowie die Niederschlagshöhe der vorhergegangenen 3 Monate und des letzten Jahres verbesserten die Modellgüte zusätzlich ($r^2 = 0.49$, für alle vier Prädiktoren). Die Modellgüte war höher in Einzugsgebieten mit geringer Abflussspende und gedämpftem Abflussverhalten. In Einzugsgebieten mit hohem Niedrigwasserrisiko war die potentielle Langzeitverdunstung wichtiger, um Niedrigwasserabflüsse zu erklären.

In Einzugsgebieten mit hohem Niedrigwasserrisiko östlich von Berlin und deutlichem Abflussrückgang im Südosten Brandenburgs besteht der höchste Anpassungsbedarf. Maßnahmen zur Erhöhung der Grundwasserneubildung sollten bevorzugt werden. Einzugsgebiete mit hohem Niedrigwasserrisiko haben verhältnismäßig tiefe Grundwasserstände, was eine Erhöhung der Grundwasserneubildung in den höher gelegenen Neubildungsgebieten möglich und sinnvoll macht. Es ist davon auszugehen, dass Niedrigwasserabflüsse weiterhin niedrig bleiben oder sogar weiter fallen werden, da die potentielle Langzeitverdunstung der wichtigste Prädiktor war und Klimamodelle einen weiteren Anstieg dieser projizieren. Des Weiteren sind die Ergebnisse dieser Arbeit wichtig für die integrierte Planung von Maßnahmen, die nicht ausschließlich die Stützung von Niedrigwasserabflüssen zur Aufgabe haben.

Contents

1 Introduction

1.1 Motivation

Smakhtin (2001) points out that low flow is a seasonal phenomenon, but drought is the result of abnormally low precipitation occurring over an extended period of time and area which can further result in below average soil moisture, groundwater levels and streamflows. Low flows are important to be considered in water resource management regarding water quality and quantity (Laaha and Blöschl, 2007). In northeast Germany measured (Stahl et al., 2010) and projected (Menzel and Burger, 2002; Milly et al., 2005; Wegehenkel and Kersebaum, 2009) negative streamflow trends increased the awareness of river low flows. Most studies focussed on larger river basins considering hydro power plants (Koch and Vogele, 2009), water allocation for the flooding of mining lakes (Koch et al., 2005), reservoir operation (Medellin-Azuara et al., 2008) and water management in entire river basins (Giacomelli et al., 2008). The relatively small groundwater storage gives reason to expect small catchments to be affected first by changing climate. Local processes become more important with decreasing catchment area (Blöschl et al., 2007) which can additionally increase vulnerability. Nevertheless, research on adaption measures to sustain minimum runoff in small catchments is scarce.

In small catchments adaption measures are necessary (i) to lower the probability of failing of an existing water management which is important for local water users (e.g. fishery) and (ii) to ensure environmentally required minimum runoff to protect flora and fauna and to guarantee good water quality. Knowledge on the first-order controls and catchment similarity regarding low flows (Chapter 4 and 5) is the basis to define appropriate adaption measures to sustain minimum runoff (Chapter 1 and 2).

1.2 Scientific background

Drought and water scarcity have to be distinguished in order to understand changes and severity of low flows (Van Loon and Van Lanen, 2013). Drought is caused by negative precipitation anomalies, while water scarcity is the consequence of unsustainable water use. Water managers can directly influence water scarcity but not drought. Ground water storage plays an important role in the evolution of streamflow droughts (Mishra and Singh, 2010) and base flow is often the main contribution during low flows. Groundwater storage is the main reason for long-term memory of the systems and pooling of multiple precipitation deficits. Different drought types are considered important for rivers in the mid-latitudes (Van Loon and Van Lanen, 2012). Rainfall deficit droughts are the most common ones, but cold and warm snow season droughts, rain-to-snow-season droughts and composite droughts probably cause more severe drought events. The focus of this thesis is on annual low flows and their anomalies especially during streamflow droughts.

There are mainly two different approaches to define low flows on an annual basis (Smakhtin, 2001). First, the volume, duration, intensity, start and end of low flows can be defined applying the threshold level approach (Yevjevich, 1967; Van Loon and Van Lanen, 2012). The threshold itself can be defined from flow statistcs (e.g. percentile of flow duration curve) or by water managers according to water demand. The threshold can be fixed or vary in time (e.g. seasonal pattern, monthly or daily threshold). Low flow consequently takes place when discharge is below the threshold. On the one hand, this approach has the advantage that various characteristics of the low flow events can be extracted. On the other hand, several choices on the calculation and temporal resolution of the threshold have to be made, and during years with higher flows, deficit volume and duration is always zero. Second, low flow can be defined as the lowest value within a specific time interval (Smakhtin, 2001). Here, the interval (usually month, year or multiple years) and the length of a moving average applied as filter have to be chosen. Calculations are mainly based on daily or monthly data. The low flow is consequently defined as the lowest averaged value in every interval. The advantage of this approach is that for every time interval a low flow is defined. This method still defines a low flow even if no extreme low flow is apparent in a time interval. In this thesis the second approach is applied because (i) the focused is on low flow as an seasonal phenomenon rather than an extreme event, and (ii) the differences between years with extreme low and high low flows are expected to be important to understand the processes and flow paths.

Northeast Germany is situated in a transition zone regarding climate as well as past and expected changes in runoff. Stahl et al. (2010) analyzed a pan-European dataset of annual, monthly and annual 7-day minimum flows (AM(7)). Between 1962 and 2004 annual flows decreased in Southern Europe and increased in northern catchments. In Northeast Central Europe trends are negative for many catchments. The spatial pattern of monthly flows during the summer months is even more homogeneous with negative trends for most catchments all over Europe. Most of the catchments in Central Europe also show negative trends in AM(7) and later occurrence of low flows during the year. Measured trends agree with those of an ensemble of large scale models (Stahl et al., 2012). These model results were able to fill the area of Northeast Germany which has not been considered in the previous data based study. Results confirm decreasing runoff trends, especially during summer months and for AM(7). The main pattern in standardized 3-monthly precipitation over the last 60 years also shows clear negative trends over Southeast Europe and positive trends over Great Britain and Denmark (Bordi et al., 2009). Trends in atmospheric inputs can lead to even more distinct trends in discharge because of damping and storage within a catchment and consequently higher proportion of low-frequencies in the time series (Gudmundsson et al., 2011b; Kumar and Duffy, 2009). Comparable spatial gradients were found in the low frequency component of discharge, precipitation and temperature (Gudmundsson et al., 2011b) and spatial cross-correlation patterns of low flows in Europe (Gudmundsson et al., 2011a). Global climate projections agree on decreasing precipitation in the Mediterranean area and increasing precipitation over Scandinavia (IPCC, 2007, A1B scenario, comparison between 1980–1999 and 2080–2099). Model ensembles do not agree significantly on the direction of change in precipitation in Northeast Germany. Consequently, the direction of change in runoff cannot be identified using the results of climate models and largely depends on the first-order controls on low flows (precipitation versus evapotranspiration) as well as on landscape and geohydrology of the catchments.

Various approaches have been used in low flow research. The relevance of meteorological variables and patterns, involved time scales, drought or low flow indices and correlations with catchment properties has been a key issue of recent research. Depending on the objectives and study area of the studies, different approaches have been used. Descriptive and retrospective studies have used models in order to regionalize measurements (Vidal et al., 2010; Holsten et al., 2009; Stahl et al., 2012), indices based on meteorological input data were developed and tested (Bordi et al., 2009; Vicente-Serrano et al., 2012; Demirel et al., 2012; Li et al., 2010), meteorological patterns and weather types were used (Piechota and Dracup, 1996; Tootle et al., 2007; Giuntoli et al., 2013; Fleig et al., 2011, 2010; Samaniego and Bardossy, 2007) and methods were directly based on streamflow datasets (Lorenzo-Lacruz et al., 2013; Pfister et al., 2006). Various drought indices have been developed, and their performance depends on the hydrologic system as well as specific objectives of each study (Dogan et al., 2012; Mishra and Singh, 2010; Vicente-Serrano et al., 2012). The applicability of an approach strongly depends on the hydrometeorology of a research area. For example, the use of sea-surface temperatures was promising to predict low flows in areas with a maritime climate (Tootle et al., 2007; Li et al., 2010). Wibig (1999) showed the association of weather types with precipitation amounts for several regions of Europe. More complex weather type classifications have evolved, which help to understand the development of streamflow droughts and low flows (Fleig et al., 2010; Samaniego and Bardossy, 2007). The regionalization of low flows is additionally important for various purposes of water resource management, and different methods exist (Laaha and Blöschl, 2007, 2006).The state-of-the-art literature shows that variables which can be used as low flow predictors differ according to the meteorology of a region. A large pool of potential predictors has been described, but no agreement on which predictors are suited best for specific regions has been reached. Krysanova et al. (2008) compared different drought indices for the Elbe catchment. There is a lack of information on the consistency of results for small headwater catchments.

hydrologic similarity is important to understand low flow vulnerability of catchments to a changing climate. Information on the internal hydrologic behavior of catchments is particularly needed to identify similarities regarding catchment response (Buttle, 2006). A general framework for catchment classification and hydrologic similarity does not exist (Wagener et al., 2007). Model parameters (e.g. Sivapalan et al., 2011), streamflow indices (e.g. Sawicz et al., 2011) and analyses on streamflow time series (e.g. Gudmundsson et al., 2011b) are used to define hydrologic similarities. Wagener et al. (2007) give a comprehensive review on catchment classification and hydrologic similarity. It is known that similarity in discharge between neighbouring catchments decreases with lower flows (Patil and Stieglitz, 2011; Gudmundsson et al., 2011a). Results from studies without any focus on low flows should not be used to describe hydrologic similarity under low flow conditions without restrictions. Consequently, results on catchment similarity during low flows are needed for water resources planning.

The water balance equation (Dyck and Peschke, 1995) of a catchment can be extended by water allocation and regulated storage to

$$Q = P - ET + R_{in} - R_{out} + \Delta S_r + \Delta S \quad (1.1)$$

where Q is discharge, P precipitation, ET evapotranspiration, R_{in} water allocation to the catchment, R_{out} water allocation from the catchment, ΔS_r the change in managed reservoir storage and ΔS the remaining change in storage. In case of anthropogenic impacts, such as reservoirs, part of stored water can be directly managed.

Adaption measures discussed in this thesis aim at changing all terms in equation 1.1 except precipitation. The water balance equation can already give some conclusions for adaption measures to sustain minimum runoff, even though it does not explicitly describe extreme events: (i) There is an upper limit of water which can be used to increase storage for later release on demand if no water allocation to and from a catchment can be regulated and water management is sustainable, (ii) there is a systematic difference between stored water which can be directly released on demand (e.g. reservoirs, groundwater recharge and recovery) and which indirectly increases baseflow (e.g. land use change, groundwater reharge) and (iii) if water management rules exist several terms of the equation become interdependent because storage and water allocation are managed according to discharge (Q), precipitation (P) or other variables.

Adaption and mitigation are part of the international strategy to minimize impacts due to climate change. Most global initiatives aim at mitigation by lowering the emission of greenhouse gases. Nevertheless, adaption becomes an important issue for regional and local strategies to lower impacts by climate change (Ikeme, 2003). According to IPCC (2012), adaption is defined as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities". It has to be recognized that uncertainties in projections hinder the development of an optimal adaption strategy (Barnett, 2001). As a consequence, adaption strategies should aim at no-regret-options and at strengthening the resilience of a system. De Loe et al. (2001) give examples of adaption options regarding the Canadian water sector. They showed appropriate measures for different stakeholders and claim that decisions have to be based on their implications for water and not only on short-term political gains. Adaption strategies need to change existing water management structures and will give rise to conflicts with stakeholders. As a consequence, it is a transdisciplinary task which needs to incorporate scientists and stakeholders (Knierim et al., 2010). This thesis elaborates the hydrologic background at the regional scale, which is necessary for subsequent discussions with stakeholders and implementations of measures.

The previous section described various methods in the field of catchment similarity and drought/low flow hydrology. Based on the results and methodologies of previous studies, differences in the low flow hydrology of catchments and the relation between low flow, weather forcing and catchment properties are analyzed in this thesis (Chapter 4-5). As depicted by the extended water balance equation, understanding the processes and relation of low flow to meteorological variables is important to define appropriate adaption measures (Chapter 6) which change fluxes and storages in the catchment.

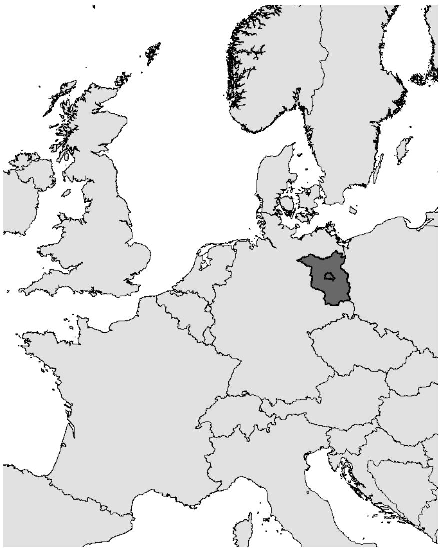

Figure 1.1: Location of the Federal State of Brandenburg in Europe and the German capital Berlin in the centre of Brandenburg. The map is based on the federal state boundaries 1:250,000 (German Federal Agency for Cartography and Geodesy, BKG) and countries of Europe (Environmental Systems Research Institute, Inc. (ESRI), Redlands, California, USA).

1.3 Regional framework

Brandenburg is located in Northeast Germany at its border with Poland (Figure 1.1). The federal state has an area of 29,479 km^2. Water is discharged either to the Baltic Sea by the river Oder or to the Northern Sea by the river Elbe. The river network is given in Figure 1.2. Water courses have been altered by humans for centuries (Nützmann et al., 2011). The landscape has been formed since the last glaciations. The ground mainly consists of glacio-fluvial deposits with several Quaternary aquifers (Nathkin et al., 2012). Soils are relatively young and mainly consist of sands and loamy sands, but less permeable soils also occur (Schindler and Müller, 2010). Close to rivers and at moist areas, gley and peat soils evolved. Cambisols, albeluvisols and luvisols are the most frequent soil types (Lieberoth, 1982). Groundwater heads of the first aquifer can be observed at the surface but also more than 50 m below ground depending on the relief condition. For most areas groundwater levels have decreased in the last decades (Germer et al., 2011). Surface relief and gradients are low and the altitude is ranges from 1 to 200 m.a.s.l.. The high soil permeability ensures groundwater recharge in most years despite the sub-humid climate. Nevertheless, at the forest sites at drier areas groundwater recharge is very low (Schindler et al., 2008). Interflow occurrence is limited and baseflow is the main water source during low flows, especially because of the mainly fast-draining soils.

In general, the hydrology in this post glacial landscape and at the meso-scale can be described as complex (Merz et al., 2009). Interactions between the aquifers and between aquifers and surface water are difficult to assess because of high heterogeneity. The surface and subsurface catchment boundaries do not equal and subsurface catchment boundaries can vary in time (Holzbecher, 2001). This is mainly due to changing groundwater levels and evolving gradients between neighbouring catchments. In this thesis numerous catchments are analyzed whereas the subsurface catchment boundaries could not be studied. Calculated areal yields applying the surface catchments have large uncertainties and are obviously wrong for some catchments. Appropriate scaling of the data and methodologies which do not need absolute values are needed. In this landscape it is impossible to calibrate a valid catchment model without a detailed survey of the geohydrologic processes.

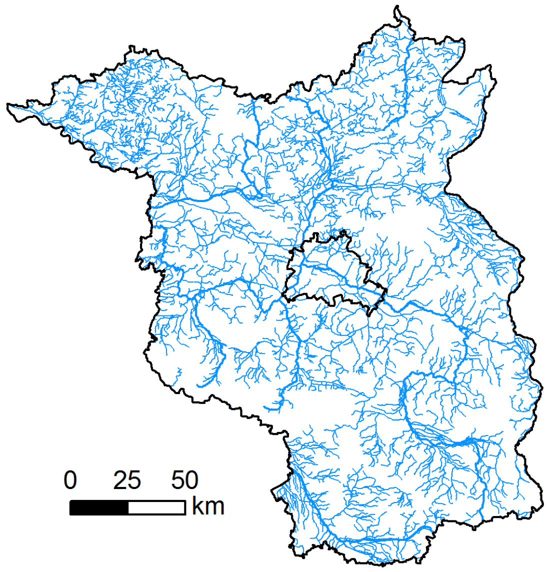

Figure 1.2: River network in the Federal State of Brandenburg, Germany. The map is based on the federal state boundaries 1:250,000 (German Federal Agency for Cartography and Geodesy, BKG) and river network data (MUGV, 2012).

Brandenburg is located at the transition zone between maritim and continental climate with an annual long-term precipitation sum of 556 mm and an annual long-term potential evapotranspiration sum of 592 mm between 1961 and 1991 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2003). The annual long-term mean temperature is 8.7 °C. Monthly long-term precipitation and potential evapotranspiration sums show that precipitation amounts are higher during the summer months, but only in the winter half year the climatic water balance (precipitation minus potential evapotranspirations) becomes positive (Figure 1.3). This implies that most groundwater recharge takes place during the winter half year or during storm events in summer (LUGV, 2000). Mean annual discharge (1976–2005) was estimated to be 128 mm by water balance modelling (MUGV, 2012).

The maximum catchment size was defined to be 500 km^2 following the definition of the ministry. This is within the meso-scale in hydrology (e.g. Exbrayat et al., 2010; Niehoff et al., 2002). This work is focused on small catchments because less attention has been given to adaption measures on this scale. Severe changes up to drying of a whole river segment during a low flow period have been observed (Ramelow et al., 2012). In the Federal State of Brandenburg, Germany, small catchments are mainly headwater catchments located at recharge areas and areas where the underground is highly heterogeneous (Hannappel and Voigt, 1997). Ground water levels are relatively deep. Especially, the moraine plateaus are characterized by relatively low discharge, low stream density, numerous depressions with-

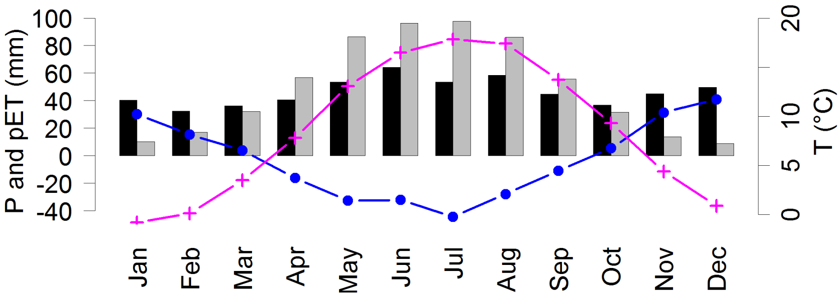

Figure 1.3: Long term (1961–1991) monthly precipitation sums (black bars), potential evapotranspiration sums (grey bars, method: Turc/Ivannov), climatic water balances (blue dots) and mean temperatures (magenta crosses) for Brandenburg. Calculations are based on areal means taken from the hydrologic Atlas of Germany (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2003).

out discharge, and a high significance of baseflow. In catchments affected by lignite mining, sustaining minimum runoff is also important to guarantee dilution of sulphur concentration to stabilize water quality.

More than 100 discharge gauges related to small catchments are maintained by the Ministry of the Environment, Health and Consumer Protection of the Federal State of Brandenburg. Combined with meteorological data and catchment properties, they are a valuable source of information to identify relevant processes and catchment similarity in this landscape. Discharge measurements differ in length, precision, temporal resolution, and catchments are differently anthropogenically impacted. In the different articles catchments had to be excluded from the analyses according to these constraints.

Several regional modeling studies have been performed for Brandenburg or the Elbe basin (e.g. Conradt et al., 2012; LUGV, 2000; Wechsung et al., 2000), but a data-driven comparison of catchments has not been carried out. Models focus on hydrologic response units rather than on catchment boundaries. The complex landscape and anthropogenic impacts complicate calibration. The large scale models could not be calibrated according to observed data but needed parameter regionalization and calibration on quasi-natural discharge conditions (Conradt et al., 2012). Statistical data-driven approaches are useful to extract spatial low flow patterns from the measured data and do not need assumptions about the governing processes and geohydrology. Moreover, spatial as well as temporal patterns derived by statistical data analysis can afterwards be used to validate models (Kirchner, 2006).

For the last centuries, the hydrologic system has been altered by humans. Some of the artificial streams and ditches have existed for more than 100 years. During the second half of the 20th century, human impacts intensified. Agricultural areas were artificially drained by melioration measures like combined tile and ditch drainage systems at many fields and smaller wetlands. Larger wetlands were equipped with drainage and sub irrigation systems to allow agricultural usage and peat extraction. Some catchments in the South of Brandenburg have been impacted by open pit lignite mining which started in the 19th century. Groundwater which is extracted to keep the mines dry has been discharged to the rivers, and today huge amounts of water are needed to refill the groundwater and flood the remaining pit holes for landscape restoration (Pusch and Hoffmann, 2000). A detailed description on human impacts on the hydrology of Brandenburg is given by Merz and Pekdeger (2011) and Germer et al. (2011).

1.4 Objectives

The overall research was carried out to analyze catchment similarity during low flows in order to be able to define appropriate adaption measures to sustain minimum runoff in small catchments of Brandenburg, Germany. Beyond the objectives of the review and research articles (Chapter 2 to 5), this thesis aims at answering the following guiding questions:

1.4.1 Guiding question 1: Which first-order controls on low flows and related time scales exist?

Comparison of future impacts on ground water recharge caused by land use change and climate change were modelled (e.g. Nathkin et al., 2012; Samaniego and Bardossy, 2006). Ground water recharge mainly takes place during winter months due to the stronger seasonality of evapotranspiration compared to precipitation (Figure 1.3 LUGV, 2000). Interflow (if existing) or flows from local aquifers decrease or diminish with increasing drought duration. The severity of low flows, most frequent in late summer, is mainly a consequence of groundwater levels and corresponding baseflow feeding the rivers. Every catchment is unique concerning its climatic boundary conditions and transformation of the precipitation signal in the vegetation layer, vadose zone and groundwater (Beven, 2000). The control of (i) precipitation and evapotranspiration and (ii) catchment properties (climate, vegetation and land use, landscape, soil and geology) on low flows of small catchments in Brandenburg has to be understood. The dependencies between first-order controls and temporal as well as spatial scale have to be analyzed. Chapter 4 and 5 aim at answering this guiding question.

1.4.2 Guiding question 2: Which are the differences between small catchments regarding low flow vulnerability?

In North America streamflow in drier catchments is more sensitive to climate change than in wet catchments (Singh et al., 2011). In Europe discharge patterns are explained by climatic differences (Gudmundsson et al., 2011b). It is assumed that landscape, geohydrology and vegetation become more important to explain discharge patterns with decreasing scale. Differences in climatic forcing seem to be negligible for a single aquifer system and 91% of the variation in groundwater heads of observation wells is explained by the damping according to depth (Lischeid et al., 2010).Potential evapotranspiration is expected to increase over the whole region, but no distinct changes in precipitation are expected on an annual basis (IPCC, 2007). Less precipitation during summer, more during winter months and more extreme precipitation and drought events are expected for the study area. Consequently, the relations between precipitation, temperature and low flows at different catchments are crucial to understand catchment vulnerability to climate change. Spatial low flow patterns have to be understood and attributed to processes in order to understand the influences of catchment properties on vulnerability. Chapter 4 and 5 aim at answering this guiding question.

1.4.3 Guiding question 3: Which adaption measures to sustain minimum runoff in small catchments of Brandenburg are appropriate considering regional low flow patterns?

Uncertainties in climate and streamflow projections hinder the development of an optimal adaption strategy (Barnett, 2001). Nevertheless, an increased knowledge on low flow processes (guiding questions 1 and 2) is expected to allow decisions on effective and appropriate measures. To conclude on appropriate adaption measures considering the regional hydrology, the results from Chapter 2 and 3 have to be intersected with the results related to guiding questions 1 and 2.

1.5 Outline of the thesis

Four articles are combined in this cumulative thesis in order to conclude on appropriate adaption measures to sustain minimum runoff based on regional low flow patterns and first-order controls. Figure 1.4 gives an overview of the organization of chapters and corresponding articles. Chapters 2–5 were originally written as review and research articles and are published or awaiting publication in international, peer-reviewed journals (the references are given on the first page of every chapter). These papers are reproduced unmodified except adding of chapter numbers to cross references.

Chapter 2 and 3 describe potential adaption measures and a case study evaluating one specific measure. Thomas et al. (2011, Chapter 2) give a review on studies on adaption measures to sustain minimum runoff in small catchments of the mid-latitudes. This review outlines potential measures which have to be evaluated for their use in Brandenburg. One of the reviewed measures has been evaluated under the conditions in Brandenburg. Gliege et al. (2013, Chapter 3) analyzed the potential of ditch water level management at a ditch irrigation site to increase base flow during low flows. Chapter 4 and 5 describe catchment similarities regarding low flow risk and the relation of low flows to standardized precipitation and potential evapotranspiration sums. Thomas et al. (2012, Chapter 4) analyze a data set of discharge at 37 catchments (daily time series, 1991-2006) in Brandenburg regarding low flow risk. A statistical framework was elaborated in order to extract the principal components of the discharge data, compare them to patterns in precipitation, catchment properties and analyze their time series. Thomas et al. (2013, Chapter 5) present a study on the first order controls on low flows in a data set of 16 catchments (mean annual 30-day minimum runoff, 1965-2006). The focus is on the temporal stability of relevant low flow predictors, the question if evapotranspiration or precipitation is more important to predict low flows and the relation to catchment properties. Finally, chapter 6 synthesizes the results of the catchment similarity studies according to the guiding questions and elaborates conclusions for adaption measures.

The major part of the work in chapter 1–2 and 4–6 was performed by the author of the thesis. Scientific discussions, minor drafting as well as commenting and proofreading by the co-authors is acknowledged. Chapter 3 is based on a diploma thesis which included supervision by the author of the thesis. The author of the thesis was involved in planning of the article, evaluation and analysis of the model results, writing parts of the paper, discussions, commenting and proofreading.

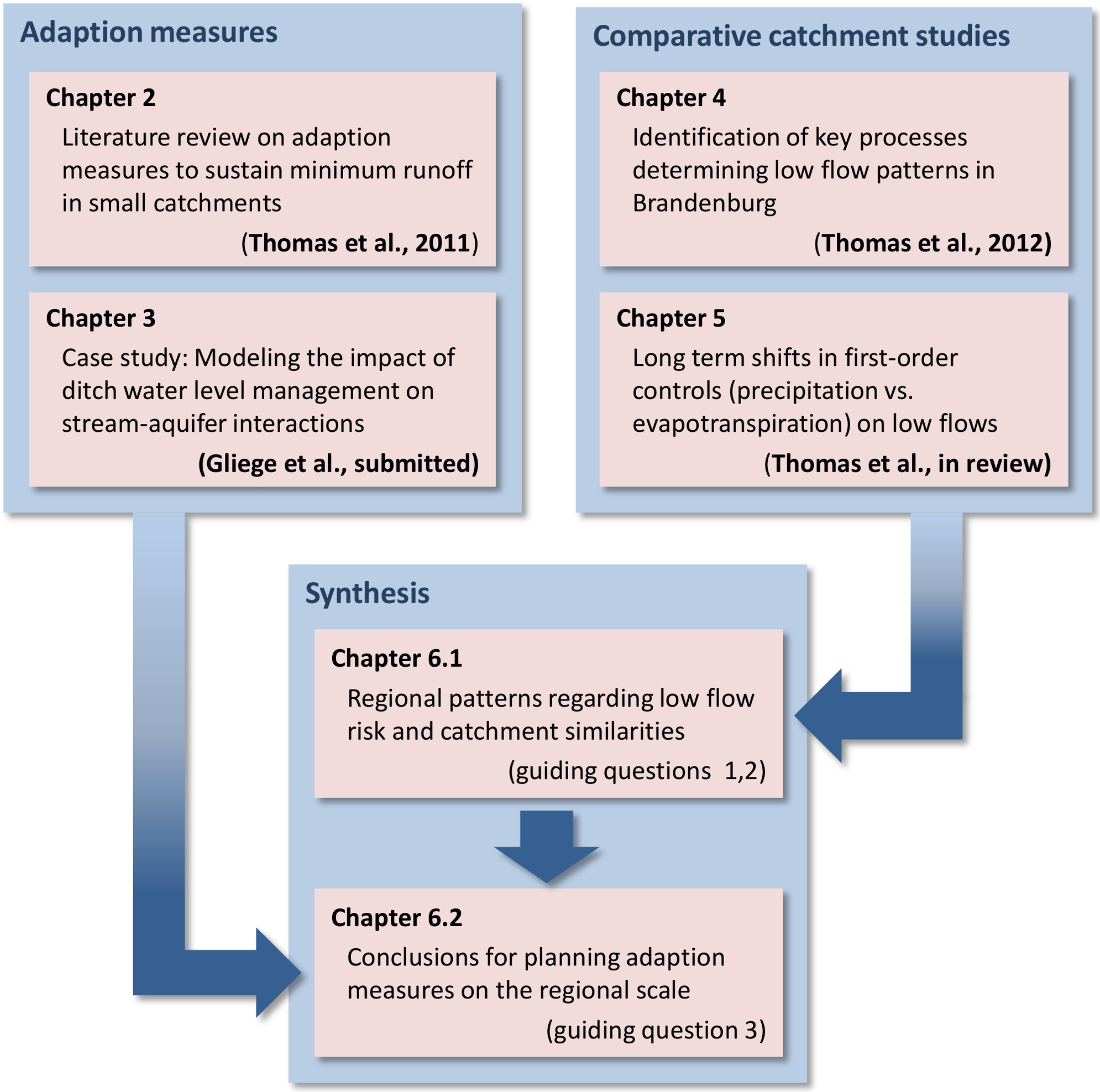

Figure 1.4: Graphical overview of the thesis.

References

Barnett, J. (2001). Adapting to Climate Change in Parcific Island Countries: The Problem of Uncertainty. *World Development 29*(6), 977–993.

Beven, K. J. (2000). Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth System Sciences 4*(2), 203–213.

Blöschl, G., S. Ardoin-Bardin, M. Bonell, M. Dorninger, D. Goodrich, D. Gutknecht, D. Matamoros, B. Merz, P. Shand, and J. Szolgay (2007). At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes 21*, 1241–1247.

Bordi, I., K. Fraedrich, and A. Sutera (2009). Observed drought and wetness trends in Europe: an update. *Hydrology and Earth System Sciences 13*(8), 1519–1530.

Buttle, J. (2006). Mapping first-order controls on streamflow from drainage basins: the T^3 template. *Hydrological Processes 20*, 3415–3422.

Conradt, T., H. Koch, F. Hattermann, and F. Wechsung (2012). Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change 12*(3), 633–648.

de Loe, R., R. Kreutzwiser, and L. Moraru (2001). Adaption Options for the near term: climate change and the Canadian water sector. *Global Environmental Change 11*, 231–245.

Demirel, M., M. J. Booij, and A. Hoekstra (2012). Identification of appropriate lags and temporal resolutions for low flow indicators in the River Rhine to forecast low flows with different lead times. *Hydrological Processes published online*, DOI: 10.1002/hyp.9402.

Dogan, S. K., A. Berktay, and V. P. Singh (2012). Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey. *Journal of Hydrology 470-471*, 255–268.

Dyck, S. and G. Peschke (1995). *Grundlagen der Hydrologie (engl.: fufundamental of hydrology)*. Verlag für Bauwesen, Berlin.

Exbrayat, J. F., N. R. Viney, J. Seibert, S. Wrede, H. G. Frede, and L. Breuer (2010). Ensemble modelling of nitrogen fluxes: data fusion for a Swedish meso-scale catchment. *Hydrology and Earth System Sciences 14*(12), 2383–2397.

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2003). *Hydrological Atlas of Germany 1961-1991 (Hydrologischer Atlas von Deutschland)*. http:// www.bmu.de.

Fleig, A. K., L. M. Tallaksen, H. Hisdal, and D. M. Hannah (2011). Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types. *Hydrological Processes 25*, 1163–1179.

Fleig, A. K., L. M. Tallaksen, H. Hisdal, K. Stahl, and D. M. Hannah (2010). Inter-comparison of weather and circulation type classifications for hydrological drought development. *Physics and Chemistry of the Earth 35*, 507–515.

Germer, S., K. Kaiser, O. Bens, and R. Hüttl (2011). Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region - a Review. *Die Erde 142*(1-2), 65–95.

Giacomelli, P., A. Rossetti, and M. Brambilla (2008). Adapting water allocation management to drought scenarios. *Natural Hazards and Earth System Sciences 8*(2), 293–302.

Giuntoli, I., B. Renard, J.-P. Vidal, and A. Bard (2013). Low flows in France and their relationship to large-scale climate indices. *Journal of Hydrology 482*, 105–118.

Gliege, S., L. H. Tobias, B. Thomas, J. Steidl, and O. Dietrich (2013). Modeling the impact of ditch water level fluctuations on stream-aquifer interactions. *Journal of Hydology submitted*.

Gudmundsson, L., L. M. Tallaksen, and K. Stahl (2011a). Spatial cross-correlation patterns of European low, mean and high flows. *Hydrological Processes 25*(7), 1034–1045.

Gudmundsson, L., L. M. Tallaksen, K. Stahl, and A. K. Fleig (2011b). Low-frequency variability of European runoff. *Hydrology and Earth System Sciences 15*(9), 2853–2869.

Hannappel, S. and H.-J. Voigt (1997). Beschaffenheitsmuster des Grundwassers im Lockergestein (engl.: Groundwater quality patterns in unconsolidated rock). In J. Matschullat, H. Tobschall, and H.-J. Voigt (Eds.), *Umweltgeochemie (engl.: Environmental geochemistry)*, pp. 360–393. Springer, Heidelberg.

Holsten, A., T. Vetter, K. Vohland, and V. Krysanova (2009). Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas. *Ecological Modelling 220*(17), 2076–2087.

Holzbecher, E. (2001). The dynamics of subsurface water divides - watersheds of Lake Stechlin and neighbouring lakes. *Hydrological Processes 15*(12), 2297–2304.

Ikeme, J. (2003). Climate Change Adaptional Deficiencies in Developimg Countries: the Case of Sub-Saharan Africa. *Mitigation and Adaption Strategies for Global Change 8*, 29–52.

IPCC (2007). Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC.

IPCC (2012). *Summary for Policymakers. In: Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaption.* Cambridge University press, Cambridge, UK, and New York, NY, USA.

Kirchner, J. W. (2006). Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research 42*, W03S04.

Knierim, A., V. Siart, S.and Toussaint, K. Müller, and H. Wiggering (2010). Development of climate change adaptation strategies within the transdisciplinary network INKA BB. In *Building sustainable rural futures : the added value of systems approaches in times of change and uncertainty ; proceedings of the 9th European IFSA Symposium, 4-7 July 2010 in Vienna, Austria.*

Koch, H., M. Kaltofen, U. Grunewald, F. Messner, M. Karkuschke, O. Zwirner, and M. Schramm (2005). Scenarios of water resources management in the Lower Lusatian mining district, Germany. *Ecological Engineering 24*(1-2), 49–57.

Koch, H. and S. Vogele (2009). Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics 68*(7), 2031–2039.

Krysanova, V., T. Vetter, and F. Hattermann (2008). Detection of change in drought frequency in the Elbe basin: comparison of three methods. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 53*(3), 519–537.

Kumar, M. and C. J. Duffy (2009). Detecting hydroclimatic change using spatio-temporal analysis of time series in Colorado River Basin. *Journal of Hydrology 374*(1-2), 1–15.

Laaha, G. and G. Blöschl (2006). Seasonality indices for regionalizing low flows. *Hydrological Processes 20*, 3851–3878.

Laaha, G. and G. Blöschl (2007). A national low flow estimation procedure for Austria. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 52*(4), 625–644.

Li, L. H., H. G. Xu, X. Chen, and S. P. Simonovic (2010). Streamflow Forecast and Reservoir Operation Performance Assessment Under Climate Change. *Water Resources Management 24*(1), 83–104.

Lieberoth, I. (1982). *Bodenkunde: Aufbau, Entstehung, Kennzeichnung und Eigenschaften der landwirtschaftland genutzten Böden der DDR (engl: Soil sience: structure, genesis, classification and properties of agricultural soils of the GDR)* (3. ed.). VEB Deutscher Landwirtschaftsverlag Berlin.

Lischeid, G., M. Natkhin, J. Steidl, O. Dietrich, R. Dannowski, and C. Merz (2010). Assessing coupling between lakes and layered aquifers in a complex Pleistocene landscape based on water level dynamics. *Advances in Water Resources 33*(11), 1331–1339.

Lorenzo-Lacruz, J., E. Moran-Tejeda, S. M. Vicente-Serrano, and J. I. Lopez-Moreno (2013). Streamflow droughts in the Iberian Peninsula between 1945 and 2005: spatial and temporal patterns. *Hydrology and Earth System Sciences 17*, 119–134.

LUGV (2000). Flächendeckende Modellierung von Wasserhaushaltsgrößen für das Land Brandenburg, Studien und Tagungsberichte 27 (engl.: water balance modelling across the whole area of the Federal State of Brandenburg). Technical report, State Office for Environment, Health and Consumer Protection of the Federal State of Brandenburg.

Medellin-Azuara, J., J. J. Harou, M. A. Olivares, K. Madani, J. R. Lund, R. E. Howitt, S. K. Tanaka, M. W. Jenkins, and T. Zhu (2008). Adaptability and adaptations of California's water supply system to dry climate warming. *Climatic Change 87*, 75–90.

Menzel, L. and G. Burger (2002). Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *Journal of Hydrology 267*(1-2), 53–64.

Merz, C. and A. Pekdeger (2011). Anthropogenic Changes in the Landscape Hydrology of the Berlin-Brandenburg Region. *Die Erde 142*(1-2), 21–39.

Merz, C., J. Steidl, and R. Dannowski (2009). Parameterization and regionalization of redox based denitrification for GIS-embedded nitrate transport modeling in Pleistocene aquifer systems. *Environmental Geology 58*, 1587–1599.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature 438*(7066), 347–350.

Mishra, A. K. and V. P. Singh (2010). A review of drought concepts. *Journal of Hydrology 391*, 202–216.

MUGV (2012). Ministry of Environment, Health and Consumer Protection of Brandenburg, Geo Informations:http:// www.mugv. brandenburg.de.

Nathkin, M., J. Steidl, O. Dietrich, R. Dannowski, and G. Lischeid (2012). Differentiating between climate effects and forest growth dynamics effects on decreasing groundwater recharge in a lowland region of Notheast Germany. *Journal of Hydology 448-449*, 245–254.

Niehoff, D., U. Fritsch, and A. Bronstert (2002). Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology 267*(1-2), 80–93.

Nützmann, G., C. Wolter, M. Venohr, and M. Pusch (2011). Historical Patterns of Anthropogenic Impacts on Freshwaters in the Berlin-Brandenburg Region. *Die Erde 142*(1-2), 41–64.

Patil, S. and M. Stieglitz (2011). Hydrologic similarity among catchments under variable flow conditions. *Hydrology and Earth System Sciences 15*(3), 989–997.

Pfister, C., R. Weingartner, and J. Luterbacher (2006). Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach. *Hydrological Sciences Journal 51*(5), 966–985.

Piechota, T. C. and J. A. Dracup (1996). Drought and regional hydrologic variation in the United States: Associations with the El Nino Southern Oscillation. *Water Resources Research 32*(5), 1359–1373.

Pusch, M. and A. Hoffmann (2000). Conservation concept for a river ecosystem (River Spree, Germany) impacted by flow abstraction in a large post-mining area. *Landscape and Urban Planning 51*(2-4), 165–176.

Ramelow, M., S. Böttcher, R. Dannowski, C. Merz, J. Steidl, and B. Thomas (2012). Bausteine eines Transdisziplinären Konzeptes zur Stabilisierung der Abflussverhältnisse am Fredersdorfer Mühlenfließ (Brandenburg) (engl.: Parts of a transdisciplinary concept to stabilize runoff at the Fredersdorfer Mühlenfließ, Brandenburg, Germany). In U. Grünewald, O. Bens, H. Fischer, R. F. Hüttl, K. Kaiser, and A. Knierim (Eds.), *Wasserbezogene Anpassungsmaßnahmen an den Landschafts- und Klimawandel (engl.: water related adaption measures for the landscape and climate change)*, pp. 258–265. Schweizerbart, Stuttgard, Germany.

Samaniego, L. and A. Bardossy (2006). Simulation of the impacts of land use/cover and climatic changes on the runoff characteristics at the meso scale. *Ecological Modelling 196*, 45–61.

Samaniego, L. and A. Bardossy (2007). Relating macroclimatic circulation patterns with characteristics of floods and droughts at the mesoscale. *Journal of Hydrology 335*, 109–123.

Sawicz, K., T. Wagener, M. Sivapalan, P. A. Troch, and G. Carrillo (2011). Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences 15*(9), 2895–2911.

Schindler, U. and L. Müller (2010). Data of hydraulic properties of North East and North Central German soils. *Earth System Science Data 2*, 189–194.

Schindler, U., L. Müller, F. Eulenstein, and R. Dannowski (2008). Along-term hydrological soil study on the effects of soil and land use on deep seepage dynamics in northeast Germany. *Archieves of Agronomy and Soil Science 54*(5), 451–463.

Singh, R., T. Wagener, K. van Werkhoven, M. E. Mann, and R. Crane (2011). A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate - accounting for changing watershed behavior. *Hydrology and Earth System Sciences 15*, 3591–3603.

Sivapalan, M., M. A. Yaeger, C. J. Harman, X. Y. Xu, and P. A. Troch (2011). Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. *Water Resources Research 47*, W02522.

Smakhtin, V. U. (2001). Low flow hydrology: a review. *Journal of Hydrology 240*(3-4), 147–186.

Stahl, K., H. Hisdal, J. Hannaford, L. M. Tallaksen, H. A. J. van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jodar (2010). Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences 14*(12), 2367–2382.

Stahl, K., L. M. Tallaksen, J. Hannaford, and H. A. J. van Lanen (2012). Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. *Hydrology and Earth System Sciences 16*, 2035–2047.

Thomas, B., G. Lischeid, J. Steidl, and R. Dannowski (2012). Regional catchment classification with respect to low flow risk in a Pleistocene landscape. *Journal of Hydrology 475*, 392–402.

Thomas, B., G. Lischeid, J. Steidl, and O. Dietrich (2013). Long term shift of first-order controls on low flows in small lowland catchments of Northeast Germany. *Journal of Hydrology in review.*

Thomas, B., J. Steidl, O. Dietrich, and G. Lischeid (2011). Measures to sustain seasonal minimum runoff in small catchments in the mid-latitudes: a review. *Journal of Hydrology 408*(3-4), 296–307.

Tootle, G. A., A. K. Singh, T. C. Piechota, and I. Farnham (2007). Long lead-time forecasting of US streamflow using partial least squares regression. *Journal of Hydrologic Engineering 12*(5), 442–451.

Van Loon, A. F. and H. A. J. Van Lanen (2012). A process-based typology of hydrological drought. *Hydrology and Earth System Sciences 16*(7), 1915–1946.

Van Loon, A. F. and H. A. J. Van Lanen (2013). Making the distinction between water scarcity and drought using an observation-modeling framework. *Water Resources Research 49*, 1483–1502.

Vicente-Serrano, S. M., S. Begueria, J. Lorenzo-Lacruz, J. J. Camarero, J. I. Lopez-Moreno, C. Azorin-Molina, J. Revuelto, E. Moran-Tejeda, and A. Sanchez-Lorenzo (2012). Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications. *Earth Interactions 16*.

Vidal, J. P., E. Martin, L. Franchisteguy, F. Habets, J. M. Soubeyroux, M. Blanchard, and M. Baillon (2010). Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite. *Hydrology and Earth System Sciences 14*(3), 459–478.

Wagener, T., M. Sivapalan, P. Troch, and R. Woods (2007). Catchment Classification and Hydrologic Similarity. *Geography Compass 1*(4), 901–931.

Wechsung, F., V. Krysanova, M. Flechsig, and S. Schaphoff (2000). May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? *Landscape and Urban Planning 51*(2-4), 177–189.

Wegehenkel, M. and K. C. Kersebaum (2009). An assessment of the impact of climate change on evapotranspiration, groundwater recharge, and low-flow conditions in a mesoscale catchment in Northeast Germany. *Journal of Plant Nutrition and Soil Science 172*(6), 737–744.

Wibig, J. (1999). Precipitation in Europe in relation to circulation patterns at the 500 hPa level. *International Journal of Climatology 19*(3), 253–269.

Yevjevich, V. (1967). *An objective approach to definition and incvestigations of continental hydrological droughts.* Colorado State University, Fort Collins, Colorado, Hydrology Papers 23, 18 pp.

2 Measures to sustain seasonal minimum runoff in small catchments in the mid–latitudes: A review

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Summary

In parts of the mid-latitudes, mitigation of critical low flows is becoming a major concern for science and water management institutions. Hydrological catchment models run with input data from global or regional climate models reveal decreasing minimum flow during the summer months. Small catchments (< 500 km^2) will be affected first. This is because even minor changes in precipitation and temperature will have a considerable impact on stream flow due to the low storage capacity and often faster reaction time of the groundwater bodies. Even a small decrease in low flow will increase the risk of water levels falling below ecologically or economically required minimum flows or even of rivers drying up. Mitigation will be necessary to prevent ecological degradation and water use conflicts.

The literature on measures that increase water yield or enhance temporal water storage is reviewed. Studies focusing on measures in small catchments are scarce. For this reason, studies on larger scales and storm water retention are also included. Such measures have to be adapted to the conditions in small catchments and evaluated with regard to the aim of ensuring minimum runoff. Measures differ with respect to such aspects as the effective volume, time scale, controllability and conflict potential. Considering these criteria, an evaluation matrix is compiled which can be used to help draw up research and water management plans. Since current concepts to integrate low flow and storm water protection are inadequate, modeling tools and decision support systems that represent measures to ensure minimum runoff need to be developed and refined.

Keywords: Low flow mitigation; Water retention; Land use change; Ground water recharge; Inter-basin transfer; Wastewater reuse

2.1 Introduction

Humans have been using artificial water stores to adapt to decreasing water availability for several thousand years (Pandey et al., 2003). The distribution of water to users has been continuously optimized to satisfy their needs and to consider the interest of the general public at the same time. Today, we have the ability to consider non-steady states of water balance (Milly et al., 2008), climate change, changing water use and overuse of resources (Konikow and Kendy, 2005; Vörösmarty et al., 2004) for water management purposes. Water scarcity will continue to be one of the greatest challenges facing water management (Postel, 2000). Shifting precipitation patterns and anthropogenic ground water depletion are the main reasons for longer or more severe low flows (Konikow and Kendy, 2005). According to climate projections (IPCC, 2007) and modeling studies (Menzel and Burger, 2002; Wegehenkel and Kersebaum, 2008), significant changes will occur in the mid-latitudes by the middle to end of this century. Stream flows during the summer months are projected to decrease in eastern and central parts of Europe and western and central parts of mid-latitude America (Milly et al., 2005). Small catchments without any external water inflow from other catchments will initially be affected. In the literature, such small catchments are also referred to as meso-scale catchments, even though their definition differs by author (Exbrayat et al., 2010; Niehoff et al., 2002). Even minor changes in precipitation and temperature will have a considerable impact on stream flow due to the low storage capacities of the groundwater bodies. Additionally, even a small decrease in water levels can result in considerable ecological conflicts. We define small catchments as those with an area not exceeding roughly 500 km^2. These catchments normally have perennial runoff, a large difference between discharge in the summer and winter months, and no permanent snow storage.

According to the German National Committee for the International Hydrological Programme (IHP) of the UNESCO and the Operational Hydrological Programme (OHP) of the World Meteorological Organization (WMO), low flow is defined as the lowest level reached in a river or lake for a specific period of time (IHP/OHP, 1992). A hydrological drought is defined as a period of abnormally dry weather sufficiently prolonged to give rise to a shortage of water as evidenced by below normal stream flow and lake levels and/or the depletion of soil moisture and a lowering of ground water levels. These definitions show that drought is just one of the phenomena that lead to low flows. Smakhtin (2001) pointed out that low flow is a seasonal phenomenon, but drought is the result of abnormally low precipitation occurring over an extended period of time. In water resources management, these definitions are not very helpful. Instead, a clearly defined threshold is required, which will be referred to hereafter as the minimum runoff. These thresholds, which have to be defined for single river reaches, can be defined with respect to habitat protection (e.g. minimum ecological flow), regional water management (e.g. targets for minimum outflow of a catchment), local water management (e.g. depending on the needs within a catchment or river section) or by statistics of the flow record (e.g. the 5% or 10% quantile of the flow values). Even if discharge is sufficient for natural flow conditions, flows may be too low for human demands. Taylor (2009) argues that recent estimates for large-scale water scarcity need to be reviewed. Intra-annual rather than mean yearly stream flows are vital, and it is imperative to include water storage in soil water, ground water and glaciers.

Water management strategies for large catchments during low flow periods and mitigation strategies to deal with climate change have been studied by numerous researchers (e.g. Giacomelli et al., 2008; Güntner et al., 2004; Karamouz and Araghinejad, 2008; Li et al., 2010; Lund, 2006; Medellin-Azuara et al., 2008; Sechi and Sulis, 2009). These studies focus on regulation rules for reservoirs, multireservoirs, higher-order river networks and the multiuse of water. Even if structures such as larger reservoirs exist in small catchments, their hydrology is likely to differ (Hofmann et al., 2008). As stated in the Braunschweig Declaration (Schumann et al., 2010), research into small catchments must be stepped up to provide important information for water management and climate change adaption.

This review focuses on regions with nearly stable yearly precipitation sums, but changing inter-seasonal distribution. The predicted reduction of summer precipitation in Eastern and Central Europe and western and central parts of mid-latitude America will cause increasing periodical water shortages. Water excess during the winter season could therefore be used to sustain minimum runoff. Possible measures include land use change, land management, urban rainwater harvesting, interbasin transfer, ground water recharge, surface water storage, wetland management and usage of cleaned wastewater. Land use can even be very heterogeneous in small catchments, which needs to be taken into account.

Although the expected climate change is likely to increase temperatures virtually everywhere, precipitation trends will differ widely from region to region (IPCC, 2007). Seasonal changes and changing frequencies and intensities of extremes also need to be considered (Cunderlik and Simonovic, 2005; Singh and Bengtsson, 2004). Furthermore, an increase in precipitation can be counteracted by increasing evapotranspiration (Arnell, 1999; Baguis et al., 2010). Studies projecting precipitation, soil moisture and runoff to the mid 21st century show that eastern and central parts of Europe and western and central parts of mid-latitude America will face more severe low flows during the summer months (Giorgi, 2006; Milly et al., 2005; Nohara et al., 2006; Wang, 2005). As an analogy for upcoming problems in the mid-latitudes, examples from semi-arid parts of Europe demonstrate increasing management and ecological protection conflicts associated with climate change (see, e.g. Nunes et al., 2008).

Impact assessment of different adaption measures is not trivial. Both the complexity of natural systems and the uncertainties of model outputs contribute to the difficulties in predicting the usability of adaption measures. The sound planning of appropriate measures is hindered by a lack of scientific-based guidelines valid for different geological and climatic conditions. To enhance the planning procedure for measures, science has to deliver application-oriented results to help planners find solutions and understand associated uncertainties. In Central Europe, the hazard posed by floods is recognized more acutely than risks associated with low flows, as shown, for instance, in a review of European studies and laws compiled by Vetter and Sondershaus (2011).

The objective of this review is to summarize options for the sustainment of minimum runoff in small catchments of less than 500 km^2, which we assume will be affected first by changing climate in the mid-latitudes. In addition, we aim to classify measures that can be taken to counteract this phenomenon. Literature on semi-arid regions is included to enable us to benefit from the experience gained in such regions.

2.2 Measures to sustain minimum runoff

Sustainment measures influence the water cycle of a catchment in different ways. Figure 2.1 shows schematically the interplay of these measures within a catchment. These measures can aim to increase water input into a catchment, temporarily redistribute water flows within it or decrease output from a catchment. The minimization of losses and reduction of water consumption should be included in the development and planning of every measure, and is therefore not considered. The measures discussed in this review are summarized in Table 2.1.

Two main compartments in which water can be stored need to be distinguished: ground water and surface water. Water saved as ground water is evapotranspired to a lesser extent, or not at all. Ground water provides base flow in rivers and can be extracted directly from wells. Storing water as ground water can be an effective measure to support flows in rivers by increased base flow if an aquifer is connected to the surface water system. However, depleted aquifers are a threat to low flows in rivers (Konikow and Kendy, 2005). Such measures are not very efficient because the base flow does not only increase during low flow periods. Effective measures that have an impact on ground water recharge are changes to land use or management, and the management of artificial ground water recharge. By contrast, surface water reservoirs allow a more precise regulation of outflow, but water is lost by evapotranspiration from the surface or surrounding vegetation and soil.

2.2.1 Increase in water yield

Land use change

Under similar site conditions, evapotranspiration is largely dependent on land use (Anderson and McDonnell, 2005; Brown et al., 2005; DVWK, 2001; Maidment, 1993). Land use types can generally be ranked from low to high evapotranspiration as follows: bare soil, cropland, grassland, deciduous forest, coniferous forest. Higher forest evapotranspiration is mainly due to interception losses, especially for evergreen coniferous tree species. It is difficult to quantify the proportion of rainwater that is evapotranspired considering land use only because plant types and plant age are often not known and soil types and other site conditions also influence the hydrological processes. Another important variable determining evapotranspiration is the availability of soil water. Moist sites usually involve greater evapotranspiration than dry ones. The water storage capacity of the soil and the water level below ground therefore has to be borne in mind when assessing the evapotranspiration of different land use classes.

The conversion of coniferous forests to mixed stands, deciduous stands or even arable land or grassland has been reported to decrease evapotranspiration and increase river runoff. Brown et al. (2005) reviewed

Table 2.1: Mitigation measures to sustain minimum runoff during periods of low flow and their general effects. The numbers correspond to those in Figure 2.1.

Topic	Measure	Principle and Effects
increase of water yield	land use change (1,11)	lowering of evapotranspiration and interception; increase in ground water recharge; increase in base flow to the rivers
	land management (11)	increase of infiltration and reduction in evapotranspiration by tillage and other management practices; minimization of irrigation losses
	urban rainwater harvesting (7)	increase of amount of water infiltrated instead of being routed directly to streams or sewage systems; increased ground water recharge
	inter-basin water transfer (10)	transfer of water from (larger reservoirs of) neighboring catchments with excess water
temporal water retention	artificial ground water recharge (and recovery) (2,8) and river restoration (5)	delayed water flow to the river as increased base flow; subsurface reservoir if water is recovered using a recovery well; increase in ground water levels in the vicinity of rivers
	surface water storage (3,4)	water storage within surface water bodies managed to sustain minimum runoff
	wetland water management (9,12)	depending on hydrogeology, wetlands can sustain minimum runoff like reservoirs and increase base flow; otherwise, evapotranspiration losses can be reduced (by lowering water levels); higher ground water levels along ditches allow less irrigation during the dry season and sometimes even an increase in base flow
	waste water recycling (6)	reuse of cleaned waste water for irrigation, groundwater recharge, etc.

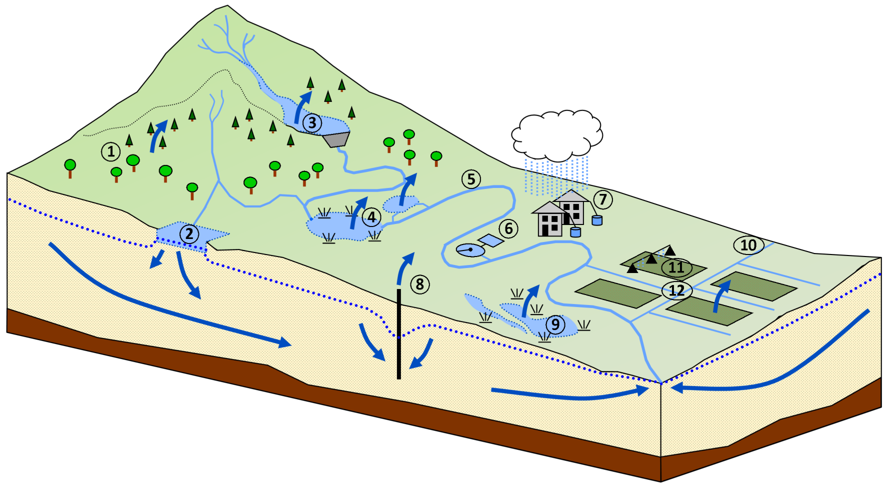

Figure 2.1: Possible mitigation measures to sustain minimum runoff during periods of low flow. Flows within the aquifer, water extraction or losses due to evapotranspiration are indicated as arrows. See Table 2.1 for a detailed description of the measures.

the results of paired catchment studies on water yields. Increased forest cover on previously sparsely vegetated land causes a decrease in annual water yield of approximately 20–25 mm yr^{-1} per 10% change in cover for coniferous land use, 17–19 mm yr^{-1} for deciduous and about 5 mm yr^{-1} for bush and grassland. This results in a 30-60 mm yr^{-1} increase in water yield, assuming 100% transformation of coniferous to deciduous forest. In addition, the variability of flows and inter annual patterns are affected. In mid-latitude catchments, the reduction of summer flows is much more pronounced than in winter flows. In a modeling study, Armbruster et al. (2004) conclude that beech stands would have a 30–50% and 7–14% (135 and 189 mm yr^{-1} mean change, respectively) higher discharge for two catchments currently covered by spruce. Transformation of coniferous forest into mixed and deciduous stands is reported to increase surface water runoff and water yield (Fohrer et al., 2001; Kovar et al., 2001; Mey et al., 2008). A study from Belgium showed that the 10 forested sites consumed approximately 100 mm yr^{-1} more water than the respective 10 cropland sites (Verstraeten et al., 2005). The actual effects depend on the proportion of forest in a catchment. In Brandenburg, Germany, the afforestation of abandoned arable land would increase actual evapotranspiration by 3.7% (25.1% in spring); the conversion of pine to oak stands would decrease actual evapotranspiration by 3.4% (Wattenbach et al., 2007). The latter would result in approximately 17 mm yr^{-1} higher groundwater recharge, assuming a actual evapotranspiration of 508 mm yr^{-1}(LUGV, 2000).

Arable land can be converted much more quickly than forested land, particularly when annual crops are used. The conversion of grassland to arable land is reported to increase runoff (Fohrer et al., 2001), but the effect depends on the crop species involved. Schindler et al. (1997) show that both soils and crops affect groundwater recharge, especially in wetter years.

Depending on crop species, groundwater recharge can differ by about 53 mm yr^{-1}. Grassland and crop rotation with long transpiration periods produce the lowest drainage rates; groundwater recharge can range from 98 to 151 mm yr^{-1} (with a mean yearly precipitation of 550 mm yr^{-1}). Wechsung et al. (2000) investigated agricultural land use in the Federal State of Brandenburg, Germany. The temporary set-aside of arable land increases runoff by 6.7%. Conversion of agricultural land along river buffer strips to meadows is followed by a decrease in runoff by 6.9% (12.4 mm yr^{-1} and 12.7 mm yr^{-1}, respectively, assuming 128 mm yr^{-1} of runoff (LUGV, 2000). The authors point out that land use change does not seem to be the most effective measure for that particular region. At the Mississippi river, the conversion of perennial vegetation to row crops (especially soy beans) resulted in an increase in discharge (2.5–15 mm) and base flow (2.5–12 mm), depending on the month (Zhang and Schilling, 2006). The difference in stream flow from 1940 to 2003 is approximately 75 mm yr^{-1}. However, it remains questionable how much change is due to the increase in soy bean cultivation.

Considering the stabilization of low flows in rivers, it would be best to lower water tables at wet sites and to convert forest to grass or arable land. This is not always possible for several reasons. Often interests of environmental protection, landscape protection and water resource management cannot be combined without compromise. The applicability of land use change measures to stabilize low flows is therefore limited. The conversion of coniferous forest to mixed or deciduous forest is considered to be the measure accepted by most stakeholders. No arable land has to be converted and no major changes are made to the landscape. Nevertheless, forest restructuring can take up to a century, which is not the case for changes to arable and grassland. With regard to arable land, sowing crops that consume less water has a promising effect. An overview of the different measures and their effects is given in Table 2.2.

Land management

In addition to land use change, land management can also influence ground water recharge and water consumption. The effectiveness of land use change and management measures is compared in Table 2.2. Oleary (1996) found that stubble-retained zero-tilled fallows techniques in agriculture can increase annual groundwater recharge by 18.5 mm yr^{-1} compared to conventionally tilled fallow. Conservative tillage or no tillage are reported to increase infiltration and groundwater recharge (Deumlich et al., 2006; Fiener et al., 2011; Green et al., 2003). Higher residue cover, residuals left after mowing and mulch cover can further increase the infiltration of water. Deep plowing is reported to increase groundwater recharge by 4 to 67 mm yr^{-1} when layers of low permeability are destroyed, but water availability for crops can be reduced depending on site conditions (Scanlon et al., 2008; Xu and Mermoud, 2003). More conservative and environmentally friendly land management can reduce surface runoff and increase infiltration of rainwater, especially in loamy soils (Molenat et al., 2007; Souchere et al., 2005). Fiener et al. (2011) point out that not only land management itself but also spatial and temporal patterns in land management affect the proportion of surface runoff. In many cases, greater patchiness within landscapes reduce surface runoff, but fails to do

Table 2.2: Effects of different land use change and management measures on water yield, demonstrating their potential to sustain minimum runoff.

measure	water balance variable	increase in water yield (mm yr^{-1})	author
coniferous to deciduous forest	water yield	30—60	Brown et al., 2005
	discharge	135–189	Armbruster et al., 2004
forest to cropland	evapotranspiration and interception	100	Verstraeten et al., 2005
change in crop species	deep seepage	0—53	Schindler et al. 1997
changes on landscape scale (different measures)	evapotranspiration	17	Wattenbach et al., 2007
	discharge	12.4	Wechsung et al., 2000
	discharge	approx. 75	Zhang and Schillling, 2006
conservational tillage	deep seepage	18.5	Oleary, 1996
deep plowing to destroy impermeable soil layers	deep seepage	51–67	Scanlon et al., 2008
	percolation	4	Xu and Mermoud, 2003

so in other cases. They also state that adjacent ditch systems increase storm water runoff from fields, and thus retain less water in the landscape.

Agricultural irrigation affects low flows in rivers. The use of groundwater wells for irrigation increases but the use of surface water decreases the river discharge during low flows (Eheart and Tornil, 1999; Wang and Cai, 2010). This is only the case if excess irrigation results in water draining to the groundwater. Nevertheless, the long-term depletion of ground water resources leads to longer and severe low flows (Konikow and Kendy, 2005). Irrigation water demand is likely to increase with increasing temperature in the mid-latitudes. Thus, irrigation is more likely to be a threat to low flows if no measures are taken to recharge depleted aquifers and to encourage the sustainable use of ground water resources.

Urban rainwater harvesting

The increase in settlement and sealed areas also influences low flows, when runoff is directed to streams or sewage systems and is not retained within the catchment. Querner and van Lanen (2001) found that infiltrating water from paved areas within the catchment reduced the duration of low flows and discharge deficits by about 10% and 13%, respectively. In Germany, 13.3% of the area is classified as settlement and traffic area (Destatis, 2009). As a rough estimate, 50% of this area can be considered impervious. This data highlights the possibilities of urban rainwater harvesting to increase water yield.

The expansion of municipal areas can decrease low flows if no appropriate measures are taken to retain water (Querner and van Lanen, 2001). Nonetheless, Brandes et al. (2005) did not find any significant long-term trends of stream flow in most of the urbanized watersheds in Pennsylvania, United States of America. This may be due to several counteracting effects of urbanization. Leaky water supply and sewer systems, wastewater discharge and industrial water discharge might increase runoff. For instance, water is often transferred to urbanized areas as drinking water, but discharged within the catchment after sewage treatment (Brandes et al., 2005). The mechanism is similar to any other kind of inter-basin water transfer. For impervious areas, ground water recharge is low. On the other hand, evapotranspiration is lower for paved areas, too. Furthermore, disconnected impervious areas can have even higher recharge because runoff converges at low-lying areas and infiltrates under relatively high heads (Brandes et al., 2005). In sealed and roofed areas, runoff generation is generally very fast. Residential lawns reduce water directed to sewage systems or streams (Müller and Thompson, 2009) and increase groundwater recharge at the same time. Swale-infiltration trench systems have been used successfully on a decentralized basis, but also to treat sewer overflows (Abida and Sabourin, 2006; Sieker, 1998). The advantage of these structures is that they increase infiltration, decrease discharge to streams and further purify the water (Gobel et al., 2008).

In recent decades, research into municipal water management in the midlatitudes concentrated on storm water protection. To decrease peak runoff and prevent the overflow of sewer systems, retention basins and other structures were introduced. Many countries have regulations that rainwater from roofs and paved areas should be infiltrated within own properties to prevent sewer systems from overflowing and to decrease storm flow. Here, increasing groundwater recharge could be a synergy, although it has rarely been considered (see, e.g. Berndtsson, 2010; Tredoux et al., 1999). Sites with low permeable soils require different solutions to infiltration structures (Abida and Sabourin, 2006). Infiltration wells including pre-treatment or surface water storage are alternatives.

In semi-arid regions, rainwater harvesting is already widely used for irrigation purposes. In municipal areas, runoff from rooftops can also be used to fill reservoirs or tanks (Cheng et al., 2009). This is also suggested for municipalities where the transfer of freshwater is difficult and expensive (Chiu et al., 2009). Such measures have proven to be effective drought mitigation measures. Such water can be used for purposes that require the quality to be below that of drinking water.

Inter-basin water transfer

Surface, ground, drinking and waste water can be transferred between catchments to sustain the water yield of a catchment prone to low flows. These are often catchments with high water consumption or depleted aquifers after overuse or mining activities. Measures can lead to the transfer of as much as 43,109 m^3 yr^{-1}, as planned for the North-South water transfer project in China; alternatively, only a few cubic meters can also be transferred to stop river beds from drying up and to restore the landscape (Chaulya, 2003; Gupta and van der Zaag, 2008; Koch et al., 2005; Pusch and Hoffmann, 2000). Whether water can be routed across channels or has to be pumped to the other catchment depends on topography. For example, South Africa is one of the water-scarcest countries in the world. Here, transfer between catchments is widely used to support areas with high water consumption. There are plans to build over 100 km long tunnels to redistribute water (Basson and Van Rooyen, 1998). Usually, this is considered only when (i) one catchment has a much higher consumption of water and (ii) water retention or yield is much higher in the other catchment. Researchers emphasize that inter-basin transfer should only be applied if all other measures within a catchment fail to solve water scarcity problems. Inter-basin water transfer projects are often controversial, they take a long time to plan and usually require the detailed assessment of hydrological and social conditions (Cox, 2007; Gupta and van der Zaag, 2008).

According to Gupta and van der Zaag (2008), such measures have to be planned within holistic integrated water management, considering environmental, social and economic factors. They point out that, due to the uniqueness of every project, it is very difficult to transfer existing measures to other locations, rendering the piecemeal planning of every measure necessary. At least two discontinuities evolve from inter-basin transfer: (i) biological connection between habitats and (ii) social connection of communities. Each measure requires its own planning procedure, especially to clarify these biological, sociological and economic constraints.

2.2.2 Temporal water retention

Managing artificial ground water recharge

Base flow from the adjacent aquifer is usually the prevailing flow component during low flow conditions. Falling ground water heads are a common phenomenon, e.g. in Central Europe and North America (Konikow and Kendy, 2005; Wegehenkel and Kersebaum, 2008). Extraction of ground water and climate change are the main reasons for this. However, Konikow and Kendy (2005) see a great need for and the potential to recharge depleted aquifers and to use them as subsurface reservoirs for low flow augmentation. Base flow would increase while more water would be available for extraction. Pumping the water into rivers implies higher costs and maintenance. Increased ground water storage can be achieved by managing artificial recharge through infiltration ponds or wells, river restoration and the regulation of weirs in rivers (Dillon, 2005).

Bouwer (2002) and (Dillon, 2005) review artificial recharge techniques (surface, vadose-zone and well infiltration). They state that subsurface storage will be of increasing importance due to population growth, their ability to store water long term and the fewer evapotranspiration losses involved compared to surface reservoirs. Even though experience has been gained in building artificial recharge sites and numerous sites have been installed worldwide, the heterogeneity of the subsurface still requires the piecemeal planning of recharge measures. All artificial recharge techniques require excess water which can be infiltrated and available space for infiltration ponds or infiltration wells. Depending on the soil and water composition, maintenance becomes necessary due to clogging and water quality issues.

It has to be distinguished between whether water is recharged to the aquifer to increase the base flow or as a subsurface reservoir, and water is extracted later from wells. Although costs are higher for the second case, it enables temporal control. The most effective recharge sites to increase the base flow are located in upslope parts of catchments, often requiring the transfer of water to the recharge sites. Alternatively, available urban rainwater may also be used. Upslope infiltration sites are preferred due to the resulting delay of groundwater flow to the river and the greater depth to groundwater, which will lower evapotranspiration loss. In contrast, infiltration at shallow ground water sites could lead to water logging and may conflict with agricultural use. Several studies show the efficiency of ground water recharge measures for low flow augmentation (see, e.g. Khan et al., 2008). In a modeling study by Barber et al. (2009), 0.425 to 0.991 m^3 s^{-1} recharge through infiltration wells or basins resulted in an 0.088 to 0.204 m^3 s^{-1} increase in summer stream flow.

In the mid-latitudes, sufficient water should be available during the winter months to allow artificial recharge without requiring additional storage, transfer or pumping of water. If flow in streams is insufficient to guarantee recharge, additional storage in reservoirs would be necessary (Abu-Taleb, 2003; Zammouri and Feki, 2005). It would be favorable to use synergies between storm water retention and managing artificial recharge (Martin-Rosales et al., 2007; Tredoux et al., 1999).

An interesting approach is to build underground dams (Dillon, 2005; Raju et al., 2006; Soni et al., 2009). This technique helps ground water to be retained in permeable aquifers, like alluvial sediments in a relatively impermeable valley. Water can be stored below ground with fewer evapotranspiration losses. An increase in river flow and the amount of available ground water is reported. Often additional surface structures, such as check dams, rock fill dams or infiltration basins, are built to increase recharge of the subsurface reservoir.

In many places, rivers are restored after realizing the benefits of a more natural river morphology, such as increased biodiversity or flood prevention. Anthropogenically caused change in flow conditions can render restoration necessary, too (Pusch and Hoffmann, 2000). River restoration can enhance ground water recharge and connectivity between stream and ground water. Constructing meanders, increasing water levels by raising the river bed and constructing ground sills are the main methods applied. After restoration, a reduction in flow velocity is observed (Bukaveckas, 2007). The restored river is generally allowed to flood the plain more often, enabling an increased storage of ground water close to the river. Riparian buffer zones react rapidly to changes in river water levels (Bosch et al., 2003; Burt et al., 2002;

Lewandowski et al., 2009). Thus their ability to effectively store water for low flow periods is questionable, especially if water needs to be stored for several months. The efficiency of storing water in buffer zones depends to a great extent on evapotranspiration losses and flow velocities in the porous medium. Querner and van Lanen (2001) show that raising the water levels and beds of small watercourses can increase the number of low flow days and duration of low flows, but might mitigate ground water drought. If such measures can reduce irrigation water demand, this would lower water extractions from rivers during the dry season. This problem is closely related to the discussion whether wetlands can function as water reservoirs for low flow augmentation.

Surface water storage

In the literature, adaption to climate change and increasing water use is reported for different scales (see, e.g. Karamouz and Araghinejad, 2008; Lund, 2006; Nicolosi et al., 2009). In many regions, the variability of precipitation is expected to increase. The storage of excess water during wet periods to sustain minimum runoff in dry periods is growing in importance. If enough storage volume is available, such conditions can even improve low flow augmentation by reservoir release (Muttiah and Wurbs, 2002). In the west and south of the United States, the optimization and adaption of the recent water management system is expected to mitigate most of the changes caused by a dryer climate (Medellin-Azuara et al., 2008). Reservoirs are expected to undergo higher storage fluctuations and an earlier seasonal maximum of storage. By contrast, one major finding of the German Research Programme GLOWA Elbe was that the magnitude of water scarcity in the Elbe catchment is projected to become worse (Koch et al., 2005; Koch and Vogele, 2009). Decision support systems will be an effective measure to adapt and modify the existing systems according to projected changes (Yao and Georgakakos, 2001).

New water reservoirs have been built worldwide to ensure sufficient water supplies during dryer seasons (Service, 2004; Vörösmarty et al., 2004). Usually, the selection of appropriate sites for such reservoirs aims to ensure losses by seepage or evaporation are minimized. Costs per m^3 of stored water are low (Keller et al., 2000; van der Zaag and Gupta, 2008). Storage capacity depends largely on the water volume available during the wet season and the volume allocated for the sustainment of minimum runoff.

Several reasons highlight why large reservoirs are not always preferable (Keller et al., 2000; van der Zaag and Gupta, 2008): (i) costs for planning and construction are high, (ii) socio-economic and environmental impacts require a difficult approval procedure, (iii) complex operation is necessary, (iv) there are usually large distances between the source of water and its users and (v) larger reservoirs cannot respond to individual demands. Last but not least, suitable sites are becoming increasingly scarce (Konikow and Kendy, 2005). According to the International Commission on Large Dams, the height of small dams is less than 15 m, and the reservoir should have a maximum storage capacity of less than 1 million m^3 (ICOLD, 1998). For the purpose of this article, this definition is not very useful because most small reservoirs or lakes which could contribute to low flow augmentation in small catchments are often much smaller.

The focus will be on lakes or ponds that already exist or could be constructed at an appropriate site within a short period of time. Mainly very simple outlet structures, compared to large reservoirs, exist.

Unlike with large reservoirs, small reservoirs often exhibit higher evaporation and seepage losses. This is mainly due to the greater influence of vegetation within or next to the water bodies and seepage losses if they lie above the groundwater level. Nevertheless, small reservoirs have several advantages over large ones (Keller et al., 2000; van der Zaag and Gupta, 2008): (i) Operation is less complex and response times short, (ii) they can be constructed close to the point of use more easily, (iii) they refill quickly after rainfall and often several times a year (annual water delivery can be much higher than the actual storage capacity), (iv) increase in ground water storage (Juszczak et al., 2007; van der Zaag and Gupta, 2008), (v) relatively few parties are involved in the approval procedure and management and (vi) many small reservoirs, built for another purpose (fish ponds, storm water retention ponds, etc.), already exist and could be converted into reservoirs for low flow augmentation. Whether a large reservoir or many small lakes should be used to retain water depends to a great extent on local conditions (van der Zaag and Gupta, 2008).

In the past, storm water retention was the prior topic in hydrologic science for mid-latitude regions (see, e.g. Scholz, 2007). Storm water retention basins are managed in a different way to retention measures for low flow augmentation. While storm water retention basins should always have enough available storage volume for a potential flood, water retention measures to sustain minimum flows should always be filled as high as possible to be able to discharge enough water for the next drought. So far, no research has been conducted on how these competing objectives can be combined.

Since there is often a lack of data on the quantity and storage volume of small reservoirs within the landscape, surveys are required as a first step to evaluate storage potential. Both ground surveys and remote sensing techniques have been conducted. Juszczak et al. (2007) established that 638 ponds smaller than 2 ha exist within a 182 km^2 catchment in western Poland. The retention volume could be raised by 886,000 m^3 surface water and 880,000 m^3 ground water by increasing lake water levels by between 0.5 and 1.5 m. Liebe et al. (2005) used remote sensing and a simplified model of the reservoirs' geometry to estimate storage volumes in small reservoirs in Ghana. A disadvantage of these studies is that no consideration is made of feedback mechanisms regarding evapotranspiration or seepage losses. Thus, values can only be considered as potential upper limits of effective storage capacities.

Wetland water management

Any evaluation of the effects of storing water in shallow aquifers, wetlands or reservoirs on low flow stabilization has to consider evapotranspiration (see, e.g. Querner and van Lanen, 2001). Water loss in wetlands is higher than in surface water reservoirs. The interaction between the hydrosphere and the biosphere complicates the assessment of such measures. Additionally, wetlands often have an ecological function and their usage for low flow augmentation is not intended. In such cases, optimization of these systems regarding water consumption can be a measure to increase their ability to stabilize minimum runoff.

In Central Europe, virtually no natural wetlands exist because they have been drained or altered. The water balance of these altered wetlands depends on water management (see, e.g. Dietrich et al., 2007). Discharge patterns from rewetted wetlands are different to natural ones because of destroyed regulation mechanisms, such as the properties of the acrotelm and the reduction of evapotranspiration by sphagnum spp. under dry conditions (Spieksma, 1999). This hinders the generation of sufficient runoff during low flow periods. Artificial wetlands have mainly been constructed for storm water retention or the purification of road or other runoff (Knight et al., 1998; Konyha et al., 1995; Koob et al., 1999; Laber, 2000; Rogers et al., 2009). None of these studies investigated effects on low flows, but reveal the potential of artificial wetlands to retain water during the wet season.

Bullock and Acreman (2003) reviewed 169 wetland studies worldwide and extracted tendencies in wetland behavior. In 47 out of 71 studies reduced downstream flow during the dry season occurs. The main reason for this is the greater evapotranspiration of wetlands compared to other land use classes. Evapotranspiration and other losses increase with water level (Kadlec, 1993). Wetlands that reduce the base flow and thus increase water scarcity are described in the literature (Kvaerner and Klove, 2008; Lindsay et al., 2004; Rogers et al., 2009). Riverine fens have to be considered as water consumers (Dietrich et al., 2007). In contrast, wetlands increased river flows during the dry season in 20% of all cases (Bullock and Acreman, 2003). Riparian and headwater wetlands have to be distinguished here. Headwater wetlands can be considered to be more like reservoirs, albeit with high evapotranspiration (McKillop et al., 1999). They seem to be more suitable as a water retention measure. Nevertheless, piecemeal evaluation is necessary because wetlands behavior is strongly dependent on the hydrogeological setting.

As mentioned above, ground water recharge is often a desired synergy of retention measures. Ground water recharge occurred in most of the studies summarized by Bullock and Acreman (2003). Recharge is highly dependent on climatic properties, elevation differences between the wetland water table and the adjacent ground water level, and the occurrence and development of impermeable layers below the wetland.

Most wetlands in Central Europe have been managed for decades, or even centuries, to enable agricultural use. Water levels in drainage ditches and the adjacent ground water have been regulated by weirs or other management structures. These areas can be seen as potential water consumers, due to their high evapotranspiration (Dietrich et al., 2007). On the other hand, wetlands are often seen as cultural and environmental heritage and are important as touristic attractions. It is therefore important to find solutions to how the water management of such systems can be optimized regarding water consumption. The effects of drought mitigation measures are often not trivial and feedback mechanisms have to be considered. It is necessary to minimize water loss whilst sustaining the multipurpose and multiuse of these areas.

It has to be borne in mind that wetlands will also be altered by climate change (Acreman et al., 2009; Andersen et al., 2006; Erwin, 2009). It is difficult to assess the extent to which these changes will affect low flows in rivers, because of the interdependencies between evapotranspiration and plant communities. Additional anthropogenic changes can be considered by scenario analyses only.

Reuse of treated waste water

In arid and semi-arid regions, reused waste water is already considered a valuable water source (Pedrero et al., 2010). Waste water is produced at every human settlement. There are several options for reusing this water after treatment. The most important applications are for agricultural or landscape irrigation and artificial ground water recharge. Such measures decrease the amount of water extracted from rivers and retain water by recycling some of the water within the catchment (Angelakis and Durham, 2008; Hamilton et al., 2007). Furthermore, new treatment plants could be built at river sections where flow augmentation is necessary. Many large metropolitan areas already have a partially closed water cycle, due to steady reuse. Approximately 700 Mm^3 yr^{-1} of water was reused in Europe in 2005, which is less than one fifth of the continent's potential for water reuse (Angelakis and Durham, 2008). Although interdisciplinary research has been carried out, it remains questionable whether the reuse of waste water is a sustainable concept (Kennedy and Tsuchihashi, 2005). Long-term data on water quality is scarce. Additionally, wastewater reuse applies only to urban catchments or catchments with sewer plants. Considering a mean water consumption of 126 litres per day and capita, as was the case in Germany in 2004 (Destatis, 2009), around 79 persons would be required to produce the amount of water required to irrigate 1 mm on an area of 1 ha. This approximation shows that the reuse of waste water can only be a solution at some sites and particularly in more densely populated regions.

Despite the focus of this paper on water quantity, water quality is an important issue regarding waste water reuse (Angelakis et al., 1999; Angelakis and Durham, 2008; Exall et al., 2004; Hamilton et al., 2007; Pedrero et al., 2010; Ternes et al., 2007). Waste water may contain residues of contaminants, microorganisms and residual nutrients (Angelakis et al., 1999; da Fonseca et al., 2007). Cleaned waste water has been used for artificial ground water recharge for two decades (Bouwer, 2002; Ishaq and Khan, 1997; Tredoux et al., 1999). It is often seen as an advantage that further purification takes place during soil aquifer treatment (SAT) (Ternes et al., 2007). If less treatment is needed within the sewer plant, SAT may also be cheaper than direct discharge to streams (Bouwer, 2002). The methods used during ground water recharge are the same as those described in the section on managing artificial recharge. Asano and Cotruvo (2004) compiled a wide spectrum of technical and health challenges associated with the usage of cleaned waste water for ground water recharge.

Most of the cleaned waste water in reuse projects is used for agricultural irrigation (Hamilton et al., 2007; Kennedy and Tsuchihashi, 2005; Pedrero et al., 2010). One of the pioneers in this field is Israel. In 1991, approximately 42% of collected wastewater was reused for irrigation and 30% for aquifer recharge. In 1991, 24.4% (188 Mm^3) of Israel's agricultural water supply, was reused wastewater (Angelakis et al., 1999). In addition, waste water is used for ground water recharge and industrial use. The amount and type of usage differs from country to country. In addition, wastewater reuse often goes hand in hand with inter-basin transfer, depending on the origin of the water delivered to the treatment plant (Querner and van Lanen, 2001). All these effects have to be considered in integrated water resource management.

2.3 Discussion

The quantifiability of the effects of measures taken differs between the groups of measures discussed in this review. The results on land use change and land management allowed a comparison to be made between different measures on a plot and catchment scale (Table 2.2). The results reported in the literature are based on different variables of the hydrological balance, and are only comparable assuming a closed and steady-state water balance. For aquifer storage and recovery (ASR), surface water storage and inter-basin transfer, no generalized quantification can be given according to the literature because the available water volume depends mainly on the dimension of each measure. It can be calculated using the water balance of the reservoir, the water channel or groundwater body, considering only the volume available for sustaining minimum runoff. Site conditions and large variations of measures, even within one group of measures, result in a wide range of efficiency for artificial groundwater recharge aiming at an increased base flow, urban rainwater harvesting and wetland water management. No general assumptions on the efficiency of these measures are given in the literature, and piecemeal planning of measures is recommended. If waste water is directly discharged into a river, the available volume is given by the size of the sewer plant, and it is part of waste water management planning. Even though the generalized quantification of the effects of measures differs, we have compiled an evaluation matrix to compare all of the measures reviewed in this article.

Five criteria were defined to evaluate the methods. First, the effective volume is the remaining volume of water that can be used to sustain minimum runoff. This volume can differ from the initial volume since part of the stored or recharged water is evaporated, lost via seepage, the ground water does not drain to the desired stream or is used for other purposes. Second, the time taken to establish the measure is the time required to plan and construct or introduce a new measure plus the delay until the measure starts sustaining water during low flows. Third, the operation time scale is the time taken for changes (e.g. to the outflow or inflow structures) to become effective. Fourth, the effort for operation is the effort required to change the amount of water used to sustain minimum runoff. Fifth, the conflict potential is evaluated. Rossi et al. (2005) emphasize that drought mitigation measures cannot be developed solely with the results of hydrologic studies. Stakeholder interests need to be considered, too.

Transdisciplinary work involving inter alia hydrologists, biologists, sociologists and economists can be useful in finding solutions that are acceptable to all parties involved. Although it would also be important to consider costs, only a few publications include cost calculations. Table 2.3 shows the measures according to the evaluation criteria. The only measures that can provide large amounts of water are inter-basin transfer, larger reservoirs and artificial groundwater recharge. The length of time minimum flow can be sustained depends to a considerable extent on the effective volume. If water scarcity increases, it will become necessary to apply one of these measures.

The establishment time depends strongly on whether water is directly released to a stream or indirectly via ground water flow. Small lakes can start operating after a short planning and construction process. Larger reservoirs and measures where stakeholder involvement is high require a longer planning process. Sustaining base flow by ground water recharge can take years to decades, depending on the hydraulic properties of the ground and the amount of water available. Transformation of land use may take even longer, such as the transformation of forest to deciduous or mixed stands, which can take more than a century. On the other hand, the measures that become operational after a short period of time tend to be able to provide surplus water for short periods only, whilst ground water recharge and land use change ensure a prolonged increase of the base flow.

The operation time scale depends on how water is released to the stream. Water can be delivered to the river via ground water flow, which is virtually impossible to regulate. This is mainly the case for land use change or managing artificial recharge and the retention in wetlands or other reservoirs without outlet structures. Second, the outflow from reservoirs, inter-basin transfer and artificial ground water recharge techniques, such as aquifer storage and recovery can be regulated. The advantage of methods that regulate release is that they can be managed according to demand. Methods affecting base flow and water yield cannot be regulated directly, and some of the water is discharged during periods without low flow.

The effort for operation is high for measures where many stakeholders are involved (inter-basin transfer, wetlands), where there are quality constraints (waste water recycling) or complex outlet structures and rules (reservoirs, ASR). On the other hand, the operation of small reservoirs and other less controllable, decentralized measures is less complex.

A community's capacity to adapt to hydrological changes depends largely on its institutional structure and how communication with stakeholders takes place, not only concerning hydrological conditions and research findings (Ivey et al., 2004; Miller et al., 1997). It is a learning process which leads to awareness, higher acceptance and willingness to adapt to these changes. Educating and informing the public should be part of the adaption process (Rossi, 2009). The use of decision support systems can be an effective tool (Yao and Georgakakos, 2001). Hydrological science has to be aware of these social aspects to guarantee transdisciplinary use of the results. Measures differ with regard to their acceptance and the number of stakeholders involved. Conflict potential is assumed to be high for measures that change the landscape and ecology, institutional structures or agricultural management, and when water quality constraints are involved. The use of existing but unused structures, such as mining lakes, former fishing ponds and rain retention basins, can decrease conflict potentials, depending on their purpose for water management, tourism and ecology. Nevertheless, the necessity of stakeholder involvement and their awareness can differ even between similar projects.

Table 2.3: Assessment of mitigation measures to sustain minimum runoff during periods of low flow. The effective volume which can sustain minimum runoff, the time needed before measures become effective, the reaction time to operational changes, the complexity of operation and a suggestion about required stakeholder involvement are evaluated.

measure	**effective volume**	**time to establish**	**operation time scale**	**effort for operation**	**conflict potential**	**source**
land use change	low - medium	decade - century	-	-	medium - high	Armbruster et al., 2004; Brown et al., 2005; Fohrer et al., 2001; Mey et al., 2008; Schindler et.al (1997); Verstraeten et al., 2005; Wattenbach et al., 2007; Wechsung et al., 2000; Zhang and Schilling, 2006
land management	low - medium	year - decade	-	-	low - medium	Eheart and Tornil, 1999; Deumlich et al., 2006; Fiener et al., 2011; Green et al., 2003; Molenat et al., 2007; Oleary, 1996; Scanlon et al., 2008; Souchere et al., 2005; Wang and Cai, 2010; Xu and Mermoud, 2003
urban rainwater harvesting	low - medium	year - decade	fast - slow	low - medium	medium - high	Cheng et al., 2009; Chiu et al., 2009; Mueller and Thompson, 2009; Querner and van Lanen, 2001; Sieker, 1998
inter-basin water transfer	medium - high	year - decade	fast - medium	medium	high	Basson and Van Rooyen, 1998; Chaulya, 2003; Cox, 2007; Gupta and van der Zaag, 2008
artificial ground water recharge (and recovery)	low - high	year - decade	slow - no	medium - high	low - medium	Barber et al., 2009; Bouwer, 2002; Dillon, 2005; Khan et al., 2008; Raju et al., 2006
river restoration	low	year - decade	medium	low	medium - high	Bukaveckas, 2007; Querner and van Lanen, 2001
(larger) reservoirs	high	decade	fast - medium	medium - high	high	Karamouz and Araghinejad, 2008; Keller et al., 2000; Lund, 2006; Medellin-Azuara et al., 2008; Muttiah and Wurbs, 2002; Nicolosi et al., 2009; van der Zaag and Gupta, 2008
(smaller) lakes, retention basins, etc.	low - medium	year	fast	low - medium	low - medium	Juszczak et al., 2007; Keller et al., 2000; Liebe et al., 2005; van der Zaag and Gupta, 2008
wetland water management	low - medium	year - decade	fast - medium	medium - high	medium - high	Bullock and Acreman, 2003; Dietrich et al., 2007; Kadlec, 1993; Konyha et al., 1995; McKillop et al., 1999; Spieksma, 1999
waste water recycling	low - medium	year - decade	fast	medium - high	high	Angelakis et al., 1999; Angelakis and Durham, 2008; Hamilton et al., 2007; Kennedy and Tsuchihashi, 2005; Pedrero et al., 2010; Ternes et al., 2007

Land use change, land management, surface water storage in smaller reservoirs and artificial groundwater recharge (and recovery) will be the most common measures. On the other hand, urban rainwater management, larger reservoirs, waste water recycling and inter-basin transfer can only be used in areas where such measures already exist, where settlements are located and the transfer of water is socially accepted and feasible.

2.4 Conclusions

Recent and projected low flow during the growing season increases the need for sustaining minimum runoff. Solutions depend to a great extent on the local properties; only integrated holistic approaches ensure appropriate and sustainable water management concepts. The applicability of the methods presented in this article depends on the regional nature of water shortages and local site conditions. This paper highlights the advantages and disadvantages as presented in the previous section, and helps appropriate methods to be chosen as a starting point for future research or planning. The detailed evaluation of methods has to be performed separately considering regional properties because even similar methods behave differently under different boundary conditions.

No detailed evaluation of methods within a regional context can be conducted without the use of modeling tools. Milly et al. (2008) points out that modern water management has to cope with instationarities because hydrological systems are changing with climate change, natural variability and changes in water management itself. Models are the only tool that can calculate the reaction of hydrological systems to climate forcing and water management scenarios. Appropriate models have to consider flow in surface and ground water, as well as the water management system and its controls (see, e.g. Koch et al., 2005; Medellin-Azuara et al., 2008). Despite structural problems and difficulties in quantifying uncertainties, models have been applied successfully for this purpose (Koch et al., 2005; Koch and Vogele, 2009; Medellin-Azuara et al., 2008; Menzel and Burger, 2002). Measures are often represented by forcing available model structures to mimic their impacts. Models with special modules that are able to represent such measures need to be developed next.

The adaption process is a transdisciplinary task. First, groups of stakeholders have different perceptions and ideas about drought and minimum runoff. For instance, from an agricultural perspective, drought risk refers to the soil water content (Schindler et al., 2007) and not so much to low flows in rivers, on which ecologists and water users would focus. Second, the aims of storm water protection and the sustainment of minimum runoff cannot be integrated easily and trivially. Both will play an important role in future water management. Third, it has to be considered that the adaption process is not only a physical problem. Stakeholder involvement and the development of institutional structures are part of the process, too.

Although present knowledge is sufficient to formulate general guidelines and water management plans, further research is required to plan regional adaption in the mid-latitudes. Rossi (2009) recommended preparing mitigation strategies and water management plans that consider water scarcity to adapt to climate change. The European Water Framework Directive (European Commission, 2000) does not appear adequate to fully address drought risk. The literature presented may serve as a starting point for appropriate research and new guidelines.

Several needs for future research exist. First, most measures were developed in semi-arid or arid regions and have to be tested under mid-latitude climate conditions. The dimension of water shortage, meteorological and hydrological conditions differ. Furthermore, the interplay of several measures as part of an integrated water management has to be evaluated. Second, possible synergies between flood protection and low flow augmentation measures need to be analyzed. Mid-latitude catchments can suffer from too high and too low flows, even within the same year. In the case of contrary objectives (e.g. storm water protection suggests that reservoirs should not be filled totally to be able to buffer storm runoff, but low flow augmentation requires filled reservoirs to be able to release water in case of shortage), solutions must be found to integrate both objectives within one single water management concept. Third, the modeling of such managed hydrological systems under climate and anthropogenic change is still unsatisfactory. Useful modeling environments incorporating water management structures and methods to quantify uncertainties urgently need to be developed. In particular, there is a lack of models that can explicitly represent different kinds of measures.

Furthermore, most of the reviewed research is applied on larger scales. Results can only be used in part for small catchments. First, river discharge is lower in small catchments. Second, water management has to focus more on decentralized demands. Third, the combination of measures is strongly dependent on local properties because different interests, institutional complexity and local hydrology have to be integrated (van der Zaag and Gupta, 2008). Research focusing on small catchments is required because these systems will be affected first by the changing climate.

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References

Abida, H. and J. F. Sabourin (2006). Grass swale-perforated pipe systems for stormwater management. *Journal of Irrigation and Drainage Engineering-ASCE 132*(1), 55–63.

Abu-Taleb, M. F. (2003). Recharge of groundwater through multi-stage reservoirs in a desert basin. *Environmental Geology 44*(4), 379–390.

Acreman, M. C., J. R. Blake, D. J. Booker, R. J. Harding, N. Reynard, J. O. Mountford, and C. J. Stratford (2009). A simple framework for evaluating regional wetland ecohydrological response to climate change with case studies from Great Britain. *Ecohydrology 2*(1), 1–17.

Andersen, H. E., B. Kronvang, S. E. Larsen, C. C. Hoffmann, T. S. Jensen, and E. K. Rasmussen (2006). Climate-change impacts on hydrology and nutrients in a Danish lowland river basin. *Science of the Total Environment 365*(1-3), 223–237.

Anderson, M. and J. McDonnell (2005). *Encyclopedia of Hydrological Sciences*, Volume 1. John Wiley & Sons Ltd, Chichester.

Angelakis, A. N., M. H. F. M. Do Monte, L. Bontoux, and T. Asano (1999). The status of wastewater reuse practice in the Mediterranean basin: Need for guidelines. *Water Research 33*(10), 2201–2217.

Angelakis, A. N. and B. Durham (2008). Water recycling and reuse in EUREAU countries: Trends and challenges. *Desalination 218*(1-3), 3–12.

Armbruster, M., J. Seegert, and K. H. Feger (2004). Effects of changes in tree species composition on water flow dynamics - Model applications and their limitations. *Plant and Soil 264*(1-2), 13–24.

Arnell, N. W. (1999). The effect of climate change on hydrological regimes in Europe: a continental perspective. *Global Environmental Change-Human and Policy Dimensions 9*(1), 5–23.

Asano, T. and J. A. Cotruvo (2004). Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. *Water Research 38*(8), 1941–1951.

Baguis, P., E. Roulin, P. Willems, and V. Ntegeka (2010). Climate change scenarios for precipitation and potential evapotranspiration over central Belgium. *Theoretical and Applied Climatology 99*(3-4), 273–286.

Barber, M. E., A. Hossain, J. J. Covert, and G. J. Gregory (2009). Augmentation of seasonal low stream flows by artificial recharge in the Spokane Valley-Rathdrum Prairie aquifer of Idaho and Washington, USA. *Hydrogeology Journal 17*(6), 1459–1470.

Basson, M. S. and J. A. Van Rooyen (1998). Tunnelling into the future: the role of water resources development in South Africa. *Tunnelling and Underground Space Technology 13*(1), 35–38.

Berndtsson, J. C. (2010). Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering 36*(4), 351–360.

Bosch, D. D., R. R. Lowrance, J. M. Sheridan, and R. G. Williams (2003). Ground Water Storage Effect on Streamflow for a Southeastern Coastal Plain Watershed. *Ground Water 41*(7), 903–912.

Bouwer, H. (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal 10*(1), 121–142.

Brandes, D., G. J. Cavallo, and M. L. Nilson (2005). Base flow trends in urbanizing watersheds of the Delaware River basin. *Journal of the American Water Resources Association 41*(6), 1377–1391.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology 310*(1-4), 28–61.

Bukaveckas, P. A. (2007). Effects of channel restoration on water velocity, transient storage, and nutrient uptake in a channelized stream. *Environmental Science & Technology 41*(5), 1570–1576.

Bullock, A. and M. Acreman (2003). The role of wetland in the hydrological cycle. *Hydrology and Earth System Sciences 7*(3), 358–389.

Burt, T. P., P. D. Bates, M. D. Stewart, A. J. Claxton, M. G. Anderson, and D. A. Price (2002). Water table fluctuations within the floodplain of the River Severn, England. *Journal of Hydrology 262*(1-4), 1–20.

Chaulya, S. K. (2003). Water resource development study for a mining region. *Water Resources Management 17*(4), 297–316.

Cheng, C. L., Y. C. Liu, and C. W. Ting (2009). An urban drought-prevention model using raft foundation and urban reservoir. *Building Services Engineering Research & Technology 30*(4), 343–355.

Chiu, Y. R., C. H. Liaw, and L. C. Chen (2009). Optimizing rainwater harvesting systems as an innovative approach to saving energy in hilly communities. *Renewable Energy 34*(3), 492–498.

Cox, W. E. (2007). North Carolina-Virginia conflict: The Lake Gaston water transfer. *Journal of Water Resources Planning and Management-Asce 133*(5), 456–461.

Cunderlik, J. M. and S. P. Simonovic (2005). Hydrological extremes in a southwestern Ontario river basin under future climate conditions. *Hydrological Sciences Journal-Journal des Sciences Hydrologiques 50*(4), 631–654.

da Fonseca, A. F., U. Herpin, A. M. de Paula, R. L. Victoria, and A. J. Melfi (2007). Agricultural use of treated sewage effluents: Agronomic and environmental implications and perspectives for Brazil. *Scientia Agricola 64*(2), 194–209.

Destatis (2009). German Federal Statistical Office (Destatis): http://www.destatis.de/.

Deumlich, D., R. Funk, M. Frielinghaus, W. A. Schmidt, and O. Nitzsche (2006). Basics of effective erosion control in German agriculture. *Journal of Plant Nutrition and Soil Science 169*(3), 370–381.

Dietrich, O., M. Redetzky, and M. Schwarzel (2007). Wetlands with concontrol drainage and sub-irrigation systems - modelling of the water balance. *Hydrological Processes 21*(14), 1814–1828.

Dillon, P. (2005). Future management of aquifer recharge. *Hydrogeology Journal 13*(1), 313–316.

DVWK (2001). ATV-DVWK-Regelwerk Verdunstung in Bezug zu Landnutzung, Bewuchs und Boden (evapotranspiration in connection with land use, plant cover and soil). Technical report, German Association for Water/ Wastewater and Waste.

Eheart, J. W. and D. W. Tornil (1999). Low-flow frequency exacerbation by irrigation withdrawals in the agricultural midwest under various climate change scenarios. *Water Resources Research 35*(7), 2237–2246.

Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a chachange world. *Wetl. Ecol. Manage. 17*(1), 71–84.

European Commission (2000). The EU Water Framework Directive - integrated river basin management for Europe. http:// ec.europa.eu/ environment/ water/ water-framework/.

Exall, K., J. Marsalek, and K. Schaefer (2004). A review of water reuse and recycling, with reference to Canadian practice and potential: 1. Incentives and implementation. *Water Quality Research Journal of Canada 39*(1), 1–12.

Exbrayat, J. F., N. R. Viney, J. Seibert, S. Wrede, H. G. Frede, and L. Breuer (2010). Ensemble modelling of nitrogen fluxes: data fusion for a Swedish meso-scale catchment. *Hydrology and Earth System Sciences 14*(12), 2383–2397.

Fiener, P., K. Auerswald, and K. Van Oost (2011). Spatio-temporal patterns in land use and management affecting surface runoff response of agricultural catchments - A reviewa. *Earth-Science Reviews 106*(1-2), 92–104.

Fohrer, N., S. Haverkamp, K. Eckhardt, and H. G. Frede (2001). Hydrologic response to land use changes on the catchment scale. *Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere 26*(7-8), 577–582.

Giacomelli, P., A. Rossetti, and M. Brambilla (2008). Adapting water allocation management to drought scenarios. *Natural Hazards and Earth System Sciences 8*(2), 293–302.

Giorgi, F. (2006). Climate change hot-spots. *Geophysical Research Letters 33*(8), L08707.

Gobel, P., J. Zimmermann, C. Klinger, H. Stubbe, and W. G. Coldewey (2008). Recommended urban storm water infiltration devices for different types of run-off under varying hydrogeological conditions. *Journal of Soils and Sediments 8*(4), 231–238.

Green, T. R., L. R. Ahuja, and J. G. Benjamin (2003). Advances and challenges in predicting agricultural management effects on soil hydraulic properties. *Geoderma 116*(1-2), 3–27.

Güntner, A., M. S. Krol, J. C. De Araujo, and A. Bronstert (2004). Simple water balance modelling of surface reservoir systems in a large data-scarce semiarid region. *Hydrological Sciences Journal-Journal des Sciences Hydrologiques 49*(5), 901–918.

Gupta, J. and P. van der Zaag (2008). Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock. *Physics and Chemistry of the Earth 33*(1-2), 28–40.

Hamilton, A. J., F. Stagnitti, X. Z. Xiong, S. L. Kreidl, K. K. Benke, and P. Maher (2007). Wastewater irrigation: The state of play. *Vadose Zone Journal 6*(4), 823–840.

Hofmann, H., K. Knoller, and D. Lessmann (2008). Mining lakes as groundwater-dominated hydrological systems: assessment of the water balance of Mining Lake Plessa 117 (Lusatia, Germany) using stable isotopes. *Hydrological Processes 22*(23), 4620–4627.

ICOLD (1998). Position Paper on Dams and Environment, International Commission on Large Dams. http://www.icold-cigb.net.

IHP/OHP (1992). *International Glossary of Hydrology* (2. ed.). Koblenz, Germany: German National Comittee for the International Hydrological Programme (IHP) of the UNESCO and the Operational Hydrology Programme (OHP) of the WMO.

INKA BB (2010). Innovationsnetzwerk Klimaanpassung Berlin Brandenburg. http://www.inka-bb.de/.

IPCC (2007). Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC.

Ishaq, A. M. and A. A. Khan (1997). Recharge of aquifers with reclaimed wastewater: A case for Saudi Arabia. *Arabian Journal for Science and Engineering 22*(1C), 133–141.

Ivey, J. L., J. Smithers, R. C. De Loe, and R. D. Kreutzwiser (2004). Community capacity for adaptation to climate-induced water shortages: Linking institutional complexity and local actors. *Environmental Management 33*(1), 36–47.

Juszczak, R., A. Kedziora, and J. Olejnik (2007). Assessment of water retention capacity of small ponds in Wyskoc agricultural-forest catchment in western Poland. *Polish Journal of Environmental Studies 16*(5), 685–695.

Kadlec, J. A. (1993). Effect of Depth of Flooding on Summer Water Budgets for Small Diked Marshes. *Wetlands 13*(1), 1–9.

Karamouz, M. and S. Araghinejad (2008). Drought mitigation through long-term operation of reservoirs: Case study. *Journal of Irrigation and Drainage Engineering-Asce 134*(4), 471–478.

Keller, A., R. Sakthivadivel, and D. Seckler (2000). Water Scarcity and the Role of Storage in Development. Technical report, International Water Management Institute.

Kennedy, L. A. and R. Tsuchihashi (2005). Is water reuse sustainable? Factors affecting its sustainability. *Arabian Journal for Science and Engineering 30*(2C), 3–15.

Khan, S., S. Mushtaq, M. A. Hanjra, and J. Schaeffer (2008). Estimating potential costs and gains from an aquifer storage and recovery program in Australia. *Agricultural Water Management 95*(4), 477–488.

Knight, R. L., R. Adams, C. O'Brian, and E. R. Davis (1998). Beltway 8 Wetland Water Quality Project - constructed wetlands for stormwater polishing and wetland mitigation banking. *Environ. Social Effects Transport 1626*, 11–20.

Koch, H., M. Kaltofen, U. Grunewald, F. Messner, M. Karkuschke, O. Zwirner, and M. Schramm (2005). Scenarios of water resources management in the Lower Lusatian mining district, Germany. *Ecological Engineering 24*(1-2), 49–57.

Koch, H. and S. Vogele (2009). Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics 68*(7), 2031–2039.

Konikow, L. F. and E. Kendy (2005). Groundwater depletion: A global problem. *Hydrogeology Journal 13*(1), 317–320.

Konyha, K. D., D. T. Shaw, and K. W. Weiler (1995). Hydrologic design of a wetland - advantages of continuous modeling. *Ecological Engineering 4*(2), 99–116.

Koob, T., M. E. Barber, and W. E. Hathhorn (1999). Hydrologic design considerations of constructed wetlands for urban stormwater runoff. *J. Am. Water Resour. Assoc. 35*(2), 323–331.

Kovar, P., P. Cudlin, M. Korytar, F. Zemek, and M. Herman (2001). Comparative study of water balance on the experimental catchments Vseminka and Drevnice. *Rostlinna Vyroba 47*(6), 260–266.

Kvaerner, J. and B. Klove (2008). Generation and regulation of summer runoff in a boreal flat fen. *Journal of Hydrology 360*(1-4), 15–30.

Laber, J. (2000). Constructed wetland systems for stormwater treatment. *J. Environ. Sci. Health Part A - Toxic/Hazard. Substan. Environ. Eng. 35*(8), 1279–1288.

Lewandowski, J., G. Lischeid, and G. Nutzmann (2009). Drivers of water level fluctuations and hydrological exchange between groundwater and surface water at the lowland River Spree (Germany): field study and statistical analyses. *Hydrological Processes 23*(15), 2117–2128.

Li, L. H., H. G. Xu, X. Chen, and S. P. Simonovic (2010). Streamflow Forecast and Reservoir Operation Performance Assessment Under Climate Change. *Water Resources Management 24*(1), 83–104.

Liebe, J., N. van de Giesen, and M. Andreini (2005). Estimation of small reservoir storage capacities in a semi-arid environment - A case study in the Upper East Region of Ghana. *Physics and Chemistry of the Earth 30*(6-7), 448–454.

Lindsay, J. B., I. F. Creed, and F. D. Beall (2004). Drainage basin morphometrics for depressional landscapes. *Water Resources Research 40*(9), W09307.

LUGV (2000). Areal modelling of water balance variables of the federal state of Brandenburg, Germany. Technical report, State Office of the Federal State of Brandenburg. http://www.mugv.brandenburg.de/cms/media.php/lbm1.a.2320.de/luabd27_1.pdf.

Lund, J. R. (2006). Drought storage allocation rules for surface reservoir systems. *Journal of Water Resources Planning and Management-Asce 132*(5), 395–397.

Maidment, D. (1993). *Handbook of Hydrology.* McGraw-Hill, Inc.

Martin-Rosales, W., J. Gisbert, A. Pulido-Bosch, A. Vallejos, and A. Fernandez-Cortes (2007). Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain). *Environmental Geology 52*(5), 985–995.

McKillop, R., N. Kouwen, and E. D. Soulis (1999). Modeling the rainfall-runoff response of a headwater wetland. *Water Resources Research 35*(4), 1165–1177.

Medellin-Azuara, J., J. J. Harou, M. A. Olivares, K. Madani, J. R. Lund, R. E. Howitt, S. K. Tanaka, M. W. Jenkins, and T. Zhu (2008). Adaptability and adaptations of California's water supply system to dry climate warming. *Climatic Change 87*, 75–90.

Menzel, L. and G. Burger (2002). Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *Journal of Hydrology 267*(1-2), 53–64.

Mey, S., H. Albert, C. Hildebrand, and P. B. (2008). Model-based analyses of option to stabilize the water balance in the catchment of the fen in the nature reserve "Lake Luchsee". *Hydrologie und Wasserbewirtschaftung 52*(6), 310–318.

Miller, K. A., S. L. Rhodes, and L. J. Macdonnell (1997). Water allocation in a changing climate: Institutions and adaptation. *Climatic Change 35*(2), 157–177.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer (2008). Climate change - Stationarity is dead: Whither water management? *Science 319*(5863), 573–574.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature 438*(7066), 347–350.

Molenat, J., B. Ndiaye, V. Hallaire, C. Gascuel, and Y. Hammon (2007). Effects of agricultural practices on hydraulic properties and water movement in soils in Brittany (France). *Soil Till. Res. 93*(2), 251–263.

Müller, G. D. and A. M. Thompson (2009). The Ability of Urban Residential Lawns to Disconnect Impervious Area from Municipal Sewer Systems. *Journal of the American Water Resources Association 45*(5), 1116–1126.

Muttiah, R. S. and R. A. Wurbs (2002). Modeling the impacts of climate change on water supply reliabilities. *Water International 27*(3), 407–419.

Nicolosi, V., A. Cancelliere, and G. Rossi (2009). Reducing Risk of Shortages Due to Drought in Water Supply Systems Using Genetic Algorithms. *Irrigation and Drainage 58*(2), 171–188.

Niehoff, D., U. Fritsch, and A. Bronstert (2002). Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology 267*(1-2), 80–93.

Nohara, D., A. Kitoh, M. Hosaka, and T. Oki (2006). Impact of climate change on river discharge projected by multimodel ensemble. *Journal of Hydrometeorology 7*(5), 1076–1089.

Nunes, J. P., J. Seixas, and N. R. Pacheco (2008). Vulnerability of water resources, vegetation productivity and soil erosion to climate change in Mediterranean watersheds. *Hydrological Processes 22*(16), 3115–3134.

Oleary, G. J. (1996). The effects of conservation tillage on potential groundwater recharge. *Agricultural Water Management 31*(1-2), 65–73.

Pandey, D. N., A. K. Gupta, and D. M. Anderson (2003). Rainwater harvesting as an adaptation to climate change. *Current Science 85*(1), 46–59.

Pedrero, F., I. Kalavrouziotis, J. J. Alarcon, P. Koukoulakis, and T. Asano (2010). Use of treated municipal wastewater in irrigated agriculture-Review of some practices in Spain and Greece. *Agricultural Water Management 97*(9), 1233–1241.

Postel, S. L. (2000). Entering an era of water scarcity: The challenges ahead. *Ecological Applications 10*(4), 941–948.

Pusch, M. and A. Hoffmann (2000). Conservation concept for a river ecosystem (River Spree, Germany) impacted by flow abstraction in a large post-mining area. *Landscape and Urban Planning 51*(2-4), 165–176.

Querner, E. P. and H. A. J. van Lanen (2001). Impact assessment of drought mitigation measures in two adjacent Dutch basins using simulation modelling. *Journal of Hydrology 252*(1-4), 51–64.

Raju, N. J., T. V. K. Reddy, and P. Munirathnam (2006). Subsurface dams to harvest rainwater - a case study of the Swarnamukhi River basin, Southern India. *Hydrogeology Journal 14*(4), 526–531.

Rogers, J. S., K. W. Potter, A. R. Hoffman, J. A. Hoopes, C. A. Wu, and D. E. Armstrong (2009). Hydrologic and water quality functions of a disturbed wetland in an agricultural setting. *Journal of the American Water Resource Association 45*(3), 628–640.

Rossi, G. (2009). European Union policy for improving drought preparedness and mitigation. *Water International 34*(4), 441–450.

Rossi, G., A. Cancelliere, and G. Giuliano (2005). Case study: Multicriteria assessment of drought mitigation measures. *Journal of Water Resources Planning and Management-Asce 131*(6), 449–457.

Scanlon, B. R., R. C. Reedy, R. L. Baumhardt, and G. Strassberg (2008). Impact of deep plowing on groundwater recharge in a semiarid region: Case study, High Plains, Texas. *Water Resources Research 44*, W00A10.

Schindler, U., J. Steidl, L. Muller, F. Eulenstein, and J. Thiere (2007). Drought risk to agricultural land in Northeast and Central Germany. *Journal of Plant Nutrition and Soil Science 170*(3), 357–362.

Schindler, U., M. wegehenkel, L. Müller, and F. Eulenstein (1997). Effect of Soil and Crops on Ground Water Recharge at Glacial Arable Sites of Ostbrandenburg. *Archives of Agronomy and Soil Science 41*, 167–179.

Scholz, M. (2007). Expert sysem outline for the classification of sustainable flood retention basins (SFRBs). *Civ. Eng. Environ. Syst. 24*(3), 193–209.

Schumann, S., B. Schmalz, H. Meeseburg, and U. Schröder (2010). Status and Perspectives of Hydrology in Small Basins - Results and Recomondations of the International Workshop in Goslar-Hahnenklee, Germany 2009 and Inventory of Small Research Basins. Technical report, International Hydrological Programme of UNESCO (IHP) and Hydrological and Water Resource Programme of WMO (HWRP), www.ihp.bafg.de.

Sechi, G. M. and A. Sulis (2009). Water System Management through a Mixed Optimization-Simulation Approach. *Journal of Water Resources Planning and Management-Asce 135*(3), 160–170.

Service, R. F. (2004). Water resources: As the West goes dry. *Science 303*(5661), 1124–1127.

Sieker, F. (1998). On-site stormwater management as an alternative to conventional sewer systems: A new concept spreading in Germany. *Water Science and Technology 38*(10), 65–71.

Singh, P. and L. Bengtsson (2004). Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes 18*(13), 2363–2385.

Smakhtin, V. U. (2001). Low flow hydrology: a review. *Journal of Hydrology 240*(3-4), 147–186.

Soni, V., A. K. Gosain, S. Datta, P. S. Datta, and D. Singh (2009). A new scheme for large-scale natural water storage in the floodplains: the Delhi Yamuna floodplains as a case study. *Current Science 96*(10), 1338–1342.

Souchere, V., O. Cerdan, N. Dubreuil, Y. Le Bissonnais, and C. King (2005). Modelling the impact of agri-environmental scenarios on runoff in a cultivated catchment (Normandy, France). *Catena 61*(2-3), 229–240.

Spieksma, J. F. M. (1999). Changes in the discharge pattern of a cutover raised bog during rewetting. *Hydrological Processes 13*(8), 1233–1246.

Taylor, R. (2009). Rethinking Water Scarcity: The Role of Storage. *Eos, Transactions, American Geophysical Union 90*(28), 237–248.

Ternes, T. A., M. Bonerz, N. Herrmann, B. Teiser, and H. R. Andersen (2007). Irrigation of treated wastewater in Braunschweig, Germany: An option to remove pharmaceuticals and musk fragrances. *Chemosphere 66*(5), 894–904.

Tredoux, G., P. King, and L. Cave (1999). Managing urban wastewater for maximising water resource utilization. *Water Science and Technology 39*(10-11), 353–356.

van der Zaag, P. and J. Gupta (2008). Scale issues in the governance of water storage projects. *Water Resources Research 44*(10), W10417.

Verstraeten, W. W., B. Muys, J. Feyen, F. Veroustraete, M. Minnaert, L. Meiresonne, and A. De Schrijver (2005). Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE. *Hydrology and Earth System Sciences 9*(3), 225–241.

Vetter, A. and F. Sondershaus (2011). *River Landscapes - Reference Areas for Regionally Specific Adaptation Strategies to Climate Change. In: Müller, B. (Ed.): Regional Resilience: How do Cities and Regions Deal with Climate Change? (German Annual of Spatial Research and Policy 2010).* Springer-Verlag, Berlin, Heidelberg.

Vörösmarty, C., D. Lettenmaier, C. Leveque, M. Meybeck, C. Pahl-Wostl, J. Alcamo, W. Cosgrove, H. Grassl, H. Hoff, P. Kabat, F. Lansigan, R. Lawford, and R. Naiman (2004). Humans Transforming the Global Water System. *Eos, Transactions, American Geophysical Union 85*(48), 509–520.

Wang, D. B. and X. M. Cai (2010). Comparative study of climate and human impacts on seasonal baseflow in urban and agricultural watersheds. *Geophysical Research Letters 37*, L06406.

Wang, G. L. (2005). Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment. *Climate Dynamics 25*(7-8), 739–753.

Wattenbach, M., M. Zebisch, F. Hattermann, P. Gottschalk, H. Goemann, P. Kreins, F. Badeck, P. Lasch, F. Suckow, and F. Wechsung (2007). Hydrological impact assessment of afforestation and change in tree-species composition - A regional case study for the Federal State of Brandenburg (Germany). *Journal of Hydrology 346*(1-2), 1–17.

Wechsung, F., V. Krysanova, M. Flechsig, and S. Schaphoff (2000). May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? *Landscape and Urban Planning 51*(2-4), 177–189.

Wegehenkel, M. and K. C. Kersebaum (2008). A first assessment of the impact of climate change on discharge and groundwater recharge in a catchment in Northeastern Germany. *Journal of Agrometeorology 10*, 274–281.

Xu, D. and A. Mermoud (2003). Modeling the soil water balance based on time-dependent hydraulic conductivity under different tillage practices. *Agricultural Water Management 63*(2), 139–151.

Yao, H. and A. Georgakakos (2001). Assessment of Folsom Lake response to historical and potential future climate scenarios 2. Reservoir management. *Journal of Hydrology 249*(1-4), 176–196.

Zammouri, M. and H. Feki (2005). Managing releases from small upland reservoirs for downstream recharge in semi-arid basins (Northeast of Tunisia). *Journal of Hydrology 314*(1-4), 125–138.

Zhang, Y. K. and K. E. Schilling (2006). Increasing streamflow and baseflow in Mississippi River since the 1940 s: Effect of land use change. *Journal of Hydrology 324*(1-4), 412–422.

3 Modeling the impact of ditch water level management on stream-aquifer interactions

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Summary

Decreasing groundwater levels in many parts of the federal state of Brandenburg and decreasing low flows in Central Europe have created a need for adaption measures to stabilize the water balance and to increase low flows. It is unclear to what degree water management of existing ditch irrigation systems can increase base flow during low flows. The objective is to estimate the impact of ditch water level management on stream-aquifer interactions by scenario analysis of water levels in ditch structures already existing in small lowland catchments of the mid-latitudes. At the investigated ditch system water levels, runoff and precipitation was monitored between 2010 and 2012. The water balance of the ditch irrigated area and fluxes between the subsurface and the adjacent stream were modeled for three runoff recession periods using Hydrus-2D. Five scenarios of different antecedent water levels in the ditch irrigation system were examined. Results show that subsurface flow to the stream is closely related to the difference between the water level in the ditch system and the stream. Evapotranspiration during the growing season reduced base flow. It was crucial to stop irrigation during a recession event to decrease water loss from the stream and generate base flow by water storage only. Mean fluxes to the stream were between 0.30 and 0.68 ls^{-1} per kilometer length of ditches for the first 20 days of a low flow period. Ditch water levels should be increased as much as possible to assure high base flow during subsequent low flow periods. Clearly, this contradicts current land use and environmental protection. This paper can be used as basis for a discussion on possible fluctuations in water levels in such areas and subsequently possible effects considering current land use have to be evaluated on catchment scale.

Keywords: Groundwater surface water interaction, Adaption measure, Required minimum runoff, Ditch irrigation, Hydrus-2D

3.1 Introduction

The effective use of water and adaption to water scarcity has always been a major challenge of societies (Pandey et al., 2003). In the 21st century adaption to water scarcity as a consequence of climate change will be one major task in many regions of the world (IPCC, 2007). Even in the mid-latitudes water scarcity is not considered a major threat at the moment but changes in climate and water use will change low flows. Adaption of water management might become necessary to sustain minimum runoff (Postel, 2000). In these regions mean annual stream runoff will still be sufficient, butthere will be increasing periods of seasonal water scarcity as a consequence of the precipitation and evapotranspiration patterns was projected (Conradt et al., 2012; Wegehenkel and Kersebaum, 2008). On the other hand sustaining minimum runoff is important to safeguard ecological functions of the stream systems and sustainable water use. Therefore, seasonal water storage will play a crucial role in mitigating water scarcity in these regions (Taylor, 2009). This requires the consideration of seasonal water yield and demand rather than annual mean values. The majority of processes generating runoff from precipitation are nonlinear. For some catchments changes can be abrupt after a threshold is reached, e.g. due to decoupling of groundwater from stream water (Kinal and Stoneman, 2012). Adaption strategies have to consider changes in the annual runoff cycle as well as differences between catchments (Chapter 4).

Recently, adaption strategies have been mainly developed in arid and semi-arid regions. Nevertheless, in the future similar measures and strategies can be useful in the mid-latitudes. Thomas et al. (2011, Chapter 2) reviewed measures to sustain minimum runoff in small catchments of the mid-latitudes. Several small measures with relatively small effects can be combined in a catchment to fulfil water management goals. Thomas et al. (2011, Chapter 2) claim that the measures have to be adapted to the conditions in the mid-latitudes and have to be tested under these conditions. In the beginning existing structures which management can be optimized regarding water storage during the wet season and release during dryer periods will be implemented. Costs are lower and acceptance of stakeholders is higher during implementation compared to the introduction of new measures. In wetlands and on the vicinity of streams, ditches have been constructed at many places in order to improve soil water conditions for agricultural use of these areas (Dietrich, 2008; Dietrich et al., 2012; Querner and van Lanen, 2001). It seems to be worthwhile investigating if these ditches can be optimized in order to increase runoff during low flows. In order to address these issues, a suitable model for an understanding of the interactions between groundwater and surface water is needed.

Traditionally, hydrological modeling has focused either on surface water or groundwater runoff without any detailed consideration of the other part. The description of relevant processes and increased understanding of the basic principles of interactions between groundwater and surface water remains necessary (Sophocleous, 2002, 2007), especially for managing water resources in a lowland basin (Nützmann and Mey, 2007). During the last years, the number of applications of coupled models and respective studies increased (Furman, 2008), particularly with respect to hydrological and biogeochemical processes (Sophocleous, 2002; Stanley and Jones, 2000). Modeling vadose zone flow processes at the scale of about a hectare (field scale) with a spatial discretization comparable to soil hydrological modeling is still rare (Twarakavi et al., 2008), which also applies to understanding flow dynamics (Howard et al., 2006) and quantifying water fluxes (Sophocleous, 2002).

In hydrology, modeling approaches are frequently used to extrapolate between point measurements and to estimate unmeasured variables like actual evapotranspiration (see e.g. Dietrich et al., 2007). Two- and three-dimensional modeling has particularly been applied to such problems (Abbasi et al., 2004; Gärdenäs et al., 2006; Kandelous and Simunek, 2010; Nützmann and Mey, 2007). Today a large number of models solving these problems are available. We refer to Rassam and Werner (2008) who reviewed the different modeling approaches.

In Central Europe ditch irrigation systems have been introduced to lower water levels of wetlands and have increased agricultural use of such areas (Germer et al., 2011). At the moment many ditch systems are used in a way that water levels are as high as possible and agricultural use is still feasible. Consequently, carbon storage and ecological functions should be increased. Thus, these kinds of wetlands are mainly water consumers because of high water levels and increased evapotranspiration losses during drier periods (Bullock and Acreman, 2003; Dietrich et al., 2007). In northeast Germany wetlands are often in the vicinity of streams in groundwater discharge areas. Consequently, changes in water levels will only affect ground water levels locally.

The objective is to assess the impact of ditch water level management on stream-aquifer interactions by altering the management of already existing ditch structures in small lowland catchments of the mid-latitudes. We present monitoring results of such a system and performed water management scenario analyses using a hydrological model.

3.2 Methods

3.2.1 Study site

The study site is situated in the Baruther Urstromtal, a postglacial valley in the lowlands of northeast Germany close to the city of Cottbus. It is located in a small lowland watershed (average altitude 65 m.a.s.l.) and represents an irrigation system with two ditches which are arranged as bypass at the western side of the Koselmühlenfließ stream. The irrigated area of about 18 ha has an average width of 130 m and a total length of 1400 m. However, the observed irrigation system with two ditches extends only to a length of 980 m (13 ha) because one ditch drains to the stream before (Figure 3.1).

The discharge of the stream Koselmühlenfließ is partly controlled by surplus water from the open pit lignite mining (Lower Lusatia) located upstream. Irrigation ditches are connected to the Koselmühlenfließ and a weir at Q17 controls the amount of irrigation water. Excess water is discharged downstream. Groundwater observation wells were installed along a transect orthogonal to the streambed (Figure 3.1) to assess the interaction between groundwater and surface water.

The irrigated area is used as pasture. Irrigation is important during summer

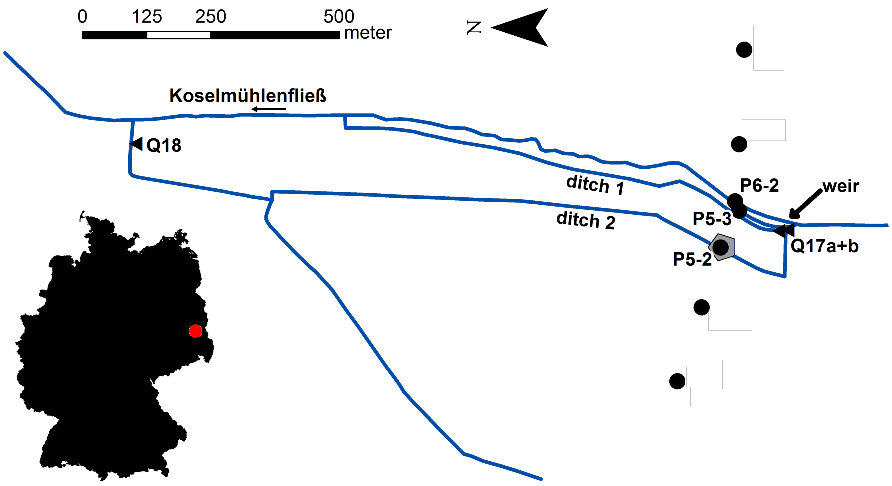

Figure 3.1: Groundwater wells (circles), discharge gauges (triangles), rain gauge (grey pentagon) and the stream and ditch system of the study site at the Koselmühlenfließ stream. At Q17 the stream is dammed and water is let to the two irrigation ditches. The modeled transect is located between the groundwater well at P5-2 at ditch 2 and the stream.

months (June to August). Higher potential evapotranspiration rates (336 mm yr^{-2}) than precipitation rates (305 mm yr^{-2}) induce a deficit in the climatic water balance and drought risk during the growing season.

3.2.2 Data

Precipitation, groundwater levels at five observation wells and surface water levels at three stream gauging stations were measured. Groundwater observation wells and weirs were equipped with MWAG (Ackermann KG) and MDS Dipper-3 (SEBA Hydrometric GmbH) data loggers with 1 mm depth resolution. Hourly water levels were available since July 8^{th}, 2010 and were aggregated to daily values. Precipitation measured by a Hellmann precipitation gauge was corrected for evaporation and wind errors according to Richter (1995). The potential evapotranspiration was calculated using the Penman equation modified by Wendling et al. (1991). Further meteorological data were available from the meteorological station in Cottbus, provided by the German Meteorological Service (DWD, 2013). Altitude along the transect of groundwater gauges was determined by leveling.

Soil hydraulic parameters were analyzed by sieving of soil samples (grading analysis) and the use of the evaporation method (Schindler et al., 2010) using 250 cm^3 soil cores. We determine the retention curves of the soil samples according to Schindler et al. (2010) and fitted the measured data to the model of van Genuchten (1980) and Mualem (1976) using the Shypfit algorithm of Peters and Durner (2006). Soil and core cutter samples were taken from two drillings and a soil profile arranged between the groundwater observation wells P5-2 and P5-3.

The predominant soil type at the study

site was gley. It is characterized by sandy layers with primarily medium grain sizes. The sands locally contained clay, fine and coarse sand as well as fine gravel. Estimated physical soil properties 3.1 were determined from the grain size distributions according to AG Boden (2005). Van Genuchten/Mualem parameters for the horizons of the soil profile were estimated by means of the evaporation method (Table 3.2). The soil horizons were classified as Ah (mineral soil with humus accumulation), Go (oxidized groundwater horizon), Gr (reduced groundwater horizon) and C (mineral layer less affected by pedogenetic processes) according to the German pedrological mapping (AG Boden, 2005). According to the FAO guidelines, the last two horizons would be merged and the horizons would be classified as Ah, Bl and C. The corresponding soil unit is Gleysoil.

3.2.3 Modeling framework

Model set-up

We used the Hydrus-2D package of Simunek et al. (2012) because it is suitable to (i) simulate water transport in variably saturated media, (ii) incorporate several time dependent boundary conditions including evapotranspiration patterns and (iii) handle spatial domains on the field scale. It is a standard tool to model water and solute transport in the unsaturated and saturated zone. Simunek et al. (2008) presented examples of various Hydrus-2D applications. Moreover, the Hydrus-2D model provides an optimal tradeoff between computational costs and accuracy of model simulations. It has already been used before to model groundwater problems at the scale of several hundred meters (Twarakavi et al., 2008).

A 2-dimensional profile section located between the groundwater observation wells P5-2 (at ditch 2) and P5-3 (at ditch 1) was defined as model domain (Figure 3.2). It was implemented as a 105 m wide and up to 5.5 m deep vertical plain with an area of 316 m^2. A finite element mesh was generated with the Hydrus tool Meshgen-2D. At the top of the model domain a fine spatial discretization was used in order to increase numerical stability in the unsaturated layers. According to Vogel and Ippisch (2008), the spatial extent of the finite elements increased from top (approx. 4 cm) to bottom (approx. 60 cm) in order to decrease computation time. The generated finite element mesh consists of 21243 nodes and 45057 elements in total.

Four layers (Ah, Go, Gr and C) with different textures were defined to consider soil stratigraphy in the model according to the depths found in the soil profile and drillings (Figure 3.2). The equations of van Genuchten (1980) and Mualem (1976) were used to model the relation between water content θ and matrix potential Ψ_m described by the water retention curve $\theta(\Psi_m)$ and the unsaturated hydraulic conductivity function $K(\theta)$. Additionally, three colmatation layers (beneath stream and ditches) were inserted to consider reduced hydraulic conductivities of the sediments in the ditches and the stream.

Measured time series of precipitation and potential evapotranspiration were implemented as atmospheric boundary conditions at the surface of the model domain. We used the root water uptake model by Feddes et al. (1978) to consider reduction of actual transpiration due to water stress. It is based on empirical relations that describe actual root water uptake as a function of the calculated pressure head. The po-

Table 3.1: Estimated physical soil properties for surface, subsurface and subsoil layers. eBD (effective bulk density); TPV (total pore volume); FC (field capacity); uFC (usable field capacity); AC (air capacity); PWP (permanent wilting point).

horizon	eBD	TPV	FC	FC	PWP
			at pF= 1.8		at pF= 4.2
	(g cm^{-3})	(vol-%)	(vol-%)	(mm)	(vol-%)
Ah	1.183	55.0	48.2	171.1	23.9
Go	1.773	33.0	25.7	136.7	5.3
Gr	1.913	28.0	14.3	506.1	0.1

horizon	PWP	uFC	uFC	AC	AC
	(mm)	(vol-%)	(mm)	(vol-%)	(mm)
Ah	84.8	24.4	86.6	6.8	24.1
Go	28.2	20.4	108.5	7.3	38.8
Gr	3.5	14.2	502.5	13.7	484.8

Table 3.2: Initial parameter set of the soil hydraulic properties determined by the evaporation method.

horizon	θ_r (-)	θ_s (-)	α (m^{-1})	n (-)	K_s (m day^{-1})	l (-)
Ah	0.198	0.546	1.67	1.383	21.82	0.5
Go	0.024	0.333	2.39	1.399	8.27	0.5
Gr	0	0.278	2.57	2.051	6.28	0.5
C	0.033	0.396	4.90	1.960	4.03	0.5

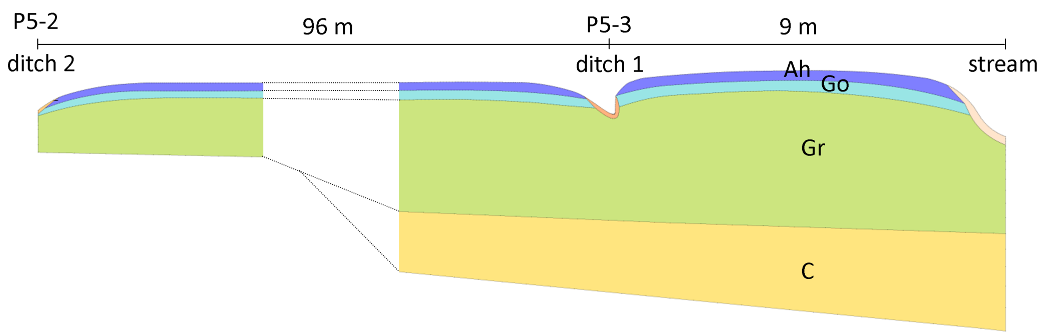

Figure 3.2: Geometry of the model domain and implemented soil layers. The soil body was divided into four different layers (Ah, Go, Gr and C) and three colmatation layers around the stream and ditches.

tential evapotranspiration (ET_p) was separated into potential soil evaporation (E_s) and potential transpiration (E_t) according to Beer's law:

$$E_t = ET_p \cdot SCF \tag{3.1}$$

$$E_s = ET_p \cdot (1 - SCF) \tag{3.2}$$

The soil cover fraction

$$SCF = 1 - e^{-a_i \cdot LAI} \tag{3.3}$$

was calculated from the leaf area index

$$LAI = 0.24 h_{grass} \tag{3.4}$$

and the extinction constant $a_i = 0.463$ (Sutanto et al., 2012). The whole study site was covered by pasture. Its grass height (h_{grass}) was uniformly set to 15 cm. Hence, 80% of the potential evapotranspiration were represented by potential transpiration and 20% by potential evaporation.

We used the Feddes parameters for grass that were suggested byWesseling et al. (1991) and Taylor and Ashcroft (1972). Maximum rooting depth was set to 40 cm and depth of maximum intensity to 15 cm according to field observations at the soil profile. The actual evaporation rate was lower than the potential only if evaporation capacity was exceeded. Therefore pressure heads at the soil surface had to be below a threshold of -15000 cm. Observed groundwater levels were always close to the surface and this threshold has never been reached in the current observation period. Thus, the potential evaporation rate was equal to the actual rate.

The lateral boundaries were specified as variable head boundary conditions. We assigned the measured groundwater heads from P5-2 and P6-2 to both lateral boundaries (identical to ditch and stream, water levels). The boundary at ditch 1 was specified by a pressure head boundary condition. were assessed by regressing periodically measured surface water levels at P5-3 with recorded groundwater levels at the same position (r^2=0.94, n=12). The bottom of the model domain was defined as no flux boundary. We found an impermeable layer by drilling which is also designated in the hydrogeologic map of Brandenburg (State Office for Mining, Geology and Raw Material of Brandenburg, 2012).

Model calibration

We used the Levenberg-Marquardt parameter estimation algorithm (Simunek et al., 2012) to optimize effective model parameters of the upper three soil layers and the colmatation layers. Van Genuchten/Mualem parameters measured in soil cores according to Schindler et al. (2010) were set as initial values. Groundwater level data observed from March 15th to April 3rd, 2012, at P5-3 were used as inverse solution data. During this time period the inflow to the ditches was stopped in the field to simulate a recession event. In a first step the unknown conductivities of the three colmatation layers were estimated. It was not necessary to calibrate the other soil hydraulic parameters because the colmatation layers were always saturated when fluxes occurred. In a second step α, n and K_s of the upper three soil layers were optimized in three calibration runs starting with the Ah followed by the Go and the Gr horizon. Values for estimated parameters were not constrained by predefined bounds.

3.2.4 Scenarios

Scenarios were used to analyze groundwater-surface water interaction for different management of water levels in the irrigation system. Three different periods which showed a clear recession in runoff were chosen (Figure 3.3). Precipitation, potential evapotranspiration and water levels of the analyzed periods are described in Table 3.3.

The aim of the scenario analysis was to quantify the fluxes between stream and groundwater depending on different antecedent water levels of the irrigation ditches before an streamflow recession event. Initial conditions were calculated using model spin-ups repeating the meteorological conditions of the day before the scenario periods for 20 days. The water levels in the irrigation ditches were defined as constant head corresponding to the respective scenario. Calculations guaranteed stationary pressure heads at the end of the spin-ups. Ditch water levels were set to 10, 20, 30, 40 and 50 cm above the bed of the first ditch at P5-3 and those at P5-2 were adapted respectively (66.4 to 66.8 m.a.s.l.). Regarding each scenario, we made the assumption that no water is flowing in the ditches. This was implemented by introducing an exponential recession in pressure heads at the western boundary (P5-2) and defining a no-flux boundary condition at the other ditch (P5-3). During the time period from March 15th to April 3rd, 2012, the irrigation was stopped and water drained to the Koselmühlenfließ according to site properties. This experiment aimed at determining recession coefficients for the boundary conditions. For the western boundary (P5-2) the recession constant was -0.011 m day^{-1} (n=19, r^2= 0.82).

The five different scenarios were modeled for each time-period. The simulated fluxes between the model domain and the stream for the different scenarios were compared to a baseline simulation used as a reference. The measured data of ditch, stream and groundwater heads were used as boundary conditions for the baseline simulation.

3.3 Results

3.3.1 Model calibration

The Levenberg-Marquardt optimization succeeded in improving model performance during the calibration period. The parameters of the three upper soil layers and the K_s values of the colmatation layers were changed (Table 3.4). Calibrated K_s values were not comparable to those obtained by the evaporation method. The n-values of the upper layers were considerably increased which seemed to be reasonable given the high sand content and the uniformity of the grain size distribution. In this regard the parameter n is very sensitive and it is significantly controlled by the textural composition of the considered soils. The value of the parameter α was decreased for the first subsurface layer and the residual water content increased for the second subsurface layer. The parameters α of the Ah horizon and α and n of the Gr horizon did not change even though they were allowed to.

Parameter estimation and optimization resulted in good agreement between calculated and measured groundwater levels at P5-3 for the calibration period (Figure 3.4). In comparison to measured groundwater levels the calculated ones revealed a root-mean-square error (RMSE) of 0.02 m and a maximum deviation of 0.04 m. The Nash-Sutcliffe efficiency was 0.89 and

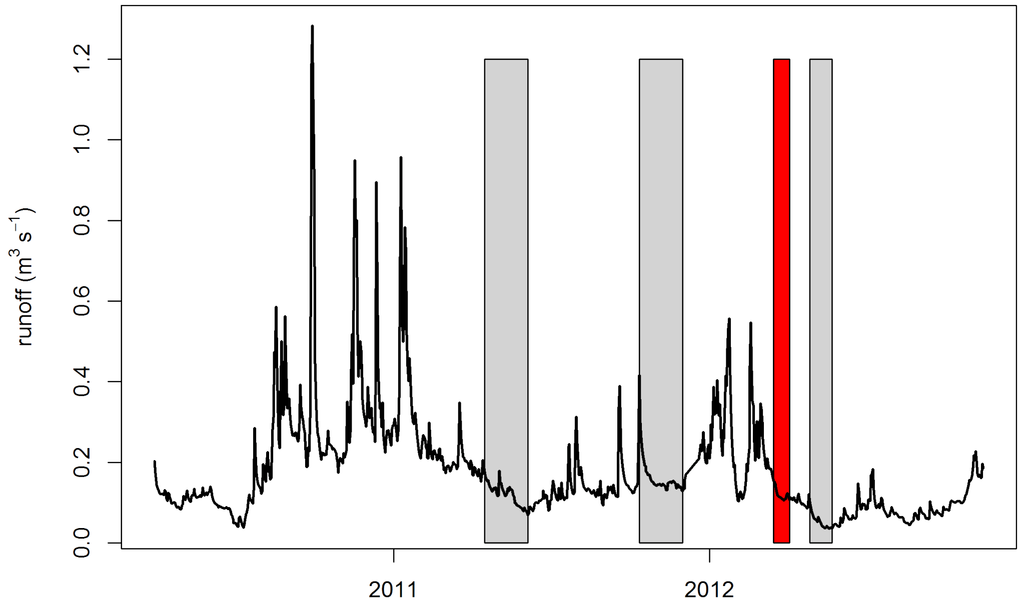

Figure 3.3: Discharge of the Koselmühlenfließ and selected time-periods for calibration (red, 15.03.–03.04.2012) and scenario analyses (grey, 16.05.–05.06.2011, 12.10.–01.12.2011 and 26.04.–22.05.2012).

Table 3.3: Meteorological conditions and water levels of the stream Koselmühlenfließ (WLS) for the three recession events and the calibration period (15.03.–03.04.2012).

	16.05.–05.06.2011	12.10.–01.12.2011	15.03.–03.04.2012	26.04.–22.05.2012
P (mm)	140	11	5	14
Etp (mm)	293	39	39	95
initial WLS (m a.s.l.)	64.28	64.62	64.25	64.11
final WLS (m a.s.l.)	64.52	64.25	64.02	63.79

Table 3.4: Optimized parameter set of the hydraulic properties of the soils and colmation layers in the model domain.

horizon	α (m^{-1})	n (-)	K_s (m day^{-1})
Ah	1.670	2.465	8.86
Go	1.929	3.399	9.16
Gr	2.570	2.051	29.69
col. layer P5-2	-	-	0.493
col. layer P5-3	-	-	0.493
col. layer stream	-	-	0.018

the Pearson correlation coefficient r^2=0.90 (n=20).

3.3.2 Scenario results

Figure 3.5 shows the temporal evolution of the groundwater head for the scenario of 50 cm water level in ditches for the period with the lowest flows (26.04.–22.05.12.). At day 0 the water table was controlled by the ditch water levels at the borders of the cross section. Higher water levels in the middle of the cross section were due to an earlier precipitation event. The modeled pressure head illustrates ongoing fluxes from the model domain to the stream for the first 20 days after ditch irrigation was stopped. The irrigated area supplied water into the stream for the entire period and water was supplied steadily from the western boundary condition (i.e. the adjacent area).

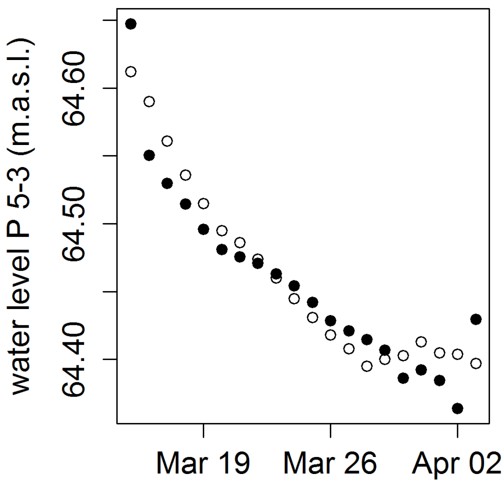

Figure 3.4: Comparison of observed (filled dots) and calculated (hollow dots) groundwater levels at the groundwater gauge P5-3 for the calibration period (15.03.–03.04.2012).

The more storage capacity is filled, the longer the system can support fluxes to the stream. Fluxes to the stream increase with increasing ditch water levels controlling the water storage before the low flow period (Figure 3.6). Additionally, the water level in the stream determines the potential volume of water which can flow towards the stream after irrigation was stopped. During the period with the lowest water levels

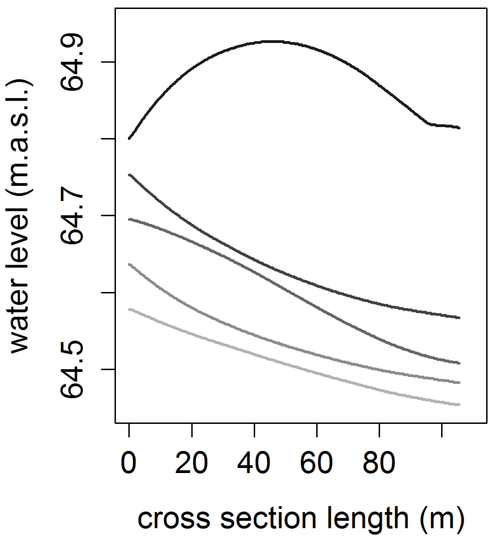

Figure 3.5: Evolution of groundwater levels for the model domain based on the scenario 50cm water level in the ditches for the period 26.04.–22.05.12 (lateral boundaries: right stream and left ditch2 at P5-2). The lines correspond to 0, 5, 10, 15 and 20 days of simulation time (from black to light grey).

in the stream, fluxes to the stream were higher.

In order to compare the calculated results we decided to take the first 20 days of the different time-periods into account. Calculated fluxes at the main boundaries: Atmospheric boundary with precipitation (P) and actual evapotranspiration (Eta), western lateral boundary (IF-P5-2), eastern lateral boundary (IF-Stream) and fluxes at ditch P5-3 (IF-P5-3), as well as storage alteration (ΔS) and mean relative error in water mass balance (MWatBalR) are listed in Table 3.5.

The highest flow rates to the stream were found in spring when the effective storage was high. In summer presumably higher evapotranspiration additionally lowered fluxes. Between the 1st of April and the 30th of September, 2011, 306 mm precipitation was opposed to 557 mm potential evapotranspiration. Evapotranspiration losses were compensated by inflow from the ditches in the baseline. Nevertheless, the irrigation system had a positive influence on fluxes to the stream during low flow conditions. These fluxes increased with increasing ditch water levels in the scenarios.

Irrigation was suspended during the low flow periods in the scenario runs preventing additional losses of water from the stream draining to the ground. We calculated the mean cumulative fluxes over 10 and 20 days as a function of mean difference between the ditch water level (before drought period) and water level in the stream (Figure 3.7). Cumulative fluxes in direction to the stream increased with increasing ditch water levels and time. Scattering was due to different evapotranspiration and precipitation during the events but was of minor importance.

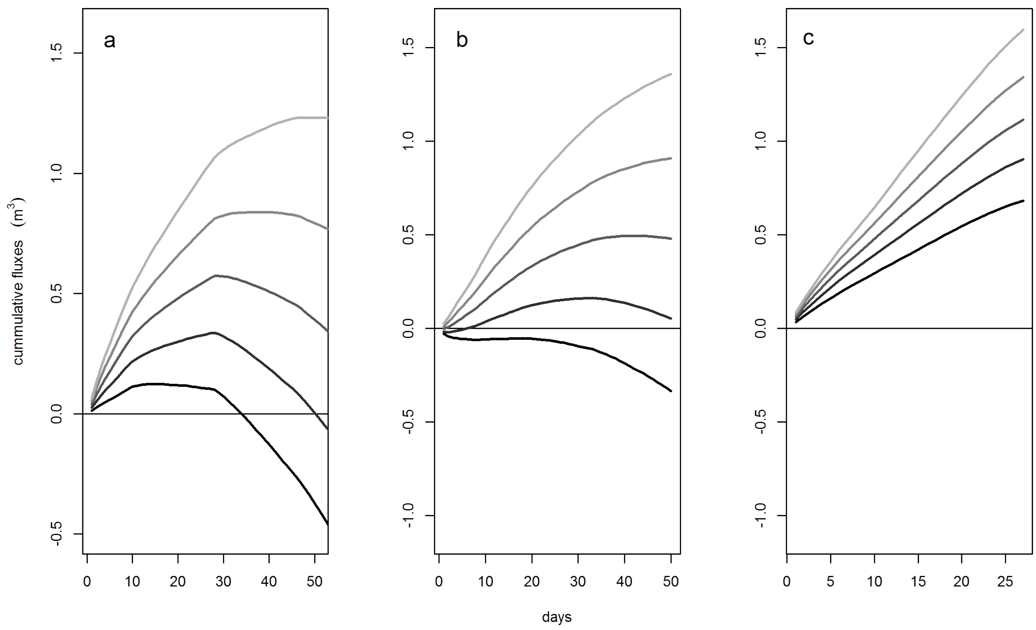

Figure 3.6: Calculated cumulative fluxes into the stream for the 5 different scenarios (10 to 50 cm ditch water level, from black to light grey, respectively). Time-periods: (a) 16.05.–05.06.2011, (b) 12.10–01.12.11 and (c) 26.04.–22.05.12.

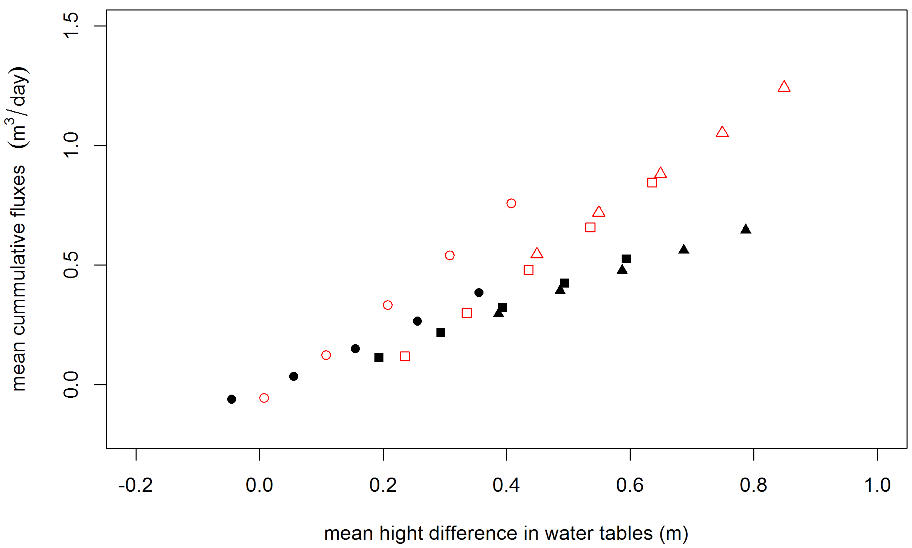

Figure 3.7: Mean fluxes in stream direction dependent on the height difference of water levels between the ditches before the recession event and the mean water levels in the stream for the three time-periods starting from 16.05.2011 (squares), 12.10.2011 (dots) and 26.04.2012 (triangles). The first 10 (black filled symbols) and 20 (red hollow symbols) days of these time-periods were evaluated.

Table 3.5: Calculated fluxes at the model boundaries for the first 20 days of the periods (a) 16.05.–05.06.2011, (b) 12.10.–01.12.2011 and (c) 26.04.–22.05.2012. Positive fluxes direct out of the model domain and vice versa. IF = in flow.

scenario	P (mm d^{-1})	ETa (mm d^{-1})	IF-stream (mm d^{-1})	IF-P5-2 (mm d^{-1})	IF-P5-3 (mm d^{-1})	ΔS (mm d^{-1})	MWatBalR (%)
(a) 16.05–05.06.2011			initial stream water level: 64.28 m a.s.l.				
10 cm	0.23	3.97	0.06	-0.76	0.00	-3.03	0.15
20 cm	0.23	3.83	0.14	-0.92	0.00	-2.82	0.25
30 cm	0.23	3.55	0.23	-1.11	0.00	-2.44	0.31
40 cm	0.23	3.16	0.31	-1.30	0.00	-1.94	0.20
50 cm	0.23	2.67	0.40	-1.42	0.00	-1.42	0.09
baseline	0.23	4.47	0.26	-0.88	-2.91	-0.71	0.14
(b) 12.10–01.12.2011			initial stream water level: 64.63 m a.s.l.				
10 cm	0.42	0.95	-0.03	0.83	0.00	-1.33	0.38
20 cm	0.42	0.87	0.06	0.58	0.00	-1.09	0.49
30 cm	0.42	0.74	0.16	0.41	0.00	-0.89	0.43
40 cm	0.42	0.60	0.26	0.23	0.00	-0.66	0.20
50 cm	0.42	0.45	0.36	0.08	0.00	-0.48	0.36
baseline	0.42	0.41	0.40	0.92	-1.52	0.20	0.94
(c) 26.04.—22.05.2012			initial stream water level: 64.11 m a.s.l.				
10 cm	0.71	3.20	0.26	-0.11	0.00	-2.64	0.36
20 cm	0.71	3.03	0.34	-0.32	0.00	-2.34	0.49
30 cm	0.71	2.76	0.42	-0.59	0.00	-1.88	0.43
40 cm	0.71	2.39	0.50	-0.81	0.00	-1.37	0.36
50 cm	0.71	1.97	0.59	-0.95	0.00	-0.90	0.22
baseline	0.71	2.60	0.43	-0.97	-1.45	0.10	0.53

3.3.3 Water balance in low flow periods

We chose the period with the lowest water levels in the stream (26.04.–22.05.12.) in order to estimate potential fluxes from the pasture to the stream during low flows. Fluxes from the irrigation system to the stream were extrapolated to the total length of the irrigation system (982 m, Table 3.6). The results of the 2D simulations were multiplied with the length of the irrigation ditches, thus changes in the relief were neglected. Fluxes significantly depended on the scenario. Streamflow was increased for all scenarios. However, larger fillings of the storage system lead to increased inflow of water to the stream. The comparison between inflow of water to the stream and discharge in the stream highlights that much larger areas would be necessary to distinctly increase low flow. Compared to the baseline streamflow was much higher in the scenario runs because no water was let to the ditch system. This effect was much larger than the increased subsurface fluxes to the stream (see also flows at the ditches in Table 3.5). Measurements at the inlet to the ditches showed that the proportion of water which was led to the ditch system could be more than 20% of the streamflow. But the water flow from the ditch system back to the stream was not measured. The baseline scenarios estimate how much water infiltrates in the ditches (Table 3.5). Here infiltration from the ditches were -1.66 ls^{-1} (P5-3) and 1.38 ls^{-1} (P5-2) for the whole irrigated area.

3.4 Discussion

The selected model proved to be suitable to analyze the interaction between ditches, the stream Koselmühlenfließ and the adjacent meadow. We chose this model because groundwater tables were shallow and interaction between groundwater, the ditches, the stream and the atmosphere had to be considered. Hydrus-2D provided algorithms to implement all of these features and allowed calculation of unsaturated flows above the groundwater table as well as of saturated flows in aquifers (Simunek et al., 2012). Calibration of the soil hydrological parameters was necessary to fit the measured recession in groundwater heads during an experiment where no water was directed to the ditches. The recession of groundwater level during the calibration period was slower than the ones in the model with the measured parameter set. The introduction of colmatation layers was reasonable because otherwise K_s values of the soil layers would have been lowered unrealistically.

Some restrictions and uncertainties have to be mentioned: (i) Regarding precipitation in Brandenburg since 1900, the years of 2010, 2011 and 2012 ranked 4th and 20th and 56th (DWD, 2013). Correspondingly, no extreme low flows were observed. The scenario analyses showed that flows to the stream are higher when stream water level decreases. Thus, we expect higher flows from the system to the stream under extreme low flow events. (ii) The vegetation was assumed to be static without changes over time and adaptation to the higher groundwater levels in the scenarios. The parameterized vegetation is considered to be typical for pasture (Taylor and Ashcroft, 1972; Wesseling et al., 1991). Actual transpiration decreased with increasing groundwater level despite the fact that more water is available to plants. The productivity of many of the plants decreases whe

Table 3.6: Mean discharge of the stream Koselmühlenfließ (Q-Stream) and mean fluxes from the irrigation system (IF-Stream) at a length of 982 m and the sum of both for the time-period: 16.05.–05.06.11.

scenario	IF-Stream (l s^{-1})	Q-Stream (l s^{-1})	sum (l s^{-1})
10 cm	0.29	52.42	52.71
20 cm	0.38	52.42	52.80
30 cm	0.47	52.42	52.89
40 cm	0.56	52.42	52.98
50 cm	0.67	52.42	53.09
baseline	0.50	45.63	46.13

groundwater levels are high. Especially regarding the scenarios with high water levels, the vegetation layer would not sustain over time and hydrophilic species would grow. The groundwater gradient had the largest impact on fluxes between the stream and the subsurface and evapotranspiration lowered fluxes during months of the growing season. (iii) At the western boundary a recession constant in water levels was introduced during scenario analysis. It was assumed that no water was let to the ditches for the scenarios and thus the measured ditch water levels were incorrect as boundary condition. The recession constant was derived from the drainage event also used for calibration. No repetition of the drainage experiment was performed and thus no uncertainties of the recession constant can be given. (iv) Comparison of uncalibrated model runs with measured groundwater tables during the calibration period showed that effective conductivity of the groundwater layer must be lower than the measured ones. Colmatation layers had to be introduced at the ditches and stream to compensate for this shortcoming in measurements. The soil profile and drillings showed that the subsurface was ordered relatively homogeneously. The introduction of colmatation layers was more reasonable to the authors than excessive reduction of conductivities of the subsurface layers during calibration. (v) The focus of this study was on the interaction of a meadow with ditch irrigation and the adjacent stream during stream flow recession. Parameter and model uncertainties were not analyzed. The analysis of equifinality and different model structures was beyond the scope of this study.

The ditch irrigated area slightly increased stream flow in the adjacent stream during periods of runoff recession. Fluxes to the stream increased with height difference between water level in the ditch system prior to stream flow recession and mean stream water level during the recession period. Fluxes were highest during the first days but sustained for more than 25 days during the scenarios with at least 20 cm water levels in the ditch system. Regarding lower water levels in the ditches flows could be reversed, from the stream to the pasture, because relief is low and the drainage ditch east of the pasture (see Figure 3.1). Water consumption by evapotranspiration was less important to describe fluxes for the first 20 days, but fluxes to the river were lower for the two events in spring (Figure 3.7). Figure 6a and b suggests that for longer time periods high evapotranspiration will deplete storage and will lead to flows from the stream to the pasture. Stopping irrigation during streamflow recession was important to lower water abstraction from the stream which is partly lost by evapotranspiration and to guarantee that fluxes to the stream result from storage change (Table 3.5). At ditch 1 (P5-3) infiltration was -2.91, -1.52 and -1.45 mm day^{-1} and fluxes to the stream were 0.26, 0.40 and 0.43 mm day^{-1}, for the three investigated periods respectively. Measurable low flow mitigation for the investigated stream would require a much larger area because flows to the stream of this approx. 13 ha large system delivered less than 1 ls^{-1} for the studied recession periods. For the first 20 days mean fluxes to the stream were between 0.30 and 0.68 ls^{-1} per kilometer length of ditches for the period with the lowest stream water levels depending on the scenario.

More extreme low flows are expected considering trends in other streams of central Europe (Stahl et al., 2010). Additionally, runoff and low flows will decrease at the investigated stream because dewatering of the adjacent lignite mine will be stopped in the future. Measures to increase base flow and stabilize the water balance during low flows must be developed. An existing ditch irrigation system was tested using different scenarios of adjusted groundwater levels before a low flow event. However, Bullock and Acreman (2003) showed that natural wetlands often decrease downstream discharge. Riverine fens with ditch systems generally have to be considered as water consumers, but temporal dynamics of such systems can also depend on the water management (Dietrich et al., 2007; Querner and van Lanen, 2001, Chapter 2). Although evapotranspiration of such systems is high, lowering the water table during low flows results in a decrease of storage and some increase in fluxes to the stream or ditch. Our results from the monitoring and modeling showed that managing the ditch water levels before a low flow period and stopping water inflow to the ditches during low fluxes to the stream. Regional modelling of groundwater recharge estimated a mean runoff of 114 mm per year (3.6 ls^{-1}km^{-2}) for Brandenburg between 1976 and 2005 (ABIMO model results, MUGV, 2013; LUGV, 2000). Considering 13 ha of ditch irrigated area and a flow to the stream of 0.5 ls^{-1} (comparable to some of the scenario calculations), the contribution of the area would be 3.9 ls^{-1}km^{-2}. It has to be considered that depending on the situation the real contributing area is larger than the area between the ditches because water is allowed to enter the western boundary of the model domain. It demonstrates that the water management of the ditch system has a positive effect on flows during low flows but managed areas have to be increased in order to obtain significant increase in low flows of the investigated stream. However, a similar irrigation system would be possible at smaller streams with lower runoff. In this case such a measure would be more effective.

The general results are transferable to the whole region despite the uniqueness of every place. . Corresponding measures will only be effective as long as the main flow direction is towards the stream. An increase in base flow can only be achieved if the ditches are regulated, water levels are as high as possible before low flow, the gradient to the stream water level is high and no water is let to the ditches during low flows. It has to be considered that such a measure is decentralized and has a relatively low efficiency compared to surface water reservoirs with higher storage capacity for the same area and more precise possibilities of regulation.

The results point at potential conflicts with other land use. After having reached a certain height, increased groundwater levels will conflict with agricultural use. Strong fluctuations of the groundwater table could be problematic for environmental protection of species adapted to moist conditions or forestry. In a next step it will be important to examine the constraints from land use and environmental protection to finally conclude on the feasibility of similar measures to stabilize the water balance and increase low flows in small catchments of Brandenburg.

3.5 Conclusion

Water fluxes between a ditch irrigated pasture and the adjacent stream Koselmühlenfließ in Northeast Brandenburg were examined for different scenarios of ditch water level management during recession of water levels in the stream. The benefit of adapting the water management of ditch irrigated areas in order to sustain minimum runoff in streams was examined. Ditch water levels have to be as high as possible before a low flow event to increase the stored water volume. Ditch irrigation should be stopped during low flows so water fluxes from the pasture to the stream are mainly due to depletion in storage and no water is lost from the stream. Evaporation was of minor importance to explain fluxes to the stream. Depending on the scenario, mean fluxes to the stream during the period with lowest observed flows were between 0.30 and 0.68 ls-1 per kilometer length of ditches. Evaporation lowered fluxes to the stream and fluxes were lower for the periods in spring compared to the one in fall and winter. Depletion of storage due to evapotranspiration is estimated to become more important for periods of low flows longer than the 20 days analyzed in this article. Current management (water always flowing to ditches) resulted in higher infiltration from the ditches than fluxes from the pasture to the stream during periods of low flows (up to 10fold depending on period).

Such decentralized systems could contribute to the stabilization of the water balance and the increase of low flows. The magnitude of flows shows that numerous of such or similar measures are needed to obtain observable effects for meso scale catchments. High and fluctuating groundwater levels can conflict with land use or environmental protection. Compromises are necessary for areas which potentially could be managed in the way suggested here. Future studies have to estimate the potential of such measures on the catchment scale and integrate compromises with current land use and environmental protection.

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References

Abbasi, F., J. Feyen, and M. T. van Genuchten (2004). Two-dimensional simulation of water flow and solute transport below furrows: model calibration and validation. *Journal of Hydrology 290*(1-2), 63–79.

AG Boden (2005). *Bodenkundliche Kartieranleitung (engl. pedrological mapping guideline for Germany)* (5. ed.). Schweizerbart'sche Verlagsbuchhandlung, Stuttgard.

Bullock, A. and M. Acreman (2003). The role of wetland in the hydrological cycle. *Hydrology and Earth System Sciences 7*(3), 358–389.

Conradt, T., H. Koch, F. Hattermann, and F. Wechsung (2012). Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change 12*(3), 633–648.

Dietrich, O. (2008). *The Spreewald integration concept and results on water balance developments. In: Integrated Analysis of the Impacts of Global Change on Environment and Society in the Elbe River Basin*, pp. 266–275. Weißensee Verlag, Berlin.

Dietrich, O., M. Redetzky, and M. Schwarzel (2007). Wetlands with concontrol drainage and sub-irrigation systems - modelling of the water balance. *Hydrological Processes 21*(14), 1814–1828.

Dietrich, O., J. Steidl, and D. Pavlik (2012). The impact of global change on the water balance of large wetlands in the Elbe Lowland. *Regional Environmental Change 12*(4), 701–7013.

DWD (2013). German Meteorological Service. http:// www.dwd.de.

Feddes, R., P. Kowalik, and H. Zaradny (1978). *Simulation of field water use and crop yield.* Centre for Agricultural Publishing and Documentation.

Furman, A. (2008). Modeling Coupled Surface-Subsurface Flow Processes: A Review. *Vadose Zone Journal 7*(2), 741–756.

Gärdenäs, A. I., J. Simunek, N. Jarvis, and M. T. van Genuchten (2006). Two-dimensional modelling of preferential water flow and pesticide transport from a tile-drained field. *Journal of Hydrology 329*(3-4), 647–660.

Germer, S., K. Kaiser, O. Bens, and R. Hüttl (2011). Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region - a Review. *Die Erde 142*(1-2), 65–95.

Howard, K. F., H. S. Maier, and S. L. Mattson (2006). *Ground-surface water interactions and the role of the hyporheic zone*, Volume 70, Chapter 10, pp. 131–143. Springer Netherlands.

IPCC (2007). Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC.

Kandelous, M. M. and J. Simunek (2010). Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agricultural Water Management 97*(7), 1070–1076.

Kinal, J. and G. Stoneman (2012). Disconnection of groundwater from surface water causes a fundamental change in hydrology in a forested catchment in south-western Australia. *Journal of Hydrology 472-473*, 14–24.

LUGV (2000). Flächendeckende Modellierung von Wasserhaushaltsgrößen für das Land Brandenburg, Studien und Tagungsberichte 27 (engl.: water balance modelling across the whole area of the Federal State of Brandenburg). Technical report, State Office for Environment, Health and Consumer Protection of the Federal State of Brandenburg.

Mualem, Y. (1976). New Model for Predicting Hydraulic Conductivity of Unsaturated Porous-Media. *Water resources research 12*(3), 513–522.

MUGV (2013). Ministry of Environment, Health and Consumer Protection of Brandenburg, Geo Informations: http:// www.mugv. brandenburg.de.

Nützmann, G. and S. Mey (2007). Model-based estimation of runoff changes in a small lowland watershed of north-eastern Germany. *Journal of Hydrology 334*(3-4), 467–476.

Pandey, D. N., A. K. Gupta, and D. M. Anderson (2003). Rainwater harvesting as an adaptation to climate change. *Current Science 85*(1), 46–59.

Peters, A. and W. Durner (2006). Improved estimation of soil water retention characteristics from hydrostatic column experiments. *Water Resources Research 42*(11), W11401.

Postel, S. L. (2000). Entering an era of water scarcity: The challenges ahead. *Ecological Applications 10*(4), 941–948.

Querner, E. P. and H. A. J. van Lanen (2001). Impact assessment of drought mitigation measures in two adjacent Dutch basins using simulation modelling. *Journal of Hydrology 252*(1-4), 51–64.

Rassam, D. and A. Werner (2008). Review of groundwater-surfacewater interaction modelling approaches and their suitability for Australian conditions. Technical report, eWater Technical Report.

Richter, D. (1995). *Ergebnisse methodischer Untersuchungen zur Korrektur des systematischen Messfehlers des Hellmann-Niederschlagsmessers.* Deutscher Wetterdienst.

Schindler, U., W. Durner, G. von Unold, and L. Müller (2010). Evaporation Method for Measuring Unsaturated Hydraulic Properties of Soils: Extending the Measurement Range. *Soil Sci. Soc. Am. J. 74*(4), 1071–1083.

Simunek, J., M. van Genuchten, and M. Sejna (2012). HYDRUS: Model use, calibration, and validation. *Trans. ASABE 55*(4), 1263–1276.

Simunek, J., M. T. van Genuchten, and M. Sejna (2008). Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal 7*(2), 587–600.

Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal 10*(1), 52–67.

Sophocleous, M. (2007). The science and practice of environmental flows and the role of hydrogeologists. *Ground Water 45*(4), 393–401.

Stahl, K., H. Hisdal, J. Hannaford, L. M. Tallaksen, H. A. J. van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jodar (2010). Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences 14*(12), 2367–2382.

Stanley, E. H. and J. B. Jones (2000). Surface-subsurface interactions: past, present, and future. In *Streams and Groundwaters*, pp. 405–417. Academic Press, San Diego.

State Office for Mining, Geology and Raw Material of Brandenburg (2012). Hydrogeologic Map of Brandenburg: http://www.geo.brandenburg.de/ hyk50si.

Sutanto, S., J. Wenninger, A. Coenders-Gerrits, and S. Uhlenbrook (2012). Partitioning of evaporation into transpiration, soil evaporation and interception: a comparison between isotope measurements and a HYDRUS-1D model. *Hydrology and Earth System Sciences 16*(8), 2605–2616.

Taylor, R. (2009). Rethinking Water Scarcity: The Role of Storage. *Eos, Transactions, American Geophysical Union 90*(28), 237–248.

Taylor, S. and G. Ashcroft (1972). Physical edaphology. W.H. Freeman, San Francisco.

Thomas, B., J. Steidl, O. Dietrich, and G. Lischeid (2011). Measures to sustain seasonal minimum runoff in small catchments in the mid-latitudes: a review. *Journal of Hydrology 408*(3-4), 296–307.

Twarakavi, N. K. C., J. Simunek, and S. Seo (2008). Evaluating interactions between groundwater and vadose zone using the HYDRUS-based flow package for MODFLOW. *Vadose Zone Journal 7*(2), 757–768.

van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Sci. Soc. Am. J. 44*(5), 892–898.

Vogel, H. and O. Ippisch (2008). Estimation of a critical spatial discretization limit for solving Richards' equation at large scales. *Vadose Zone Journal 7*(1), 112–114.

Wegehenkel, M. and K. C. Kersebaum (2008). A first assessment of the impact of climate change on discharge and groundwater recharge in a catchment in Northeastern Germany. *Journal of Agrometeorology 10*, 274–281.

Wendling, U., H. Schellin, and M. Thomä (1991). Bereitstellung von täglichen Informationen zum Wasserhaushalt des Bodens für die Zwecke der agrarmeteorologischen Beratung. *Zeitschrift für Meteorologie 41*(6), 468–475.

Wesseling, J., J. Elbers, P. Kabat, and B. Van den Broek (1991). SWATRE: instructions for input. *Internal Note, Winand Staring Centre, Wageningen, the Netherlands.*

4 Regional catchment classification with respect to low flow risk in a Pleistocene landscape

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Summary

The classification of small catchments with respect to low flow risk is needed by water and environmental managers to plan adaptation measures for freshwater streams. In this study a new approach is presented to assess the risk of seasonal low flow in the Pleistocene landscape of the Federal State of Brandenburg in Germany. Seasonal low flow and drought in small streams is very common in this region and is predicted to increase due to climate change within the next decades. Data of fifteen years (1991–2006) of daily discharge at 37 small catchments (< 500 km^2) and rainfall data from the same region were used. Principal component analyses were applied to the two data sets separately.

The first five principal components of the discharge data, principal components of a precipitation data set covering the same catchments and catchment characteristics were used to explain the patterns found. The first five discharge components explained 72.9% of the total variance in the data set. The first component reflected the general regional discharge pattern. Component 2 and 3 of the discharge data could be related to spatial patterns of precipitation. Component 4 and 5 of the discharge data reflected geohydrologic processes within the catchments. In order to identify catchments with high risk with respect to low flows, component three and five were important as they both identified catchments with faster decrease of flows during summer. These components were used to estimate low flow risk. Catchments located in the northeast of Brandenburg, especially those in the Barnim highlands north and east of Berlin, were identified to be prone to seasonal low flow. There water management measures to adapt to climate change are needed the most.

Keywords: Catchment Classification; Principal Component Analysis; Catchment Characteristics; Precipitation Pattern; Regional Scale

4.1 Introduction

Our motivation was to assess and classify catchments regarding low flow risk using measured discharge time series and a data driven approach. In particular knowledge about key processes related to low flows of streams can be of use to water and environmental managers to plan the adaptation of water systems and stream habitats to the change in future climate.

Small catchments in Pleistocene regions are highly complex from a hydrologic perspective. Main reasons are (i) uncertainties in groundwater flow paths due to the genesis of the subsurface by glacial deposition, (ii) not always closed water balance at the gauge of catchments if small streams do not totally drain the large, sometimes confined, aquifers, (iii) often no congruency of surface and subsurface catchments and temporal changes of subsurface catchment boundaries. Anthropogenic impacts have to be considered in addition, for most of these catchments (Conradt et al., 2012; Germer et al., 2011; Merz and Pekdeger, 2011). Using assigned surface catchment area and ignoring anthropogenic impacts hinder classification. To date, many management plans are still based on steady flow conditions, as in the implementation of the European Water Framework Directive.

Against this background, the method should describe the differences between discharge time series which were measured at flow gauges of streams in low flow periods. A modeling approach using conceptual models was hindered by difficulties in incorporating anthropogenic influences and missing information on the contributing catchment area and thus high uncertainties in estimates on catchment yield. Approaches using indices calculated from runoff, often in comparison with other catchment properties, require assumptions on the contributing area, too (e.g. Sawicz et al., 2011). Thus, the methodology must be independent from the contributing catchment area.

The focus of this study is on streams of the Federal State of Brandenburg, Germany, which catchment area is less than 500 km^2. This is within the range of meso (regional) scale in catchment hydrology (e.g. Exbrayat et al., 2010; Niehoff et al., 2002). Using the threshold approach (Hisdal et al., 2001) low flow is often defined as a volume deficit or time the threshold is undershot. The threshold can be determined statistically according to the behavior of runoff or by definition, which is especially necessary in catchments with extensive water management (Chapter 2). As a consequence droughts are only one possible phenomenon leading to low flows (Smakhtin, 2001). Catchments differ according to their sensitivity in changing their low flow behavior. As vulnerable regarding low flows we define catchments which show runoff processes favoring pronounced decrease of runoff during the summer season.

Low flows are the consequence of variations in climatic boundary conditions which propagate through the geohydrological system. The input is altered by processes and storage within the catchments. Tongal et al. (2013) calculated a minimum number of 4 variables being necessary to calculate discharge at subcatchments of the Rhine river in Germany using correlation dimension and rescaled range analysis. Climate change is projected to increase temperature and decrease summer precipitation and increase the amplitude of extremes in precipitation. In Europe mid latitude catchments are located within the transition zone of projected decreasing runoff in the Mediterranean region and increasing runoff in the north. The projected change in less summer but more winter precipitation with no significant changes in annual precipitation and possible changes in evapotranspiration will be the main drivers altering low flows in mid latitude catchments on the long term (Cubasch and Kadow, 2011; Menzel and Burger, 2002; Milly et al., 2005; Wegehenkel and Kersebaum, 2009). Additionally, decreasing summer runoff has been detected in measurements all over Europe (Stahl et al., 2010). In Germany, with exception of the Alps and some other lower mountain ranges, discharge is high after the recharge period in late winter and low during late summer when evapotranspiration has been high for a long time. The main period of low flows is within the months August to September (Stahl et al., 2010). However, for rivers in Europe it has to be considered that longer time scales especially regarding precipitation are necessary to understand low flow dynamics (Demirel et al., 2012). The precipitation amounts of the preceding winter half year and to a lower degree of the preceding summer half year can partly explain low flow dynamics (Booij and de Wit, 2010; de Wit et al., 2007). It will be important to understand the underlying delay times and appropriate temporal and spatial scales in order to give more precise predictions about changes in low flows according to climate scenarios.

The reaction of catchments to changing boundary conditions differ even though the change in input is quite similar due to the surface and subsurface hydrological processes and storage. As a consequence knowledge about these processes and storage characteristics is crucial to understand which catchments will be affected first and most severe by the changing climate. In addition to the climatic drivers, anthropogenic impact and catchment properties like hydro geologic conditions, land cover and geomorphology determine catchments' risk towards low flows. The discharge signal thus contains information on processes taking place in the catchment. Demirel et al. (2012) e.g. showed the explanatory power of precipitation, potential evapotranspiration, groundwater storage, snow storage and lake storage regarding low flows in subcatchments of the river Rhine, Germany. They correlated these variables with low flows altering the lag time and temporal resolution. The precipitation input signal is transformed by the action and interaction of hydrological processes within a catchment. As a consequence similarity between catchments concerning low flow risk is determined by spatial differences in meteorological patterns and catchment properties. Nevertheless, it has been argued by other authors that available data on catchment properties are not always valuable in determining catchments' similarity (Masih et al., 2010). Furthermore, Patil and Stieglitz (2011) showed that similarity in discharge dynamics is dependent on flow conditions and is lower during low flows.

We aim at using a dimension reduction approach to extract information about the key runoff generating processes. There are various approaches to explore catchment similarity. Wagener et al. (2007) reviewed and classified approaches within the field of catchment characteristics and hydrologic similarity. Studies on the regional scale are mainly based on models (Deckers et al., 2010; Holsten et al., 2009; Wegehenkel and Kersebaum, 2009) while those on the global or continental scale use different approaches like models (Milly et al., 2005), indices derived from discharge and driving forces, as well as catchment characteristics (Sawicz et al., 2011) and analysis of the discharge time series (Gudmundsson et al., 2011b; Stahl et al., 2010). Furthermore, all of these studies differ according to their scopes (i.a. regionalization, floods, droughts and trend analyses) and time scale (daily time series, monthly means, monthly time series or annual time series). At smaller scales, discharge dynamics are more explained by hydro geologic properties than at the continental scale where patterns related to the driving forces are reported to be the most important ones. Beven (2000) introduced the idea of uniqueness of place. On the other hand, information provided by discharge data should to some degree relate to catchment properties. Thus, at the regional scale methodology has to be able to extract key patterns even though a large amount of the variance is due to highly variable climate drivers and unique processes within the catchments.

Algorithms for dimension reduction have been widely used in environmental studies to display main patterns in large datasets (Bordi et al., 2009; Lischeid, 2009) but also to identify relevant processes (Lischeid et al., 2010; Longuevergne et al., 2007). In hydrology, principal component analysis (PCA) has successfully been applied to discharge (Gudmundsson et al., 2011a; Kumar and Duffy, 2009) and groundwater data (Lewandowski et al., 2009; Lischeid et al., 2010; Longuevergne et al., 2007). The mentioned studies show that PCA is an effective tool to objectively extract components which can be interpreted as independent processes. PCA can also be used in regionalization of streamflow and other hydrological variables (e.g. Kahya et al., 2008; Timilsena and Piechota, 2008). In these studies, rotation of the principal components was often applied because this resulted in stronger correlation of gauges with one specific component. This allowed grouping of gauging stations. It has been demonstrated that PCA is valuable in extracting components which often correlate to processes. With respect to our objectives, purely descriptive methods like trend analyses on streamflow and low flow statistics (e.g. Stahl et al., 2010; Pfister et al., 2006) are not effective in classifying catchments in terms of low flow risk. Trend analyses only describe changes in a variable without considering different processes. Results are sensitive to the time period used (Stahl et al., 2010; Lischeid et al., 2012) and only a linear approximation. According to Kirchner (2006) hydrology has to go beyond "black box" models and find "gray box" models which better capture the character of hydrologic systems. Gudmundsson et al. (2011b) discuss that "[...] spatial patterns in streamflow trends are an element of a more general pattern of interannual streamflow dynamics". In contrast to trend analyses, PCA can help identifying not only the causes but also processes and drivers determining the data structure (Lischeid et al., 2012). In meteorology PCA is a common tool to analyze precipitation and weather patterns (Jaagus, 2009; Shorthouse and Arnell, 1999; Stathis and Myronidis, 2009; Wibig, 1999).

The main objective is to identify key processes determining low flow patterns in a Pleistocene landscape. Further, we determine catchments' risk regarding low flows as the sum of processes favoring pronounced decrease of runoff during the summer season. To a certain degree catchments influenced by water management are included because anthropogenic impacts are common in this cultural landscape. The potential of principal component analyses to separate regional and catchment specific processes on the meso scale is evaluated.

4.2 Material and methods

4.2.1 Study area

The spatial scope is on small catchments within the Federal State of Brandenburg, Germany (including Berlin in its center it has an area of 30,554 km^2). Brandenburg is located within the Northeast German lowlands between the rivers Elbe and Oder draining to the Northern See and Baltic See, respectively (Figure 4.1). The whole region is part of a postglacial landscape which formed since the last Pleistocene glaciations. Low gradients in land surface as well as in surface and subsurface flows, a large number of closed depressions and periglacial channels exposing locally raised relief energy, complex interaction of different aquifers and a rather unstable but ecologically crucial interplay between groundwater and streams are major hydrological characteristics of this landscape. In general, catchment boundaries cannot be delineated based on topography only, and are known not to be constant in time (Holzbecher, 2001). Different are the most southern rivers draining northern parts of the Federal State of Saxony. These rivers have rather shallow soils and sediments above bedrock within their catchment boundaries. Without further inspection, it remains unclear if the whole surface catchment area of small catchments is relevant for fast runoff generation. Smaller rivers also do not always drain the first groundwater complex totally (both temporal and spatial patterns can occur) and the mean groundwater flow direction can be towards the larger glacial valleys. For a more detailed description and overview on hydrological changes within this landscape we refer to Merz and Pekdeger (2011) and Germer et al. (2011).

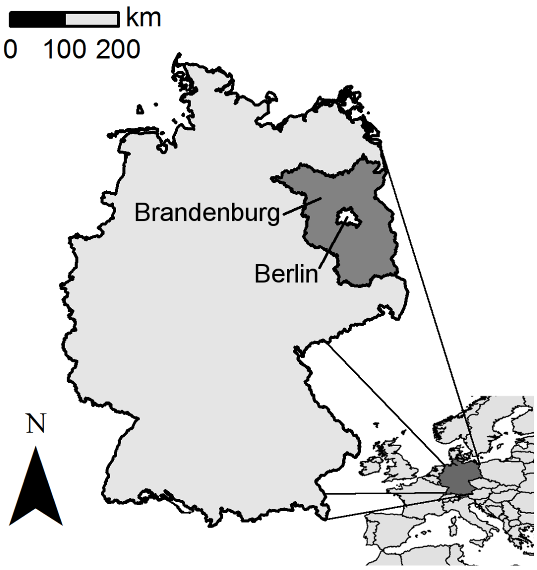

Figure 4.1: Location of the study area (Federal State of Brandenburg, Germany) with the capital Berlin in its center.

4.2.2 Data

Daily discharge data from 130 catchments with less than 500 km^2 area each was provided by the State Office of Environment, Health and Consumer Protection of the Federal State of Brandenburg, Germany. Discharge data were checked with respect to quality, length of record, artifacts and known anthropogenic impacts. Some gauges were excluded because they were visually read and their empirical cumulative distribution functions (ECDF) showed steps due to limited resolution of the gauge scales. We decided to analyze gauges with data between 1st November 1991 and 31st October 2006 only considering that data should be as recent as possible, the time series should be long enough to guarantee statistical saturation and as many gauges as possible should be included in the analysis. In a final step gauges from areas influenced by open pit lignite mining and those strongly influenced by water management were excluded. Applying these constraints 37 gauges were selected for statistical analysis (Figure 4.2). The area of selected catchments (5897 km^2) is 20% of the total area of Brandenburg (29479 km^2, excluding Berlin). The catchments are representative for the whole area except those areas strongly influenced by mining (in the south) and in the lowland areas of the rivers Havel, Spree and Rhin (northwest Brandenburg) located on sanders and in glacial valleys with mainly large catchment areas and strongly regulated rivers. As a consequence the selected catchments are mainly representative for the Pleistocene moraine areas.

REGINE precipitation data from 75 precipitation stations distributed all over Brandenburg from 1961 to 2006 were provided by the German Meteorological Service (DWD, 2012). Correction for wind and evaporation errors had already been performed. Interpolation to the catchment areas was done using Thiessen polygons of the precipitation data and delineated catchment boundaries based on topography. Thiessen polygons have been used in various hydrological studies of the area (e.g. Wechsung et al., 2000). Only the precipitation data of the 37 catchments and for the same period of time (November 1991 to October 2006) were included in order to have the same areal weighting as for the discharge data.

Catchment properties were derived from topographical, geohydrologic, hydrometeorological and land use data sources. Mean catchment values were calculated after intersection of these data with surface catchment boundaries. We used (i) the digitalized contour lines of the groundwater table of the hydrogeological map of Brandenburg, HyKa50, 1:50,000 (State Office for Mining, Geology and Raw Material of Brandenburg, 2012, ;contour lines were calculated considering long-term measurements, reference measurements, waterworks and surface water levels) and the digital elevation model of Germany to calculate mean depth to groundwater, (ii) the Hydrological Atlas of Germany 1961–1991 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2003) to calculate mean potential evapotranspiration, (iii) the map of the mean discharge modeling study (ABIMO) for 1976 to 2005 (MUGV, 2012) for calculating mean actual evapotranspiration, (iv) the CORINE land cover data (Bossard et al., 2000) for calculating percentage coverage of forest and agricultural area and (v) the surface catchment area (MUGV, 2012) to calculate mean surface catchment area. Additionally, the discharge trend calculated as Sen's slope (Sen, 1968) was used as catchment characteristic. Ranges and basic statistics of discharge, precipitation and catchment properties data are given in Table 4.1.

4.2.3 Statistical analyses

Principal component analysis (PCA) is also known as empirical orthogonal function or Karhunen-Loeve transform. PCA is a linear method used to reveal few principal components explaining most of the

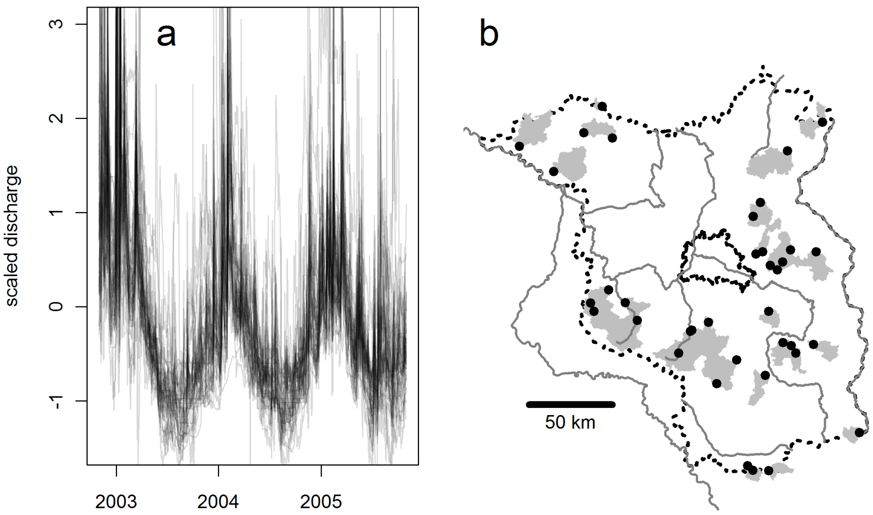

Figure 4.2: (a) All 37 scaled discharge time series (mean = 0 and variance = 1) between November 2003 and October 2005 (b) Location of rivers (grey lines), federal state borders (black dashed lines), gauges (points) and catchment areas (grey polygons).

Table 4.1: Statistics of discharge time series, precipitation time series and catchment properties (min: minimum, max: maximum, st.dev.: standard deviation). Discharge and precipitation statistics are calculated combining all 37 time series (15 years of daily values). Statistics for each catchment property are based on 37 values each.

variable	min	max	median	mean	st.dev.
Discharge (mm)	0.0	10.1	0.21	0.27	0.25
Precipitation (mm)	0	110	0.08	1.70	3.74
Forest cover (%)	2	75	40	40	20
Agricultural land cover (%)	23	97	56	56	20
mean Depth to groundwater table (m)	3.0	30.0	9.1	11.9	7.4
mean Potential evapotranspiration (mm)	573	610	598	597	10
mean Actual evapotranspiration (mm)	428	545	496	497	25
Discharge trend (mm yr^{-1})	$-1.5 \cdot 10^{-2}$	$2.9 \cdot 10^{-3}$	$-4.0 \cdot 10^{-3}$	$-4.2 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$
Surface catchment area (km^2)	21.8	466.8	122.9	159.4	115.5
mean Altitude (m.a.s.l)	39	137	79	82	28

variance in the data set, that is, a low-dimensional representation of the data (Lee and Verleysen, 2007). The resulting components are uncorrelated. Mathematically PCA is based on the single value decomposition of the correlation matrix of z-normalized data (i.e. normalized to zero mean and unit variance). It extracts axes (eigenvectors) within a multidimensional data set which are along the main directions (i.e. explain most of the variance) of the data. If all relationships are linear and the data are metric PCA is the optimal solution (Lee and Verleysen, 2007). The squared eigenvalues divided by the number of variables gives the proportion variance in the high dimensional data space explained by the single principal components. The principal components are sorted according to their total explained variance. The projections of the data on the new axes are called scores. In our case the scores are a time series because input data are time series, too. Correlations of the scores with the measurements yield the loadings of the components. Loadings are a measure describing the positive or negative importance of principal components to explain the input data at a specific site. Thus, the loadings can be used to analyze the spatial pattern of single components. The squared loadings give the amount of explained variance at a gauge according to the principal components. Communalities are the fraction of variance of a discharge time series explained by selected components calculated as the sum of squared loadings. Communalities are used to display to which extent discharge time series can be explained by the components selected.

The advantage of our approach is that no absolute values of discharge are needed. Data is scaled (z-normalization) and thus the dynamics rather than the absolute values are analyzed. PCA enables the comparison of catchments within the geohydrologically complex landscape of the northeast German lowlands. It solves the problem that contributing catchment areas could not be assigned to the catchments and normalization of discharge using surface catchment areas led to incorrect discharge estimates. The use of common indices, as the Q95 (streamflow that is exceeded for 95% of time), Q355 (mean streamflow that is equaled or exceeded during 355 days in a year) and 7Q10 (mean 7-day low flow with 10-year return period), for catchment comparison was not feasible for the same reason.

All gauges were given equal weight because of z-normalization. As a consequence principal components explaining more than a variance of 1 explain more variance than a single variable and can be used to assess general patterns in the data set which is also known as Kaiser criterion (Kaiser, 1960).

Principal component analysis was applied separately to the discharge and precipitation data. A direct comparison of precipitation and discharge data with a combined data set would be misleading because of the different data structure of both types of time series. The separated analysis allowed to extract the main components within each data set and allowed comparison of spatial and temporal patterns. The principal components of precipitation data were used as explanatory variables regarding the spatial patterns of the loadings of the principal components of the discharge data. High correlation of precipitation loadings with discharge loadings should help to identify those discharge components which are due to different precipitation forcing. Additionally, PCA on precipitation data was repeated for the periods of 1961 to 2006 and 1961 to 1991 separately in order to evaluate the consistency of spatio-temporal patterns.

We analyzed the results of the PCA in the time and in the space domain. Temporal analyses were performed using the scores $L_i(t)$. We analyzed the effects of principal components by generating time series $Q^*(t)$ in which the first component explained half of the variance and another component the other half:

$$Q^*(t) = -\sqrt{0.5}L_1(t) \pm \sqrt{0.5}L_i(t) \quad for\ i \leq 2 \tag{4.1}$$

These time series allowed us to investigate how a selected component is changing the main pattern described by the first component. From these time series autocorrelation functions, average seasonal patterns and powerspectra (i.e. the Fourier transform of the autocorrelation function) were calculated and compared. Additionally, yearly sums of scores of discharge and precipitation data were calculated and correlated. Spatial analyses were based on correlations between catchment properties and loadings. Principal components help to understand dynamics in the time series but do not give direct implications on absolute values. Results of the PCA showed that the scores of the 2nd and 3rd components are high for the periods 1995-1997 and 1997-1999, respectively, applying a moving average of 182, 365 and 730 days. Therefore the indices $I_{c,1995\text{-}1997}$ and $I_{c,1997\text{-}1999}$ were introduced to get a rough estimation if the outcome of PCA has some implication on absolute values. They are calculated for every catchment using the corresponding precipitation data and give the percentage of rainfall within two specific years compared to those of the whole time period used in this study:

$$I_{c,1995-1997} = \frac{P_{c,1995-1997}}{P_{c,1991-2006}} \tag{4.2}$$

$$I_{c,1997-1999} = \frac{P_{c,1997-1999}}{P_{c,1991-2006}} \tag{4.3}$$

where $P_{c,1995\text{-}1997}$ is the precipitation sum at catchment c from 1995 to 1997, $P_{c,1997\text{-}1999}$ from 1997 to 1995 and $P_{c,1991\text{-}2006}$ from 1991 to 2006. Mann-Kendall statistics and Sen's slopes of the components were calculated applying prewhitening (Yue et al., 2002) in order to identify the influence of components on trends. All correlation analyses are based on the Pearson correlation coefficient (r) and its square, the coefficient of determination (r^2). Statistical significance was calculated using an F test which tests the hypothesis H_0 that r^2 equals zero.

4.2.4 Estimation of low flow risk

Our estimation of low flow risk is the sum of loadings at every catchment for those principal components related to seasonal low flows. Loadings are multiplied by -1 before summation if loadings pointing on increased low flow risk are negative. The decision if a component is considered to estimate low flow risk is part of the analyses and discussion. The low flow risk LR at every catchment c can be calculated according to:

$$LR_c = \sum_i (s_i W_{i,c}) \tag{4.4}$$

W is the loadings matrix and i is a vector giving the selected components for low flow risk estimation. If positive loadings increase low flow risk the corresponding entry in the vector s is 1 and vice versa. By means of the method loadings are already weighed according to the proportion of explained variance of the corresponding principal component.

4.3 Results

4.3.1 Principal component analysis on discharge data

Only principal components with an eigenvalue greater than 1 were selected for further analyses according to the Kaiser criterion (Kaiser, 1960). The first five discharge components had eigenvalues greater than 1 and thus explained more variance than a single discharge time series (Table 4.2). The first component explained by far the most variance (57.4%). Altogether the first 5 principal components accounted for 72.9% of the total variance. Higher order components explain less and less variance because variance is decreasing monotonously.

The time series of the scores of the first component is similar to a mirrored discharge time series (Figure 4.3). Scores of the second component are rather high around 1995. The scores of the first and fifth component show seasonal patterns. Significant trends ($\alpha = 0.05$) could be detected for the first four scores (Sen slopes: $5.9 \cdot 10^{-4}$, $-2.2 \cdot 10^{-4}$, $-9.4 \cdot 10^{-5}$ and $-1.6 \cdot 10^{-4}$ mm day^{-1}, respectively) The first component explained by far the largest fraction of the variance, that is, the negative of mean behavior at all sites. The mean of all time series is nearly identical with the scores of the first discharge component ($r^2 = 0.98$). Additional components explained subsequently additional fractions of variance, that is, deviation from the mean behavior at single gauges. Thus, the effects of single components were investigated using the time series of the negative scores of the first component and adding or subtracting time series of other components as described in the method section (Figure 4.4). First, the additional components modified the seasonal patterns. Positive loading of the 3rd component leads to lower flows during late summer to fall. Negative loading of the 5th component enhanced the annual cycle. Second, the 3rd and 4th component increased the autocorrelation of the time series. Correspondingly, the power spectra of the 3rd and 4th component are more damped for high frequencies (< 1/30 day^{-1}) and the time series are smoothed.

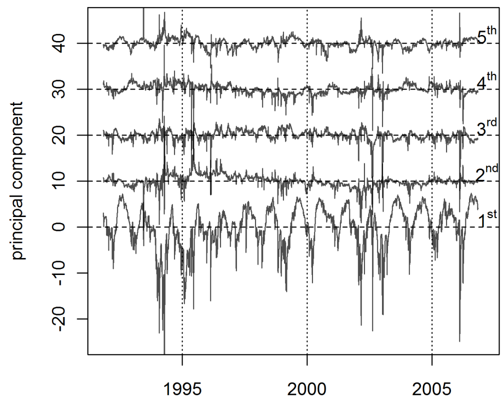

Figure 4.3: Scores of the first five principal components. Every component is shifted by +10 to improve visibility.

Loadings were compared according to the unit circle (Figure 4.5). Especially some catchments clearly loaded negative for the 2nd, 3rd and 5th component compared to the other catchments. All loadings of the first component are negative and range from r = -0.55 to r = -0.87. No clear spatial pattern emerges (Figure

Table 4.2: Explained variance for principal components of the discharge and the precipitation data set exceeding an eigenvalue of 1.

principal	discharge (Q)		precipitation (P)	
component	expl. variance	cumulative	expl. variance	cumulative
1	57.4	57.4	67.4	67.4
2	5.0	62.4	8.8	76.2
3	4.1	66.5	6.4	82.6
4	3.3	69.7	3.7	86.3
5	3.2	72.9	—	—

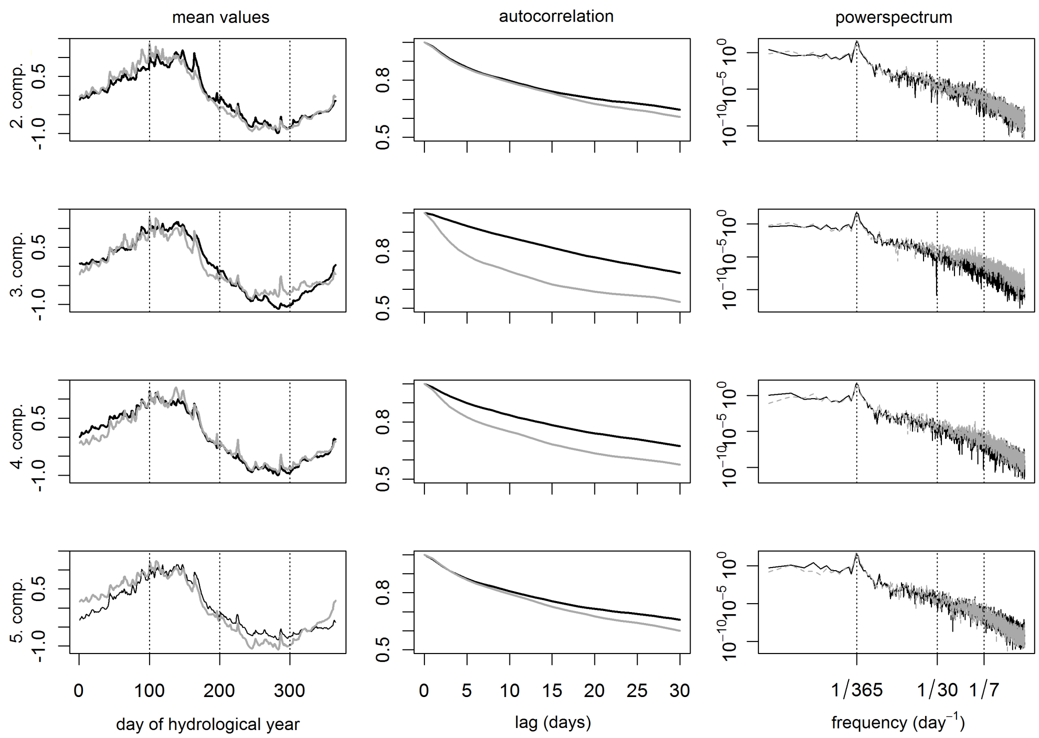

Figure 4.4: Deviation from the mean behavior explained by adding (black) and subtracting (grey) the 2nd to 5th principal component's scores to/from the negative of the first component. Mean of every day of the hydrological year (1st of November to 31st of October), the autocorrelation functions and power spectra are presented.

4.6) which is in contrast to component 2, 3 and 4. For the 2^{nd} component loadings follow a northwest-southeast gradient with lower values in the northeast. For the 3^{rd} component loadings are lower in the southwest and increase towards the northeast. The lowest loadings of component 4 can be found for catchments in the south close to the border of the Federal State of Saxony. The explained variance by the first five components together (communalities) sums up to minimum 49% and maximum 90% depending on the catchment. There is no clear spatial pattern of these communalities. Several components of higher order have high loadings at one catchment only. No spatial patterns were observed for higher order components.

4.3.2 Principal component analysis of precipitation data

The first four precipitation components had eigenvalues greater than 1 (Table 4.2). The first component explained by far the most variance (67.4%). Altogether the first four principal components accounted for 86.3% of the total variance.

Loadings of the precipitation components show clear spatial patterns (Figure 4.7). All loadings of the first component are negative with highest values in the northwest and southeast, and lowest values in the center. Loadings of the 2^{nd} and 3^{rd} component follow a northwest to southeast and a west-southwest to east-northeast gradient with lowest values in the northwest and west-southwest, respectively. Additionally, using precipitation time series from 1961 to 2006 yielded very similar scores and loadings compared to those values obtained from data only considering data between 1991 and 2006.

4.3.3 Correlations between discharge and precipitation variables

Loadings of the 2^{nd} and 3^{rd} discharge component correlate strongly with the 2^{nd} ($r^2 = 0.74$) and 3^{rd} ($r^2 = 0.62$) precipitation component, respectively. All other correlations of loadings are below $r^2 = 0.27$. Yearly sums of scores from the 2^{nd} discharge and precipitation component correlate, too ($r^2 = 0.61$ while all other correlations are below $r^2 = 0.42$). Furthermore, the cumulative scores of the 2^{nd} and 3^{rd} components are correlated ($r^2 = 0.62$ and $r^2 = 0.66$, respectively). The cross correlation functions of the cumulative scores reveal that the discharge signal is delayed in comparison with the precipitation signal. Additionally, we calculated the two indices $I_{1995\text{-}1997}$ and $I_{1997\text{-}1999}$. $I_{1995\text{-}1997}$ correlated with loadings of the 2^{nd} discharge component ($r^2 = 0.71$) while $I_{1997\text{-}1999}$ correlated with loadings of the 3^{rd} component ($r^2 = 0.52$).

4.3.4 Correlations between discharge components and catchment properties

Loadings of the first five components were correlated with catchment properties. Only correlations which were significant according to an F test ($\alpha = 0.05$) are presented. For the first component hardly any significant correlation was found. In contrast, component 2 exhibited numerous significant correlations (Table 4.3): positive correlation with forest cover and potential evapotranspiration, and negative correlations with cover of agricultural land, discharge trend (Sen's slopes of the discharge data) and surface catchment area. Additional significant correlations were found between the 3^{rd} component's loadings and mean altitude (negative), the 4^{th} compo-

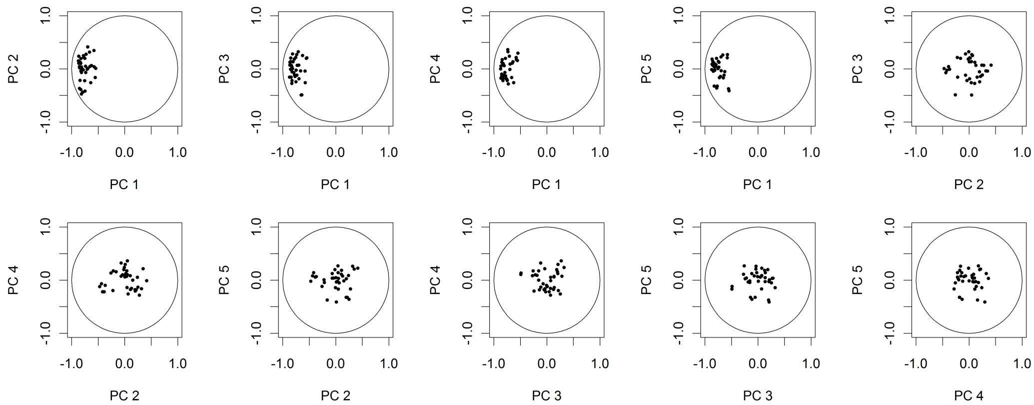

Figure 4.5: Biplots of loadings of the first five components compared to the unit circle.

nent's loadings and forest cover (positive), the 4th component's loadings and depth to groundwater table (negative) and the 5th component's loadings and depth to groundwater table (negative). No significant correlations were found for the 6th to 10th component.

4.4 Discussion

Five components associated to regional discharge patterns could be extracted from a dataset of 37 discharge time series of small catchments of Brandenburg, Germany. These components explained more than 50% of the variance in most of the discharge time series and more than 72% of the variance in the whole data set. Further components could not be associated to regional patterns with the methodology used or strongly represented the uniqueness of single catchments. These components were of minor value for this regional study. The first five discharge components contain information on possible meteorological and geohydrological processes generating runoff at the regional scale. Especially the 3rd and 5th component can be used to evaluate low flow risk of these small catchments. The methodology succeeded despite the length of record, data quality used and the fact that some catchments are managed in an unknown way.

The first discharge component reflects the general regional climate pattern. Differences in the annual cycle at different stations resulted in respective components at studies on larger scales (Kumar and Duffy, 2009). At the regional extent of our study the major variance of all time series is due to the annual cycle with higher discharge during late winter and spring. All of the time series show this behavior to some extent, because all loadings are lower than -0.55 and the first component is very closely related to the inverse of the mean time series of all input data. As a consequence, the first component is not relevant to analyze low flow risk. Local deviations from this mean behavior are described by the other components.

Component 2 and 3 of the discharge data could be related to spatial patterns of precipitation. They both correlate with loadings of the 2nd and 3rd precipitation component, and the indices $I_{1995\text{-}1997}$ and $I_{1997\text{-}1999}$, respectively. In addition, yearly

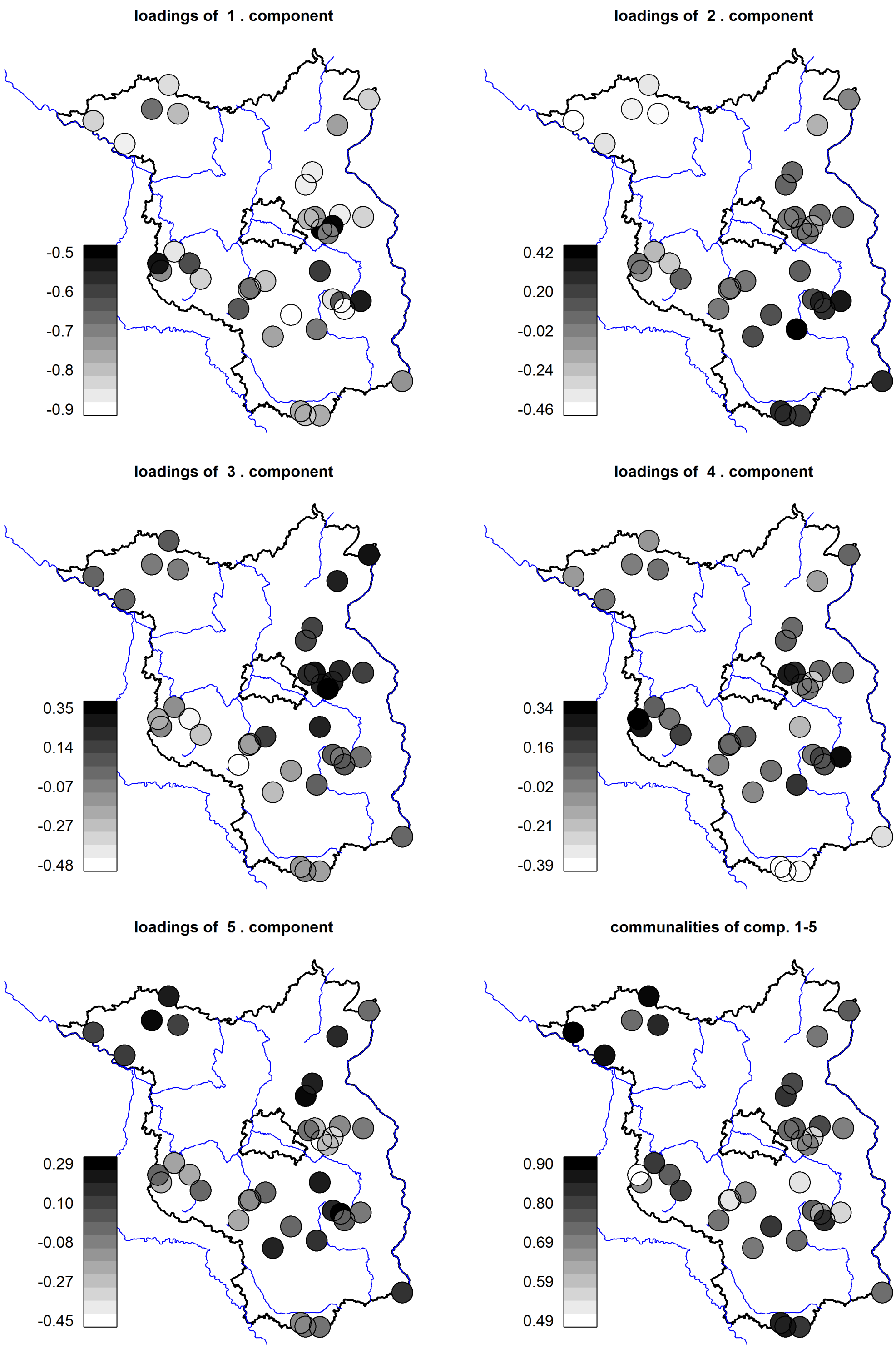

Figure 4.6: Loadings and communalities of the first five principal components of discharge data.

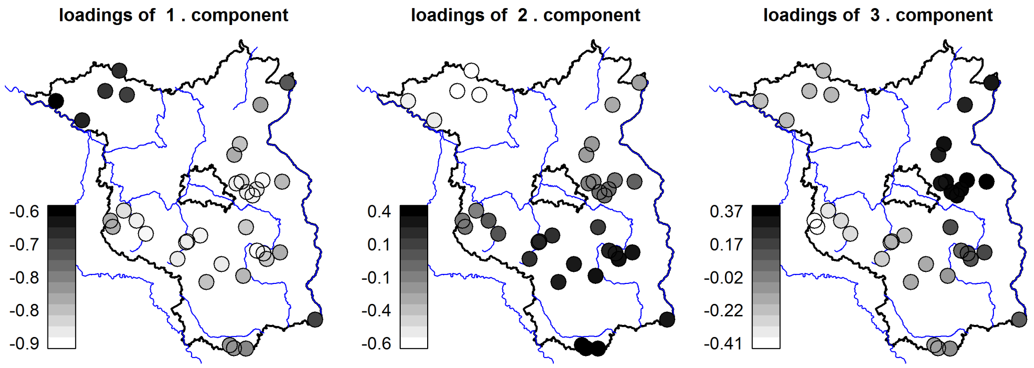

Figure 4.7: Loadings of the first three principal components of precipitation data (1991 to 2006).

Table 4.3: Correlation coefficients (r) between discharge components and catchment properties. Only those correlations being significant according to F statistics ($\alpha = 0.05$) are shown.

catchment property	2nd comp.	3rd comp.	4th comp.	5th comp.
Forest cover	0.50	—	0.46	—
Agricultural land cover	-0.52	—	—	—
Depth to groundwater table	—	—	0.51	-0.44
Potential evapotranspiration	0.87	—	—	—
Actual evapotranspiration	—	—	—	—
Discharge trend (Sen's slope)	-0.44	—	—	—
Surface catchment area	-0.45	—	—	—
Altitude	—	-0.51	—	—

sums of the 2nd discharge and the 2nd precipitation component are correlated. Visual comparison of the 2nd and 3rd component of Figure 4.6 and 7 indicates, that the signal in the discharge data is more noisy compared to the precipitation data. We propose that this is due to different transformation of precipitation to discharge and anthropogenic impacts at the catchments. Despite these constraints, high correlation between discharge and precipitation components highlight the explanatory power of precipitation dynamics for discharge patterns. Applying principal component analysis on precipitation data at the same stations but between 1961 and 2006 resulted in nearly identical scores and loadings for both components. Obviously the spatial patterns of precipitation are fairly persistent over longer time periods. Regarding low flow the 3rd component seems to be more important than the 2nd. At gauges with positive loadings of the 3rd component runoff dynamics tend to show stronger declines during summer towards lower scaled discharges until fall (Figure 4.4). Higher autocorrelation and damping of higher frequencies indicate higher proportion of base flow. Correlations with precipitation patterns are much higher than those with catchment properties. Loadings of component 2 correlate strongly with long term means of potential but not with long term means of actual evapotranspiration. It remains questionable if there is a correlation between the 2nd component and evapotranspiration because the calculation of actual evapotranspiration is still quite uncertain and could explain missing correlation. It cannot be concluded here if differences in altitude are to some extent responsible for the precipitation pattern correlating with the 3rd component.

Bordi et al. (2009) analyzed the Standardized Precipitation Index on a time scale of 24 months (SPI-24) for gridded precipitation data of Europe. Their main pattern is similar to the loadings of the 2nd component indicating stronger precipitation deficits in the southeast. Gudmundsson et al. (2011b) applied the ISOMAP algorithm on low frequency time series all over Europe derived by the SLT algorithm. Spatial gradients of precipitation and discharge ISOMAP components were similar to gradients of the loadings of our 2nd and 3rd component. They relate these patterns to the zonal structure of atmospheric circulation and the shift between Atlantic and continental weather systems. Regarding stream flow trends, the scope of our regional study was too small to see similarities with the results from a pan European study (Stahl et al., 2010). Correlations between European weather systems and precipitation (Bouwer et al., 2008; Wibig, 1999) and discharge (Shorthouse and Arnell, 1999) do not explain the patterns found in Brandenburg. The spatial gradients in those studies suggest that our research area is located in the transition zone of decreasing influence of weather systems described by the North Atlantic Oscillation Index (NAOI) but their spatial resolution is too low to check this hypothesis.

Loadings and yearly scores of component 4 and 5 of discharge data do not show any correlation with loadings and yearly scores of precipitation data components, respectively. Their loadings do not have a clear spatial gradient or pattern. Both components' loadings correlate with mean depth to groundwater table, the 4th positively and the 5th negatively. Lischeid et al. (2010) showed that the depth to groundwater table is related to a damping coefficient calculated from the first two principal components of groundwater head time series. Catchments with positive loadings on the 4th component have higher autocorrelation and somewhat damping of high frequencies but no clear differences in the annual dynamics were observed. The annual dynamics is more pronounced at catchments with negative loadings of the 5th component. Recession during late summer und rewetting in winter is much faster in these catchments.

We hypothesize that the 4th and 5th components reflect catchment properties even though only correlations to depth to groundwater table were found. Catchments with strong negative loadings on the 4th component are located in the very south of Brandenburg with rather shallow soils and sediments above bedrock. This is reasonable as damping of the rainfall is less for these catchments as described before. Catchments with strong negative loadings on the 5th component are located at the Barnim highlands. These catchments also do not show pronounced flood events in terms of absolute values (no event is exceeding 1mm of peak discharge). Available data on catchment properties have been shown to be not always helpful to explain catchment similarity (Ley et al., 2011; Sivapalan et al., 2011). Studies on regionalization show that catchment properties can only describe runoff behavior to a very limited extent (e.g. Deckers et al., 2010; Laaha and Blöschl, 2005). For example, hydrogeological maps are generated using information from single bore holes and areal information usually is very uncertain. This information does not seem to be sufficient to explain processes on the scale of small catchments. Methods are needed which can reliably estimate the mean groundwater table of catchments from point data because this is beyond the scope of this study. We postulate this could improve the interpretability of our results.

About 72% of the variance in the discharge data is explained by the first five components. Besides the first component, reflecting the mean annual pattern, climate driven patterns (9.1%) explain somewhat more variance than the patterns associated with catchment properties (6.5%). No other components could be related to climate patterns or catchment properties. If further components related to regional patterns exist they are of minor importance due to their low proportion of explained variance .Thus, the variance explained by the remaining components is mainly related to catchment uniqueness (Beven, 2000), water management activities and measurement errors. Hypothesizing that measurement errors can be neglected, low communalities on the first five components indicate catchments with a more unique behavior due to regional hydrological processes and water management (Figure 4.6). In addition, catchments with low communalities on the first five components have higher loadings on some of the other components. If these components are related to low flow processes, maybe a unique phenomenon at one catchment, this information would be missing in our low flow risk estimate.

According to the interpretations of the principal components and their characteristics mainly component 3 and 5 determine low flow behavior in the catchments. Both components indicate faster decrease of flows during summer and lower flows during late summer and fall for catchments with positive loadings on the 3rd and negative loadings on the 5th component, respectively, even though they could be related to different processes (precipitation pattern and catchment characteristics). Precipitation deficits are one major reason for low flows and the propagation of droughts through the precipitation, the soil moisture and the stream flow has been investigated elsewhere (e.g. Vidal et al., 2010). We estimated low flow risk according to equation 4 (subtracting the loadings of the 5th from those of the 3rd component). The spatial pattern of catchments' low flow risk shows that catchments in the northeast and especially those located in the Barnim highlands north and east of Berlin are prone to seasonal low flows (Figure 4.8).

Drought vulnerability studies in Brandenburg mainly focus on the spatial distribution of soil water contents and their change during future climate change (Holsten et al., 2009; Schindler et al., 2007). Conradt et al. (2012) evaluated discharge scenarios within the Elbe catchment. They projected average discharge to decrease from 171 to 91-110 mm yr^{-1} until 2053 but spatial patterns of runoff contribution

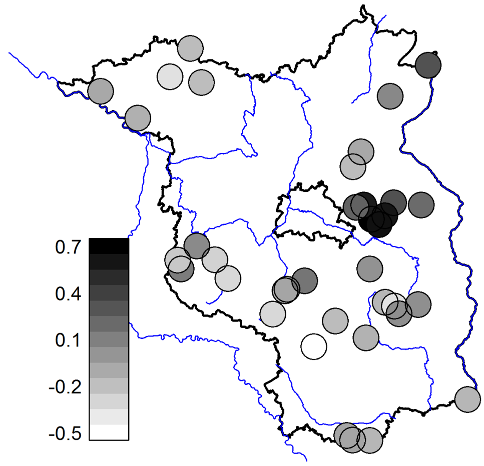

Figure 4.8: Estimation of low flow risk according to the loadings of the 3rd minus the 5th discharge component.

did not correspond to the spatial patterns found in this study. To the knowledge of the authors no other corresponding studies covering Brandenburg at the same scale have been published. The advantage of our method compared to modeling studies is that no parameter estimates are necessary because our components are extracted from time series of discharge only. In addition, no assumptions on the contributing catchment areas had to be made. In contrast to simple hydrological models catchments with anthropogenic impacts can be considered. However, results are limited to the observed behavior so far and no projections on future changes can be drawn directly.

To understand the alteration during climate change it is necessary to analyze precipitation projections regarding the pattern described by component 3 under climate change. Nevertheless, consistency of precipitation components on different time scales (1991–2006, 1961–1990 and 1961–2006) suggest that climate patterns will be persistent in near future. To understand the behavior of the catchments in the Barnim highlands investigations on the geohydrologic patterns leading to the runoff dynamics described by component 5 have to be undertaken. It will be important to know whether development in climate variables will favor this runoff dynamics in the future but this will be the task of climate modeling. Nevertheless, our findings are valuable for water managers to decide which catchments have a high priority regarding low flow adaptation measures. Those catchments with low communalities on the first 5 components need to be evaluated by the corresponding water managers. From a water management perspective it would be of importance to intersect our findings with present and future water demands to incorporate management issues. Analyses on weather patterns would be favorable to better understand the climatic impact on low flows in this region. Furthermore, analyses on related weather situations should be put forward as done for other regions in Germany (Stahl and Demuth, 1999).

Our findings suggest that regionalization of our results based on relationships with catchment properties would only be valid for the meteorological components. Correlations between the 2nd ($r^2 = 0.74$) and 3rd ($r^2 = 0.62$) components are within a range where it would be inevitable to quantify uncertainties associated with this kind of regionalization. Correlations with catchment properties were too low for the 4th and 5th component. Additionally, it has to be kept in mind that at the regional scale less similarity of catchments was observed during periods of low flows (Gudmundsson et al., 2011a; Patil and Stieglitz,

2011) or at least different catchment properties would be important. Our results suggest that the pattern of river discharge is mainly described by the mean annual cycle and the understanding of subsequent components is more difficult. The spatial scale of the study determines if geological or meteorological components become more important to understand the general patterns. This can be illustrated comparing our regional study with similar studies on the continental (Gudmundsson et al., 2011b) and local scale (Lewandowski et al., 2009).

4.5 Conclusion

Five components explaining 72% of the total variance and with regional significance could be extracted from a data set of 37 discharge time series located all over Brandenburg. A principal component analysis has been successfully used to extract the structures explaining most of the variance in a linear way. All additional data was used to test hypotheses of the processes which can be related to the principal components found in the discharge data.

Modeling studies (Conradt et al., 2012) and trend analyses (Stahl et al., 2010) showed decreasing flows in the northeast of Germany during summer months for the past as well as future projections. Generally the intensity of low flows is expected to increase because late summer is the main period of seasonal low flow. In this study we investigated the difference in runoff dynamics in order to identify catchments with discharge patterns favoring low flows during late summer months. Temporal consistency in precipitation components over the past 45 years indicates stability of these components in the medium-run. Components related to geohydrologic properties can be considered stable on this time scale. As a consequence, our estimates on low flow risk are applicable for the observed period and the next decades.

Analyses of the components themselves and correlations of their loadings with catchment characteristics and precipitation patterns allowed the formulation of hypotheses on processes explaining the discharge components found. The first component is due to the relatively homogeneous regional driving forces and explains the mean behavior of all time series. The subsequent components two and three are correlated to spatial precipitation patterns. Component four and five point to differences in catchment characteristics such as flow paths and storage capability leading to damping of the precipitation input on different time scales (high frequencies and annual cycle, respectively). In order to identify catchments with high risk towards low flows, component three and five were important as they both identify catchments with faster decrease of flows during summer. Consequently, risk assessment of catchments of Brandenburg has to consider regional precipitation patterns as well as catchment characteristics. Better understanding of these relationships should be a key task to future research in this field. Furthermore, the Barnim highlands should be investigated in more detail to understand the hydrologic processes leading to the highest low flow risk, especially the effects indicated by the 5^{th} component.

We demonstrated the strength of data driven analyses to extract the prevailing patterns in data sets of discharge time series. Results were valuable to map and understand the most important processes and relate them to climatic and catchment properties. Furthermore these results deepened understanding in differences in risk towards low flows. The application of the methodology requires long term measurements, therefore stressing the need for continuous long term monitoring.

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References

Beven, K. J. (2000). Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth System Sciences 4*(2), 203–213.

Booij, M. J. and M. J. M. de Wit (2010). Extreme value statistics for annual minimum and trough-under-threshold precipitation at different spatio-temporal scales. *Hydrological Sciences Journal 55*(8), 1289–1301.

Bordi, I., K. Fraedrich, and A. Sutera (2009). Observed drought and wetness trends in Europe: an update. *Hydrology and Earth System Sciences 13*(8), 1519–1530.

Bossard, M., J. Feranec, and J. Otahel (2000). CORINE land cover technical guide - Addendum 2000. Technical report, European Environment Agency.

Bouwer, L. M., J. E. Vermaat, and J. C. J. H. Aerts (2008). Regional sensitivities of mean and peak river discharge to climate variability in Europe. *Journal of Geophysical Research 113*, D19103.

Conradt, T., H. Koch, F. Hattermann, and F. Wechsung (2012). Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change 12*(3), 633–648.

Cubasch, U. and C. Kadow (2011). Global Climate Change and Aspects of Regional Climate Change in the Berlin-Brandenburg Region. *Die Erde 142*(1-2), 21–39.

de Wit, M. J. M., B. van den Hurk, P. M. M. Warmerdam, P. J. J. F. Torfs, E. Roulin, and W. P. A. van Deursen (2007). Impact of climate change on low-flows in the river Meuse. *Climatic Change 82*(3-4), 351–372.

Deckers, D. L. E. H., M. J. Booij, T. M. Rientjes, and M. S. Krol (2010). Catchment Variability and Parameter Estimation in Multi-Objective Regionalisation of a Rainfall-Runoff Model. *Water Resources Management 24*(14), 3961–3985.

Demirel, M., M. J. Booij, and A. Hoekstra (2012). Identification of appropriate lags and temporal resolutions for low flow indicators in the River Rhine to forecast low flows with different lead times. *Hydrological Processes published online*, DOI: 10.1002/hyp.9402.

DWD (2012). German Meteorological Service. http:// www.dwd.de.

Exbrayat, J. F., N. R. Viney, J. Seibert, S. Wrede, H. G. Frede, and L. Breuer (2010). Ensemble modelling of nitrogen fluxes: data fusion for a Swedish meso-scale catchment. *Hydrology and Earth System Sciences 14*(12), 2383–2397.

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2003). *Hydrological Atlas of Germany 1961-1991 (Hydrologischer Atlas von Deutschland).* http:// www.bmu.de.

Germer, S., K. Kaiser, O. Bens, and R. Hüttl (2011). Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region - a Review. *Die Erde 142*(1-2), 65–95.

Gudmundsson, L., L. M. Tallaksen, and K. Stahl (2011a). Spatial cross-correlation patterns of European low, mean and high flows. *Hydrological Processes 25*(7), 1034–1045.

Gudmundsson, L., L. M. Tallaksen, K. Stahl, and A. K. Fleig (2011b). Low-frequency variability of European runoff. *Hydrology and Earth System Sciences 15*(9), 2853–2869.

Hisdal, H., K. Stahl, L. M. Tallaksen, and S. Demuth (2001). Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology 21*(3), 317–333.

Holsten, A., T. Vetter, K. Vohland, and V. Krysanova (2009). Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas. *Ecological Modelling 220*(17), 2076–2087.

Holzbecher, E. (2001). The dynamics of subsurface water divides - watersheds of Lake Stechlin and neighbouring lakes. *Hydrological Processes 15*(12), 2297–2304.

INKA BB (2012). Innovationsnetzwerk Klimaanpassung Berlin Brandenburg. http://www.inka-bb.de/.

Jaagus, J. (2009). Regionalisation of the precipitation pattern in the Baltic Sea drainage basin and its dependence on large-scale atmospheric circulation. *Boreal Environment Research 14*(1), 31–44.

Kahya, E., S. Kalayci, and T. C. Piechota (2008). Streamflow regionalization: Case study of Turkey. *Journal of Hydrologic Engineering 13*(4), 205–214.

Kaiser, H. (1960). The application of electronic computers to factor analysis. *Educational and Psychological Measurement 20*, 141–151.

Kirchner, J. W. (2006). Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research 42*, W03S04.

Kumar, M. and C. J. Duffy (2009). Detecting hydroclimatic change using spatio-temporal analysis of time series in Colorado River Basin. *Journal of Hydrology 374*(1-2), 1–15.

Laaha, G. and G. Blöschl (2005). Low flow estimates from short stream flow records - a comparison of methods. *Journal of Hydrology 306*(1-4), 264–286.

Lee, J. and M. Verleysen (2007). *Nonlinear dimensionality reduction* (18 ed.). Information Science and Statistics. Springer, New York.

Lewandowski, J., G. Lischeid, and G. Nutzmann (2009). Drivers of water level fluctuations and hydrological exchange between groundwater and surface water at the lowland River Spree (Germany): field study and statistical analyses. *Hydrological Processes 23*(15), 2117–2128.

Ley, R., M. C. Casper, H. Hellebrand, and R. Merz (2011). Catchment classification by runoff behaviour with self-organizing maps (SOM). *Hydrology and Earth System Sciences 15*(9), 2947–2962.

Lischeid, G. (2009). Non-linear visualization and analysis of large water quality data sets: a model-free basis for efficient monitoring and risk assessment. *Stochastic Environmental Research and Risk Assessment 23*(7), 977–990.

Lischeid, G., M. Natkhin, J. Steidl, O. Dietrich, R. Dannowski, and C. Merz (2010). Assessing coupling between lakes and layered aquifers in a complex Pleistocene landscape based on water level dynamics. *Advances in Water Resources 33*(11), 1331–1339.

Lischeid, G., J. Steidl, and C. Merz (2012). Functional versus trend analysis to assess anthropogenic impacts on groundwater heads. *Grundwasser 17*(2), 79–89.

Longuevergne, L., N. Florsch, and P. Elsass (2007). Extracting coherent regional information from local measurements with Karhunen-Loeve transform: Case study of an alluvial aquifer (Rhine valley, France and Germany). *Water Resources Research 43*, W04430.

Masih, I., S. Uhlenbrook, S. Maskey, and M. D. Ahmad (2010). Regionalization of a conceptual rainfall-runoff model based on similarity of the flow duration curve: A case study from the semi-arid Karkheh basin, Iran. *Journal of Hydrology 391*(1-2), 190–203.

Menzel, L. and G. Burger (2002). Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *Journal of Hydrology 267*(1-2), 53–64.

Merz, C. and A. Pekdeger (2011). Anthropogenic Changes in the Landscape Hydrology of the Berlin-Brandenburg Region. *Die Erde 142*(1-2), 21–39.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature 438*(7066), 347–350.

MUGV (2012). Ministry of Environment, Health and Consumer Protection of Brandenburg, Geo Informations:http:// www.mugv. brandenburg.de.

Niehoff, D., U. Fritsch, and A. Bronstert (2002). Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology 267*(1-2), 80–93.

Patil, S. and M. Stieglitz (2011). Hydrologic similarity among catchments under variable flow conditions. *Hydrology and Earth System Sciences 15*(3), 989–997.

Pfister, C., R. Weingartner, and J. Luterbacher (2006). Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach. *Hydrological Sciences Journal 51*(5), 966–985.

Sawicz, K., T. Wagener, M. Sivapalan, P. A. Troch, and G. Carrillo (2011). Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences 15*(9), 2895–2911.

Schindler, U., J. Steidl, L. Muller, F. Eulenstein, and J. Thiere (2007). Drought risk to agricultural land in Northeast and Central Germany. *Journal of Plant Nutrition and Soil Science 170*(3), 357–362.

Sen, P. K. (1968). Estimates of Regression Coefficient Based on Kendalls Tau. *Journal of the American Statistical Association 63*(324), 1379–1389.

Shorthouse, C. and N. Arnell (1999). The effects of climatic variability on spatial characteristics of European river flows. *Physics and Chemistry of the Earth Part B - Hydrology Oceans and Atmosphere 24*(1-2), 7–13.

Sivapalan, M., M. A. Yaeger, C. J. Harman, X. Y. Xu, and P. A. Troch (2011). Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. *Water Resources Research 47*, W02522.

Smakhtin, V. U. (2001). Low flow hydrology: a review. *Journal of Hydrology 240*(3-4), 147–186.

Stahl, K. and S. Demuth (1999). Linking streamflow drought to the occurrence of atmospheric circulation patterns. *Hydrological Sciences Journal 44*(3), 467–482.

Stahl, K., H. Hisdal, J. Hannaford, L. M. Tallaksen, H. A. J. van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jodar (2010). Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences 14*(12), 2367–2382.

State Office for Mining, Geology and Raw Material of Brandenburg (2012). Hydrogeologic Map of Brandenburg: http://www.geo.brandenburg.de/ hyk50si.

Stathis, D. and D. Myronidis (2009). Principal Component Analysis of Precipitation in Thessaly Region (Central Greece). *Global Nest Journal 11*(4), 467–476.

Timilsena, J. and T. Piechota (2008). Regionalization and reconstruction of snow water equivalent in the upper Colorado River basin. *Journal of Hydrology 352*(1-2), 94–106.

Tongal, H., M. Demirel, and M. J. Booij (2013). Seasonality of low flows and dominant processes in the Rhine River. *Stochastic Environmental Research and Risk Assessment 27*(2), 489–503.

Vidal, J. P., E. Martin, L. Franchisteguy, F. Habets, J. M. Soubeyroux, M. Blanchard, and M. Baillon (2010). Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite. *Hydrology and Earth System Sciences 14*(3), 459–478.

Wagener, T., M. Sivapalan, P. Troch, and R. Woods (2007). Catchment Classification and Hydrologic Similarity. *Geography Compass 1*(4), 901–931.

Wechsung, F., V. Krysanova, M. Flechsig, and S. Schaphoff (2000). May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? *Landscape and Urban Planning 51*(2-4), 177–189.

Wegehenkel, M. and K. C. Kersebaum (2009). An assessment of the impact of climate change on evapotranspiration, groundwater recharge, and low-flow conditions in a mesoscale catchment in Northeast Germany. *Journal of Plant Nutrition and Soil Science 172*(6), 737–744.

Wibig, J. (1999). Precipitation in Europe in relation to circulation patterns at the 500 hPa level. *International Journal of Climatology 19*(3), 253–269.

Yue, S., P. Pilon, B. Phinney, and G. Cavadias (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes 16*(9), 1807–1829.

5 Long term shift of first-order controls on low flows in small lowland catchments of Northeast Germany

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Summary

Runoff, especially during summer months, and low flows have decreased in Central and Eastern Europe during the last decades. A detailed knowledge on processes and flow paths during low flows and reliable long-lead forecasts are necessary to optimize regional adaption strategies to sustain minimum runoff. The objective of this study is to identify first-order controls on low flow risk for 16 small catchments in Northeast Germany and their long-term shifts between 1965 and 2006. Non-linear regression models (support vector machine regression) were calibrated to iteratively select the most powerful low flow predictors regarding annual 30-day minimum flow (AM_{30}). The data set consists of standardized precipitation (SPI) and potential evapotranspiration (SpETI) indices on different time scales and lag times. The potential evapotranspiration of the previous 48 and 3 months, as well as the precipitation of the previous 3 months and last year were the most relevant predictors for AM_{30}. r^2 of the final model is 0.49 and if annual means of all catchments are taken r^2 increases to 0.80 because extremes are smoothing out. Evapotranspiration was the first-order control on low flow risk for the study period. However, distinct long-term shifts in the predictive power of variables became apparent. The potential evapotranspiration of the previous 48 months explained most of the variance, but its relevance decreased during the last decades. The importance of precipitation variables increased with time. Model performance was higher at catchments with a more damped discharge behavior. The results indicate changes in the relevant processes or flow paths generating low flows. The identified first-order controls, temporal patterns and patterns between catchments will support the development of low flow monitoring systems and determine those catchments where adaption measures should aim more at increasing groundwater recharge.

Keywords: Low flow indicator, Post-glacial landscape, Catchment classification, Support vector machine regression, Annual 30-day minimum flow, Standardized precipitation index, Standardized potential evapotranspiration index

5.1 Introduction

Extreme low flows are becoming an important issue in hydrological research in several regions of the mid-latitudes. The identification of widely applicable low flow predictors and the understanding of processes and flow paths is one major task in this context. Global hydrological projections show decreasing runoff in Central and Eastern Europe and Central North America until the middle of the 21st century (IPCC, 2007). Regional climate projections coupled with hydrological models show that decreasing groundwater recharge is leading to decreased runoff during summer months in Northeast Germany (Conradt et al., 2012; Wegehenkel and Kersebaum, 2008, 2009). In measured data, runoff widely decreased in Northeast Germany, especially during summer months (Stahl et al., 2010). Also the 7-day minimum flow decreased in most of the catchments in this region (Hisdal et al., 2001; Stahl et al., 2010). Bordi et al. (2009) showed that the northeastern regions of Germany are located in a transition zone between an increasing trend in the standardized precipitation index (SPI, 24 months) in the northwest of Europe and a decreasing trend in the southeast. A similar gradient has been identified in studies on streamflow on the European (Gudmundsson et al., 2011b) and northeast German scale (Thomas et al., 2012). These results are a hint that low flows in catchments within this transition zone will react differently to a changing climate depending on geohydrological properties despite close proximity.

In this paper hydrological drought as one of the four main drought categories, meteorological, hydrological, agricultural and socio-economic drought (Mishra and Singh, 2010), is investigated. Mishra and Singh (2010) stress the importance of groundwater droughts within the category of hydrological droughts. Precipitation and evapotranspiration are the meteorological variables influencing groundwater recharge and subsequently base flow being the main source of streamflow during periods of low flow. Van Loon and Van Lanen (2012) distinguished between different hydrological droughts. While rainfall deficit droughts are prevailing, cold and warm snow season droughts, rain to snow season droughts and composite droughts can occur and tend to be the most severe ones in the mid-latitudes.

Lowland catchments in Northeast Germany are characterized by a complex geohydrology and different kinds of anthropogenic impacts (Hannappel and Voigt, 1997). The upper aquifer complex can be more than 100m deep and consists of Pleistocene deposits. Locally, shallow low permeable layers and preferential flow paths can lead to smaller local aquifers and interflow. For small catchments the surface area and the area of the subsurface catchments do not have to be identically.

We assume that several reasons are responsible for changes in low flows of small catchments: (i) Small catchments are mainly situated at higher elevated ground water recharge areas with higher depth to the groundwater table and less groundwater storage compared to larger catchments. These areas have shown decreasing groundwater heads for the last decades (Germer et al., 2011). Storage of water as ground water can decrease further and even result in decoupling of groundwater from streams (see e.g. Kinal and Stoneman, 2012). Additionally, the importance of local effects decreases with catchment size (Blöschl et al., 2007). (ii) In contrast to large catchments small catchments provide less damping of climatic inputs because of a more homogeneous input signal. It is more likely that the whole catchment is affected by drought. (iii) Additionally, anthropogenic impacts superimpose the natural processes in most of the catchments (Merz and Pekdeger, 2011). Melioration, artificial ditch systems, lake management, drinking water abstraction and regulation by weirs change low flows of such catchments.

The need for adaptation to changes in stream flow and droughts has already been recognized and the scientific background has to be set during the next decade. A review of potential measures is available (Chapter 2) but experiences with implementations mainly exist in arid and semiarid areas. Efficiency and management of measures have to be adapted to midlatitude conditions. The most important processes, variables and time scales responsible for low flows in such Pleistocene catchments are necessary to optimize adaption. Increased knowledge about the relevant processes and relevant variables will help to find low flow predictors. Required measurements should be widely available and need to be measured for longer time in order to enable calibration to past streamflow data.

In many studies catchments are compared regarding specific variables (e.g. low flow index) and on a defined spatial scale (see e.g. Sawicz et al., 2011, Chapter 4). Comparison of catchments is mainly done by using parameters of hydrologic models (Sivapalan et al., 2011), streamflow indices (Sawicz et al., 2011) or properties derived by statistical analysis of streamflow data (Gudmundsson et al., 2011a,b, Chapter 4). A review on catchment similarity is given by Wagener et al. (2007). In our case the method has to be able to meet the hydrologic characteristics of the postglacial landscape. Thomas et al. (2012, Chapter 4) give an example how to efficiently compare catchments of such landscapes using statistical methods. They identified most susceptible catchments having annual dynamics favoring low flows. They do not focus on low flow events and the relation to meteorological variables.

On the regional to continental scale climate gradients seem to be important to understand differences between catchment discharge (Gudmundsson et al., 2011b; Sawicz et al., 2011, Chapter 4). Nevertheless it is recognized that catchment similarity is lower during low flows (Gudmundsson et al., 2011a; Patil and Stieglitz, 2011) and that dry catchments are more sensitive to climate change (Singh et al., 2011). In runoff time series the variance explained by low frequency modes (i.e. long term dynamics beyond annual patterns) is higher under drier and warmer conditions (Gudmundsson et al., 2011b). During low flow conditions base flow is the dominant source of water and geohydrologic properties of the catchments become more important. Especially for screening and comparative studies, detailed knowledge about the geohydrology is not available. This also complicates the interpolation of groundwater data in small catchments where wells are scarce and mainly measuring water levels in the upper aquifer complex, but not in the smaller local aquifers which can also only have temporal water storage. Thus, meteorological variables are the only ones widely available to predict low flows. Depending on climate and geohydrology, the most useful variables to explain low flows, the appropriate aggregation length and lag time differ (Demirel et al., 2012).

In drought forecasting it is distinguished between short-term or operational (the next days) and long-lead (the next month, season or year) models. Short-term forecasts are mainly based on time series models using past flow data (e.g. ARIMA models) or physically based models driven by weather forecasts. Water systems with larger memory need long-lead predictions in order to initiate effective measures for operation. Long-lead forecasts cannot use hydrological models because weather forecasts are not reliable exceeding some weeks in the mid-latitudes. Statistical models are mainly based on predictors like past precipitation, sea surface temperature or air pressure fields (see e.g. Li et al., 2010), but also on past stream flows (Lin et al., 2006; Mishra and Desai, 2005; Modarres, 2007; Samsudin et al., 2011). Many studies focused on homogeneous response regions affected by known climate phenomena like El Nino (Piechota and Dracup, 1996) or other sea surface temperature anomalies (Tootle et al., 2007) in order to make estimates on future low flows. In several studies Support Vector machines (SVMs) have been proven to be an appropriate tool with better performances than linear models or artificial neuronal networks (Li et al., 2010; Lin et al., 2006; Samsudin et al., 2011).

The objective is to identify first-order controls on low flow risk for small catchments of Northeast Germany and to analyze if low flow risk is explained more by a lack in precipitation or high evapotranspiration. First, the most powerful low flow predictors for mean annual 30-day minimum runoff (AM_{30}) were identified using a nonlinear regression approach. Second, performance of low flow predictors for time windows and different catchments were assessed. Results were compared to catchment properties and are evaluated regarding low flow processes and implications for water management.

5.2 Material and Methods

5.2.1 Study area

The spatial scope of this study is the federal state of Brandenburg located in Northeast Germany (Figure 5.1). The area is 29,479 km^2 excluding Berlin in its center. With a mean annual precipitation of 557 mm and a mean annual temperature of 8.7 °C (period: 1960-1990; German Weather Service, 2012) it is one of the areas in Germany with the lowest climatic water balance. According to climate projections Brandenburg is located in the transition zone between increasing streamflow in Northern Europe and decreasing streamflow in southern Europe (IPCC, 2007). Smaller rivers belong either to the Elbe or Oder catchment draining to the North and Baltic Sea, respectively.

The study area is part of a postglacial landscape which has formed since the last Pleistocene glaciations. Low gradients in land surface as well as in surface and subsurface flows, a large number of depressions without surface runoff, periglacial channels and complex interactions of different aquifers are major hydrological characteristics of this landscape. For many gauges catchment boundaries cannot be delineated based on topography only, and are known not to be constant over time (Holzbecher, 2001). Smaller rivers do not always drain the first groundwater complex but smaller local aquifers. For a more detailed description and overview on hydrological changes

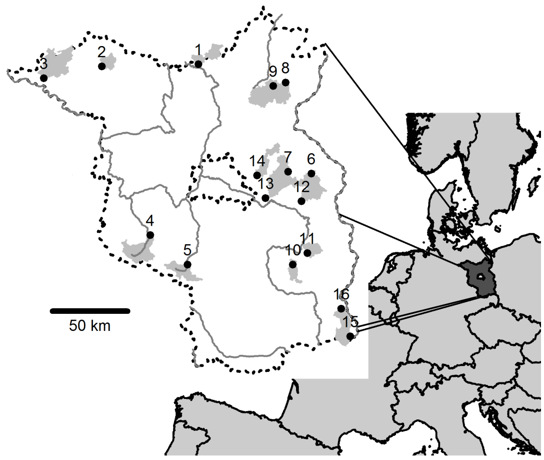

Figure 5.1: Location of the study area (the Federal State of Brandenburg) and location of the 16 catchments (grey polygons) and gauging stations (black dots). The borders of the Federal State of Brandenburg (dashed black lines) and main rivers (grey lines) are shown.

within this landscape we refer to Merz and Pekdeger (2011) and Germer et al. (2011).

5.2.2 Data

Discharge data of catchments smaller than 500 km^2 were provided by the State Office of Environment, Health and Consumer Protection of the Federal State of Brandenburg. It is the definition of small catchments according to the state office and within the range of meso (regional) scale in catchment hydrology. We used data associated to small catchments between 29 and 467 km^2 (Table 5.1). Only catchments with daily discharge data for at least 15 years and low anthropogenic impacts were considered. In total 16 catchments were chosen (Figure 5.1). They are headwater catchments situated at higher altitudes and at the water divides between the larger rivers. No catchment influenced by brown coal mining (Southwest Brandenburg) was included because of high anthropogenic impacts. The area northwest of Berlin is dominated by the lowland rivers Rhin and Havel. Rivers draining small catchments are uncommon in these areas. Previous model calculations estimated a mean runoff of 114 m per year (3.6 l s^{-1} km^{-2}) for Brandenburg between 1976 and 2005 (ABIMO model results; MUGV, 2013; LUGV, 2000). The respective catchment yields already give a rough estimate for which catchments surface and subsurface catchments do not match (Table 5.1).

The real contributing area of the catchments is unknown as described before. In order to be able to compare the discharge values of the catchments in one data set we had to transform the data. This was done similar to the algorithm to calculate standardized precipitation indices (McKee et al., 1993) but on daily time steps. Daily values of discharge contained zeros and thus fitting of a gamma distribution was not possible. We used the empirical cumulative distribution function instead. Discharge data of every catchment was transformed to cumulative probabilities according to their ranks and the number of observations n.

$$Q_{cp} = \frac{rank(Q)}{n} \tag{5.1}$$

In a second step the obtained probabilities are used in a cumulative normal distribution to obtain the final transformed values. This transformation has the advantage that high and low values are equally weighted. Differences in absolute values do not matter any more but the dynamics are preserved. This makes the time series of the different catchments comparable. Values are based on cumulative probabilities instead of abso-

Table 5.1: Topographic catchment areas, length of time series and discharge statistics of analyzed catchments (min: minimum, max: maximum, st. dev.: standard deviation).

No.	area (km^2)	period	missing years	min (m^3s^{-1})	mean (m^3s^{-1})	max (m^3s^{-1})	st.dev. (m^3s^{-1})	mean yield ($ls^{-1}km^{-2}$)
1	204.9	1966-2006	0	0.10	0.94	3.03	0.45	4.6
2	75.9	1977-2005	0	0.05	0.36	8.89	0.31	4.7
3	466.8	1965-2006	0	0.05	2.33	22.20	1.89	5.0
4	226.7	1965-2006	4	0.09	0.69	5.50	0.24	3.0
5	141.4	1969-2006	4	0.01	0.19	4.23	0.16	1.3
6	174.7	1970-2006	2	0.06	0.35	2.06	0.17	2.0
7	122.3	1977-2006	0	0.06	0.46	2.81	0.18	3.7
8	333.5	1970-2006	10	0.08	0.96	11.50	0.75	2.9
9	28.5	1968-2006	6	0.04	0.19	4.98	0.11	6.6
10	72.4	1982-2006	0	0.01	0.26	1.59	0.16	3.5
11	36.9	1982-2006	4	0.01	0.07	1.02	0.04	1.8
12	37.4	1988-2006	3	0.00	0.10	1.37	0.13	2.6
13	173.5	1979-2006	0	0.02	0.72	3.36	0.36	4.2
14	116.6	1965-2006	5	0.00	0.26	2.62	0.20	2.3
15	76.3	1979-2006	0	0.03	0.33	2.09	0.18	4.4
16	120.9	1979-2006	0	0.01	0.38	5.08	0.33	3.2

lute values. For subsequent calculations the transformed discharge values were used.

Different approaches to define low flows exist (Smakhtin, 2001). The annual minimum discharge applying a moving average (here 30 days) was chosen for this study. The advantage is that a continuous time series of annual values are generated and information on annual low flows during wetter years are included. For every catchment and year the annual 30-day minimum flow (AM_{30}) was calculated. The 30-day flow (MA_{30}) is the mean of the previous 30 days calculated for every day of the time series.

$$MA_{30,j} = \sum_{i=j-29}^{j} \frac{Q_{transformed,i}}{30} \tag{5.2}$$

The AM_{30} is calculated as the minimum of all MA_{30}s of a corresponding year. In total 492 AM_{30}s from the 16 catchments were calculated.

Precipitation data (REGINE based) from 75 precipitation stations distributed all over Brandenburg from 1961 to 2006 were provided by the German Meteorological Service (DWD, 2012). Correction for wind and evaporation errors had already been performed. Potential evapotranspiration data was provided by the Potsdam Institute of Climate Impact Research (Österle et al., 2006). It was calculated for all stations according to the algorithm of Turc (Turc, 1961) and Ivanov (Wendling and Müller, 1984). Interpolation of meteorological data to the catchment surface areas was done using Thiessen polygons. Thiessen polygons have been proven a reasonable method in various hydrological studies of the area (e.g. Wechsung et al., 2000). Despite the constraints mentioned above, we had to use surface catchment areas for interpolation. Information on subsurface area was neither available nor possible to calculate from the data available.

Numerous drought indices have been developed to describe the severity of drought in different compartments (Mishra and Singh, 2010). Compared to other indices, the standardized precipitation index (SPI) can be adjusted to different time scales, is able to compare different stations due to its standardization and is parameter free. It has been proven to be one of the most useful indices (Dogan et al., 2012). The SPI has been widely applied for reanalysis of drought events (Bordi et al., 2009; Vidal et al., 2010) as well as forecasting (Mishra and Desai, 2005). Vidal et al. (2010) applied the same standardization to soil moisture and discharge data in order to describe the propagation of drought through the different compartments.

Standardized precipitation (SPIs) and potential evapotranspiration (SpETIs) indices were calculated according to the algorithm of McKee et al. (Dogan et al., 2012; McKee et al., 1993). First, a moving average of 1, 2, 3, 6, 12, 24, 36 and 48 months was applied to all time series. Second, a gamma distribution was fitted to the empirical probabilities of the aggregated data using maximum likelihood estimation and probabilities were calculated for every value. Third, the probabilities were used in a cumulative normal distribution to obtain the standardized indices. This standardization allows high and low values to be equally weighted and to be expressed in times of standard deviations compared to a mean value. The same algorithm was used for precipitation and potential evapotranspiration.

For all indices we use a code in this paper. It consists of the Index name and an abbreviation of the aggregation length and lag time. The index name can be either SPI for precipitation or SpETI for potential evapotranspiration. The abbreviations for the aggregation lengths and lag times are given in Table 5.2. In total, 44 meteorological variables were associated with every of the 492 AM_{30}s.

5.2.3 Non-linear support vector machine regression

In hydrology support vector machines (SVM) have been used for long-lead streamflow prediction (e.g. Li et al., 2010; Lin et al., 2006). A SVM is a supervised learning model which was originally invented for classification and later extended to regression (Vapnik, 1995). SVMs use the advantage that, according to Mercer's theorem, to every space a higher dimensional space exists, that makes a non-linear regression problem a linear one. Even though the mapping to the higher dimensional space is unknown a kernel function can be used as a kind of local mapping (this is called the kernel trick). We use the radial-basis functions (RBF) with one parameter σ as kernel like most studies applying SVM to streamflow data (Lin et al., 2006). The RBF is defined as

$$k(x_i, x_j) = exp(-\sigma\|x_i - x_j\|^2) \qquad (5.3)$$

where x is the input data vector. For a detailed description we refer to Lin et al. (2006).

The linear regression problem can be written as

$$f(x) = \langle w, x\rangle + b \qquad (5.4)$$

Table 5.2: List of codes for aggregation lengths and lag times.

description	code
month starting at the date of the AM30	lm
1–48 months starting with a lag of 30 days to the AM30	1, 2, 3, 6, 12, 24, 36, 48
last two calendar years	1yr, 2yr
the last two winter (November to April) and summer (May to October) half years	1why, 1shy, 2why, 2shy
the last two winter (December to February), fall (September to November), summer (June to July) seasons and last spring (March to May) season	1win, 1fal, 1som, 1spr, 2win, 2fal, 2som

where $\langle w, x \rangle$ is the dot product between weights w and input variables x and b is the error. In contrast to a least squares regression the ϵ-insensitive loss function is used on the deviations ξ from the regression line.

$$|\xi|_\epsilon = \begin{cases} 0 & \text{if } |\xi| \leq \epsilon \\ |\xi| - \epsilon & \text{otherwise} \end{cases} \tag{5.5}$$

In the hyper tube with distance ϵ from the regression line no errors are accounted for. The problem is solved minimizing the cost function

$$0.5\|w\|^2 + C \sum_{i=1}^{N} (|\xi|_{\epsilon,i}) \stackrel{!}{=} min \quad \text{for } C > 0 \tag{5.6}$$

where C is a constant giving the trade-off between flatness and tolerating deviations larger than ϵ.

For a detailed description of the method and mathematical solution of the regression problem we refer to Bennet and Campell (2000) and Vapnik (1995). For all computations we used the package "e1071" written in R language (Meyer et al., 2012). The package is described and compared to other SVM packages in Karatzoglou et al. (2006). In contrast to other packages, it has the advantage that a grid search parameter optimization has already been implemented.

Three free parameters, σ the kernel parameter, ϵ the radius of the hyper cube and C the trade-off between flatness and tolerating deviations larger than ϵ, have to be calibrated. The constant C was set to 1 in order to equally weight flatness of w and the distances from the hypercube. We used a grid search algorithm to optimize the two remaining parameters σ and ϵ. For every parameter combination the performance of the SVM was calculated using a bootstrapping approach. Randomly 50 times $\frac{1}{3}$ of the data was drawn. For every of the 50 sub models the mean squared error (MSE) was calculated and the performance was determined using the mean MSE of all 50 runs. The parameter combination obtaining the best performance measure was used to calibrate the final SVM model. We tested this bootstrapping approach taking the model with the 4 selected low flow predictors (see results) and a bootstrap sample size of 25, 50, 100 and 250. Differences in mean validation r^2 were below 0.01.The standard deviations in validation r^2 using different sample sizes were 0.010, 0.006, 0.004 and

0.003, respectively. Thus, the used sample size of 50 guarantees precise results. In order to save computation time we nested three grid searches starting with a precision of 0.01 (from 0.0025 to 0.0425) and 0.1 (from 0.05 to 0.55) and ending with a precision of 0.0014 and 0.01 for σ and ϵ respectively. Changes in model performance were not very sensitive to further refinement of the grid search algorithm as tested for part of the data.

Starting with all 44 variables the two parameters σ and ϵ were calibrated 44 times, always leaving one variable out. SVM tends to over-fitting without validation procedure, especially if the number of explanatory variables is high and sample size is low. For every of the resulting 44 models 100 times $\frac{2}{3}$ of the input data was used to set up a SVM and the remaining $\frac{1}{3}$ of the input data was used for validation. The SVM parameters were kept constant as determined by the grid search algorithm. The mean Pearson correlation r^2 of all calibration and validation runs was calculated. The variable left out in the model with the highest r^2 was the most redundant one and was discarded in the next iteration step. For the next iteration 43 models were built always leaving one of the 43 remaining variables out. Iteratively, this procedure was repeated until only one variable was left.

Evaluating the results from the iterative variable reduction, we chose as few variables as possible which guaranteed a high model performance and less over-fitting at the same time. The models using one up to the optimum number of variables were used in order to evaluate the model performance for different catchments and over time. Thus, first a model using the variable excluded last during iterative reduction, second a model using the two variables excluded last and so on were used for further analyses.

5.2.4 Evaluation of model performance in time and between catchments

For all analyses the models were run globally including all data. Afterwards the results were split according to time windows or catchments. The explained variance corresponding to the variables was calculated as the difference in model performance to the model using one variable less. If for numerical reasons a model using more variables has a lower r^2 the explained variance by the variables was set to zero. This could occur because of uncertainties induced by the data and method. For spatial analysis the model performance was calculated separately for every catchment. To show temporal differences a moving window of 15 years was applied in order to calculate the temporal evolution of model performance. The chosen window length was a compromise between temporal resolution and statistical saturation.

The model performances for the different catchments were correlated with catchment properties. Catchment properties were calculated by intersecting maps with topographic catchment boundaries and by using results from a previous comparative study of river discharge. We included the following data sources: (i) Topographic catchment areas were provided by the Ministry of Environment, Health and Consumer Protection (MUGV, 2013). (ii) Percentage of area used as forest, for agriculture and as settlement was calculate from CORINE land cover data (Bossard et al., 2000). (iii) Mean distance to groundwater table was calculated subtracting the mean groundwater table, given by the hydrogeological map of Brandenburg, HyKa50, 1:50,000 (State Office for Mining, Geology and Raw Material of Brandenburg, 2012), from the digital elevation model at a resolution of 25 m times 25 m (Land Surveying Office of the Federal State of Brandenburg, 2012). (iv) To obtain the long term mean annual, winter and summer precipitation as well as mean summer and annual potential evapotranspiration the Hydrological Atlas of Germany 1961-1991 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2003) was used. (v) The long term mean discharge, long term mean actual evapotranspiration and percentage of sandy and loamy soils were contained in the results of ABIMO water balance modeling between 1976 and 2005 (MUGV, 2013). (vi) Thomas et al. (2012, Chapter 4) performed a catchment characterization with respect to low flow risk based on a principal component analysis of daily discharge. The loadings of the leading components gave an estimate on how important the corresponding climatic and Geohydrologic processes are for the different catchments. We included those loadings as catchment properties. Those components which show correlations with model performances will be explained in the discussion section. The ranges and basic statistics of all catchment properties are given in Table 5.3.

Additionally to model performances, we looked at the model residuals for different catchments. First, we used a t-test to determine catchments with significant different mean residuals from zero. Second, we also correlated the mean residuals of every catchment with catchment properties.

All correlation analyses are based on the Pearson correlation coefficient (r) and its square, the coefficient of determination (r^2). Statistical significance of r^2 was calculated using a permutation test which tests the hypothesis H_0 that r^2 equals zero (Dwass, 1957; Good, 2005). In order to determine if correlation between the model results and a catchment property is significant, 10000 times the correlation coefficient was calculated, randomly permutating the indices of one variable. Only correlations which were higher than 95% ($\alpha = 0.05$) of the randomized correlation coefficients were significant different from zero.

5.3 Results

5.3.1 Iterative variable reduction to predict AM_{30}

The iterative variable reduction discriminated variables according to the correlation coefficient of the different models (Figure 5.2). Despite some minor deviations the correlation coefficient corresponding to the calibration data is decreasing steadily during variable reduction. r^2 is decreasing particularly for the last four variables compared to the deviations in r^2 at higher numbers of variables. These are the variables having the highest explanatory power in the data set. The last four variables are the 48 month standardized potential evapotranspiration (SpETI48), the 3 month standardized potential evapotranspiration (SpETI3), the 3 month standardized precipitation (SPI3) and the standardized precipitation of the last year (SPI1yr). The variable SpETI48 is increasing model performance the most. Previous high potential evapotranspiration and small precipitation sums indicate low AM_{30}s. r^2 using the calibration data was always higher than using the validation data. The differences in r^2 using calibration and validation data show

Table 5.3: Statistics of catchment properties (n: number of catchments, min: minimum, max: maximum, st. dev.: standard deviation).

catchment property	n	min.	max.	median	mean	st. dev.
% forest	16	6	66	37	37	19
% agriculture	16	30	91	57	58	20
% settlement	16	0	13	3	4	3
mean depth to ground water (m)	16	4.5	23.9	8.7	10.5	5.9
surface catchment area (km^2)	16	28.5	466.8	121.6	150.5	116.6
mean annual P (mm)	16	528.4	625.6	555.9	570.7	28.0
mean summer P (mm)	16	171.1	196.1	178.7	180.4	8.1
mean winter P (mm)	16	221.6	278.1	243.1	251.2	18.3
mean annual pET (mm)	16	573.1	609.0	597.8	595.0	11.5
mean summer pET (mm)	16	270.6	284.5	281.4	280.2	4.2
mean yield (mm)	16	100.5	179.8	143.5	144.1	21.1
mean aET (mm)	16	419.4	532.4	500.5	494.0	29.3
% sandy soils	16	32	91	65	64	21
% loamy soils	16	1	66	28	30	22
loadings of PC1	10	-0.87	-0.66	-0.80	-0.78	0.06
loadings of PC2	10	-0.47	0.28	0.03	-0.04	0.25
loadings of PC3	10	-0.49	0.22	0.07	0.01	0.23
loadings of PC4	10	-0.28	0.20	0.06	-0.02	0.17

that over-fitting increases with number of variables.

We choose the last 4 variables (SpETI48, SpETI3, SPI3 and SPI1yr) for further analyses according to the results of the iterative variable reduction. For further analysis we used four models containing one to four variables according to the ranking of the iterative variable reduction. The explained variance of the corresponding variable is calculated as the difference in r^2 between one model and the model containing one variable less. SpETI48, SpETI3, SPI3 and SPI1yr explained 28%, 12%, 6% and 4% of the variance in the calibration data and 28%, 12%, 4% and 4% in the validation data. It shows that over-fitting is low for these four variables. r^2 of the final model is 0.49 and if annual means of all catchments are taken r^2 increases to 0.80 because extremes are smoothing out. The scatter plot of the final model shows that low AM_{30}s are overestimated and vice versa (Figure 5.3). The annual means and ranges for NM30Q, the four variables SpETI48, SpETI3, SPI3 and SPI1yr and the relation between SpETI48 and NM30Q is given in Figure 5.4.

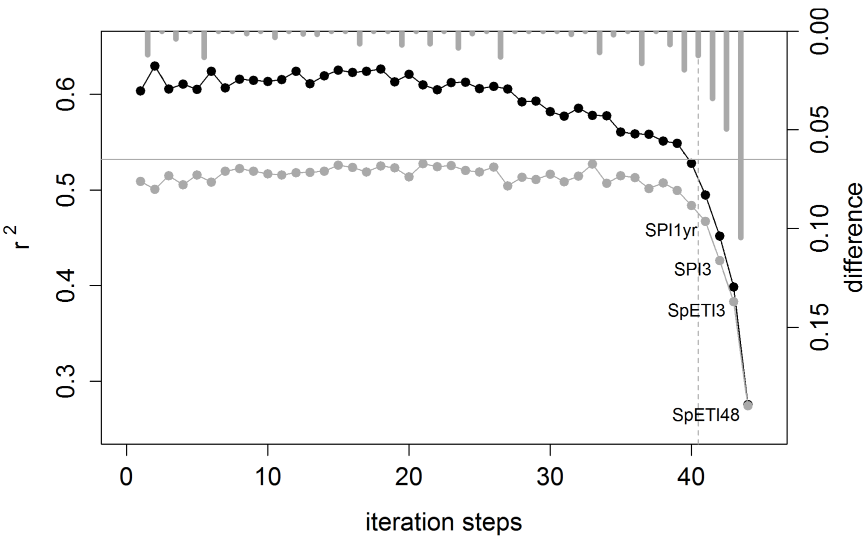

Figure 5.2: Mean r^2 of the calibration (black points) and validation (grey points) data sets during the iterative variable reduction starting with 44 variables. The difference between mean r^2 of two successive iteration steps of the validation data is shown (grey bars).

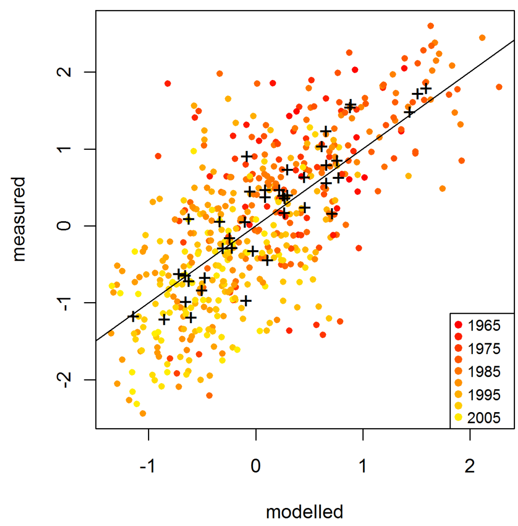

Figure 5.3: Scatter plot of modeled versus measured AM_{30}s (z-normalized values) colored according to the year. The annual means of all catchments are shown (black crosses). r^2 is 0.49 for all data points and 0.80 for annual means. The 1:1 ratio is included as black line.

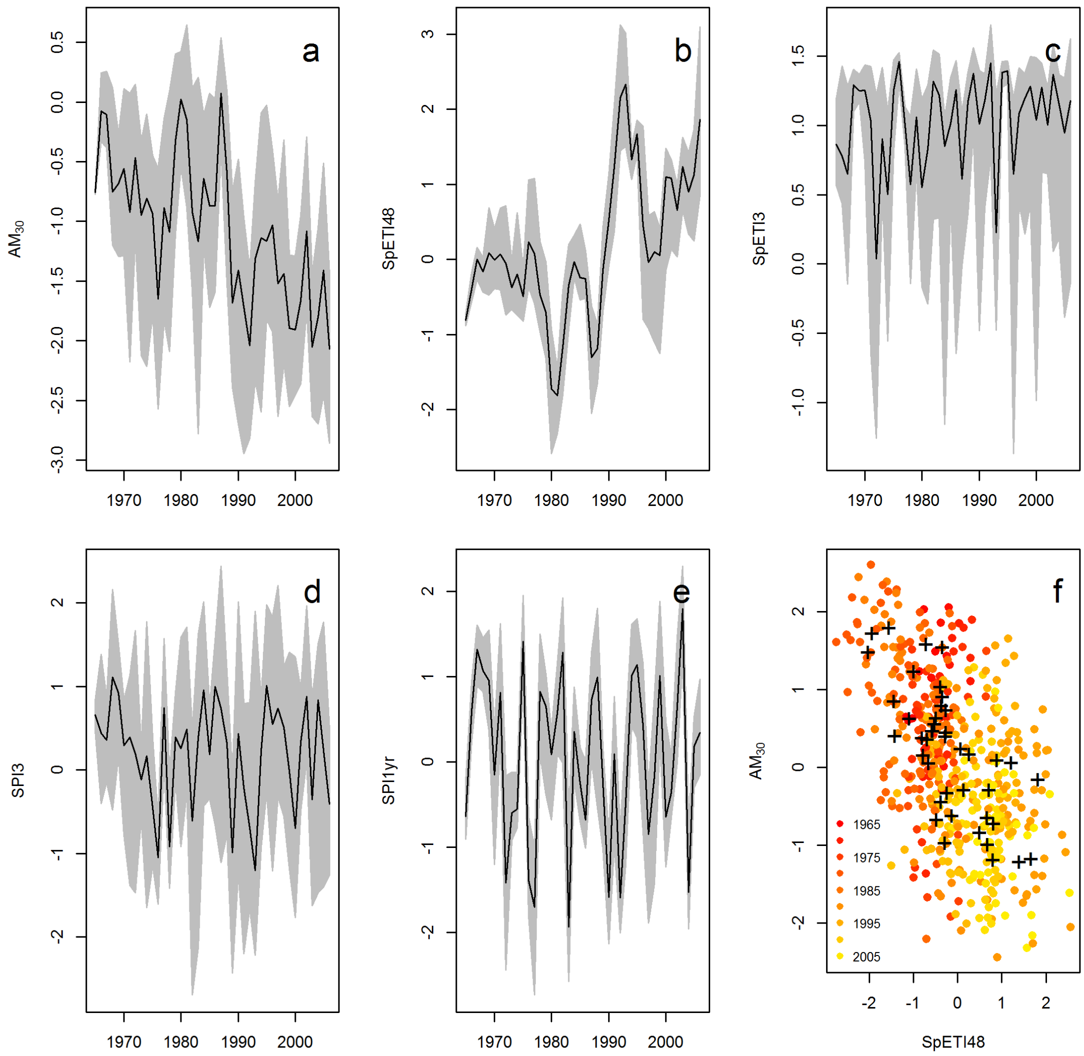

Figure 5.4: Annual mean (black line) and range (grey area) of (a) AM_{30}s of all catchments, (b) SpETI48, (c) SpETI3, (d) SPI3 and (e) SPI1yr. (f) z-normalized values of AM_{30}s and SpETI48 colored according to the year. Annual means of all catchments are included (black crosses).

5.3.2 Temporal evolution of model performance

The temporal evolution of the model performance gives information on changes in the relations between variables and AM_{30}s in different time windows (Figure 5.5). Using a window of 15 years the variable SpETI48 is most important in the middle of the analyzed period. The changes in explained variances of further variables are small. While the importance of SpETI3 is decreasing the other two precipitation variables are increasing over time. Except for catchment 3 discharge and the AM_{30}s were decreasing for all catchments (Mann-Kendal statistics, $\alpha = 0.05$). The decline in explained variance by the Model using SpETI48 and all four variables is parallel to the decline of NM30Qs in the last decades but model performance is also quite low in the beginning of the study period where low flows were high (Figure 5.4a). The general pattern of the last decades was that the explained variance is decreasing for the potential evapotranspiration variables and increasing for the precipitation variables.

5.3.3 Spatial patterns of model performance

The model performance (r^2) using 4 variables varied between 0.45 and 0.88 for the different catchments (Figure 5.6). In contrast to the temporal pattern the importance of the different variables showed larger deviations between catchments. Except catchment number 11 the model performance increases with number of variables used. In catchment 1, 3, 5, 6, 8, 10, 12 and 16 a larger part of the model performance is not only determined by the first variable SpETI48 in contrast to the other catchments where model performance is mainly due to this variable.

The r^2 related to the four variables, their sum and the sum of the two pET and P variables were correlated with catchment properties (Table 5.4). Significant correlations for single variables were only found for SpETI48 and SPI3. Nevertheless, further significant correlations were found for the combination of all and the pET and P variables. The r^2 ranged between 0.27 and 0.61. The explained variance of SpETI48 correlated with mean depth to groundwater table and mean summer pET. Mean annual and summer precipitation, mean discharge and percentage of sandy soils correlated with the explained variance of the variable SPI3. The total explained variance of the model using all 4 variables correlated with mean discharge and especially with the loadings of the 4th principal component described in Thomas et al. (2012). The meaning of this variable will be given in the discussion section. The sum of explained variance by the pET variables correlated with percentage coverage of settlements and the loadings of the 4th principal component. Mean summer precipitation correlated with the sum of explained variance by the precipitation variables.

Also the means of model residuals differed between catchments. For catchment 3, 6, 7, 8 and 12 mean residuals were significantly different from zero (t-test, $\alpha = 0.05$). The only significant correlation with catchment properties was found between mean residuals and topographic catchment area ($r = -0.52$). With larger topographic area mean model residuals were lower.

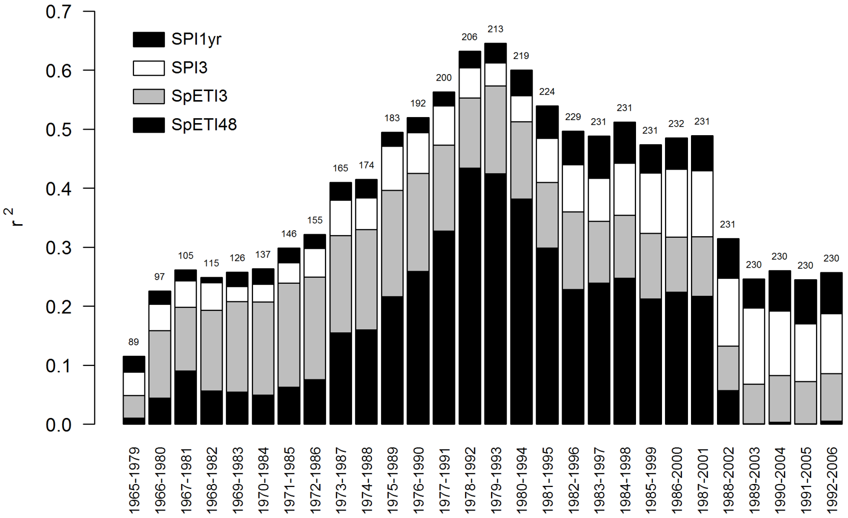

Figure 5.5: Temporal evolution of the model performance using a window of 15 years and four models including one to four variables. The number above each bar indicates the number of data points in the corresponding time window.

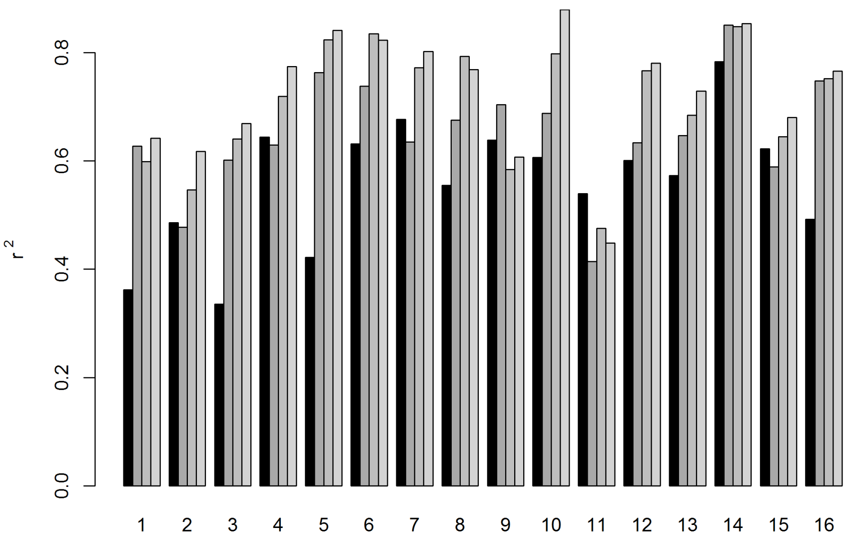

Figure 5.6: Model performances for all 16 catchments using one (black bars) up to all the 4 variables (dark grey to light grey bars).

Table 5.4: Correlations between explanatory power and catchment characteristics. Only correlations which are significant ($\alpha = 0.05$) are shown. The columns full model, SpETIs and SPIs correspond to the sum of explained variances by all four , the two pET and the two precipitations variables.

	SpETI48	SpETI3	SPI3	SPI1yr	full model	SpETIs	SPIs
% forest							
% agriculture							
% settlement						0.57	
mean depth to ground water	0.52						
surface catchment area							
mean annual P			-0.58				
mean summer P			-0.61				-0.53
mean winter P							
mean annual pET							
mean summer pET	0.62						
yield			-0.67		-0.56		
mean aET							
% sandy soils			-0.58				
% loamy soils							
loadings of PC1							
loadings of PC2							
loadings of PC 3							
loadings of PC 4					0.78	0.74	

5.4 Discussion

As we wanted to incorporate data of several catchments in one data set to find general patterns, a regression model was chosen. A non-linear approach was chosen because the data structure was not known a priori. Regression or time series models were favored for long lead prediction of discharge due to decreasing accuracy of meteorological boundary conditions for numerical models after some days (Diomede et al., 2008). Therefore, we were able to give implications on long-lead predictions with our results. Additionally, In numerical modeling the model performance during low flows is often lower than the overall performance (e.g. Ahmed, 2012; Staudinger et al., 2011). The approach used has the advantage that interdependencies between the variables are considered in contrast to studies where only one variable is evaluated at a time ((see e.g. Demirel et al., 2012).

Several uncertainties arise from the data and method. (i) Measurement errors and uncertainties are contained in the discharge and precipitation time series. They cannot be quantified because the state office does not give any information on measurement precision. It has to be considered that transformed values are used and dynamics rather than absolute values were analyzed. Thus, systematic errors would not ad uncertainties. (ii) Uncertainties associated to the calculation of potential evapotranspiration according to the algorithm of Turc is estimated to be 20–40% for monthly values (Foken, 2006). Such uncertainties are common for calculated values of the potential evapotranspiration. Again it has to be considered that values are transformed and no absolute values but dynamics were anayzed in our analysis. (iii) Three parameters had to be calibrated for SVM regression. The C constant was set to 1 and the other two were estimated using a grid search algorithm. The Parameter estimation was limited by the coarseness of the grid search algorithm but uncertainties were low as described in the method section. Thus, it was supposed to be important during iterative variable reduction of the first, less important, variables and the influence on the selection of low flow predictors is negligible. (iv) The number of bootstraps during the validation procedure needs to be high enough to give precise results. As described in the method section the used sample size of 50 guarantees precise results. Colinearity between the used variables is high and model performance would not decrease a lot by e.g. replacing SpETI48 with SpETI36. The final ranking of variables depends on which variable is reduced first during the iterative algorithm. The discussion on uncertainties enumerates the different sources which could lead to uncertainties in the results. Nevertheless a change in closely related variables would not lead to different conclusions and interpretations.

The results of the iterative variable reduction showed that over-fitting increased with number of variables. We preferred a reduction instead of an aggregation algorithm because non-linear interdependencies of variable combinations were included from the beginning. The application of a validation procedure ensured more robust results, especially for many variables at the beginning of the iterative variable reduction. Theoretically, the model performance should decrease monotonically with variable reduction. Deviations from this rule were due to the discrete SVM parameter calibration, measurement errors and insufficient statistical saturation. Nevertheless, these changes in model performance were small compared to those which were used to identify the most important low flow predictors.

According to the reduction in model performance with decreasing number of variables we chose four variables (SpETI48, SpETI3, SPI3 and SPI1yr) as low flow predictors. In the study period evapotranspiration variables were by far the most important first-order controls on low flows but long-term shifts in model performance was apparent. Differences of the chosen predictors in r^2 clearly separated from those between other variables. According to the validation data they were able to explain $r^2 = 0.46$ of the AM_{30}s which is more than 87% of the maximum r^2 at 20 variables. The r^2 increases to 0.80 if annual means of all catchments are taken. Taking annual means would be meaningful to develop an index generally describing the low flow risk for Brandenburg. It has to be considered that only meteorological input variables were used and no assumptions on hydrological processes were introduced. Additionally, the data of several catchments were combined in one data set. Demirel et al. (2012) found that for several subcatchments of the river Rhine correlation between potential evapotranspiration and low flow is higher than using precipitation data for specific lag times and aggregation lengths. The correlations they found are within the range of those identified in this study even though catchment sizes are much lower in our study.

The standardized potential evapotranspiration on a time scale of 48 month (SpETI48) is the most important low flow predictor for the study period. The results of the temporal evolution of model performance (Figure 5.5) and the evolution with mean AM_{30} of the corresponding periods (Figure 5.4a) indicate clear long-term shifts in model performance, especially for SpETI48.with deceasing AM_{30} SpETI48 predicts AM_{30}s less precise. The decrease in explained variance by SpETI48 took place when years with higher AM_{30}s were not included in the time window. Nevertheless, SpETI48 is important to separate high from low AM_{30}s in the whole data set (Figure 5.4f) and explain variations between higher AM_{30}s. It has to be considered, that in contrast to high flows low flows can become zero. This was only the case in few events. The correlation between AM_{30}s and SpETI48s is $r^2 = 0.26$ considering the whole data set but can be higher than 0.60 for several catchments. The model performance attributed to precipitation predictors (SPI3 and SPI1yr) increased at the same time but model performance is not as high as in the middle of the study period. All these are indications that the processes and flow paths leading to the AM_{30}s changed during the study period. In two modeling studies a decrease in groundwater recharge, especially for coniferous forests, was found for the Ucker catchment, northeast Brandenburg (Wegehenkel and Kersebaum, 2008, 2009). In Brandenburg ground water levels at the recharge areas, mainly located at higher elevation within the headwater catchments, have decreased during the last decades (Germer et al., 2011). This could have led to nonlinear decrease in base flow or even decoupling of parts of the streams from ground water due to non-permanent water supply from the upper aquifer.

The proportion of model performances according to the low flow predictors differed between catchments (Figure 5.6). Several significant but rather low correlations with catchment properties were identified (Table 5.4). The highest correlation was found between the performance of the model using all 4 variables and the 4th component found by Thomas et al. (2012, Chapter 4). Thomas et al. (2012, Chapter 4) characterized small catchments in Brandenburg according to their streamflow time series. They found several principal components which described dissimilarity between catchments due to meteorological forcing and geohydrological properties. Positive loadings on the 4th component indicate catchments with higher damping of the input signal. The correlations found indicate model performance to increase for catchments with higher damping. This is reasonable because with increased damping the memory of the system becomes more important to describe low flows and processes within the unsaturated zone have a large influence on groundwater recharge. Respectively, the model performance associated to the most important predictor SpETI48 correlates positively with mean depth to ground water table and mean summer potential evapotranspiration. Additional, the model performance is high for catchments with low mean yield (i.e. groundwater recharge). While the sum of explained variance of the potential evapotranspiration predictors correlates positively with percentage of settlement area, the sums of explained variance of the precipitation predictors decreases with mean summer precipitation. This indicates that precipitation predictors become more important for dryer catchments. Nevertheless no correlations with the meteorological patterns PC2 and PC3 of Thomas et al. (2012) were found. Thus, no correlations to the patterns found on the European scale (Gudmundsson et al., 2011b) could be found. Geohydrological properties seem to be more relevant to describe differences in low flows on the regional scale. The impacts by water management and other anthropogenic impacts could not be determined in this study. The correlation with percentage settlement area is a small indication on anthropogenic influences.

This study demonstrates the usability of support vector regression to identify low flow predictors. The aggregation time scale and lag time of the input variables were discrete. Other studies screened single variables in order to find the best variables. An advantage is that they can identify the aggregation length and lag time more precisely (Demirel et al., 2012). On the other hand they do not consider interdependencies between variables in non-linear space. We do not expect our model performance to increase distinctly by introducing finer resolution and lag times, especially for variables with longer aggregation time scales. This is due to high colinearity of variables. Furthermore, only meteorological data and no ground water and other hydrological data was considered. The main constraint with such data was that it is not widely available for small catchments and interpolation to the whole catchment area is highly not trivial.

This study tries to identify the first-order controls on low flows in small rivers of Brandenburg. The high importance of potential evapotranspiration shows that groundwater recharge and thus base flow was strongly dependent on storage and release of water from the soil column. For the study period Evapotranspiration is found to be the first-order control on low flow risk. Differences in model performance between catchments and model performance attributed to precipitation variables exist. The results deepened understanding on hydrologic low flow processes of small catchments in a post glacial landscape. It will help to improve model structures and parameterization in the future. The comparison of our results with model outputs and the evaluation of model structures will help to improve model performances in the way claimed by Kirchner (2006).

Regarding climate change, our results give several implications. The partition of model performance to potential evapotranspiration variables suggests decreasing low flows in the future to be very likely. These findings are parallel to modeling studies (Conradt et al., 2012; Wegehenkel and Kersebaum, 2009). Risley et al. (2011) showed an increase in actual evapotranspiration to precipitation ratio if potential evapotranspiration to precipitation ratio increases for most of 14 investigated catchments distributed over the United States. It shows that potential evapotranspiration is to some extend related to the actual evapotranspiration. The relationship between actual and potential evapotranspiration depends on catchment properties and changes can change according to the system state. On the other hand extreme changes can occur if low flow processes change abruptly, e.g. due to decoupling of streams from the first ground water layer (see e.g. Kinal and Stoneman, 2012). Our results cannot be extrapolated to such cases because changes in runoff behavior will be very unique and depend on the catchments' hydrogeology. Research is needed to describe the groundwater recharge as a function of the soil, predicted evapotranspiration and precipitation under climate change. Additionally, modeling studies are needed which investigate possible breakpoints in runoff behavior and compare vulnerability of catchments to abrupt changes.

Two implications for authorities and water managers arise. First, the identified low flow predictors can be used to develop low flow monitoring or drought forecasting on the catchment and state scale. Our results show that validation of low flow predictors over time is very important to guarantee stability of predictors for the near future. The past ranges of the predictors (Figure 5.4a-e) and corresponding absolute values (Table 5.5) help to roughly estimate low flows for a specific catchment. Eventually, performance can be increased if additionally knowledge on the specific catchments, ground water levels and water management would be included. Including previous streamflow would be reasonable for catchments with autocorrelation in their streamflow time series. Second, the correlations between explained variances and catchment properties can help to optimize adaption strategies. In catchments where low flows are strongly controlled by groundwater recharge controlled by evapotranspiration, land use changes and ground water recharge measures are likely to be more effective. Differences in model performance due to SpETI48 can be used to estimate catchments where low flows are strongly controlled by ground water recharge dynamics.

The obtained low flow predictors are valid for a wide range of small catchments in the area. Results can be used as a starting point if low flow predictors for specific catchments or management options are required or decision support systems have to be built. Our global approach combining several catchments has the advantage to extract the more general patterns in the region and will be used as basis for more detailed studies in the future.

Table 5.5: Mean value and standard deviation (st.dev.) of potential evapotranspiration (pET) and precipitation (P) sums of the 16 catchments according to standardized values.

standardized	pET 48 months		pET 3 months		P 3 months		P last year	
value	mean	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.
-3.0	2174	87	1	0	41	5	346	28
-2.5	2215	88	4	1	53	6	382	29
-2.0	2256	90	10	1	66	7	420	30
-1.5	2298	91	21	2	82	7	462	32
-1.0	2340	93	41	3	100	8	506	33
-0.5	2383	95	73	5	121	8	552	35
0.0	2426	97	118	6	144	9	602	38
0.5	2469	99	181	8	171	10	654	40
1.0	2514	102	261	9	200	11	709	43
1.5	2558	104	361	12	233	13	768	47
2.0	2604	107	483	15	268	14	829	50
2.5	2650	110	626	19	307	17	893	55
3.0	2696	113	792	24	350	19	961	59

5.5 Conclusion

Starting with 44 variables of standardized precipitation and potential evapotranspiration at different aggregation lengths, iteratively variables have been reduced using support vector machine regression to estimate the annual minimum 30-day mean flow (AM_{30}) of 16 catchments in Brandenburg, Germany. The potential evapotranspiration of previous 48 months (SpETI48), potential evapotranspiration of previous 3 months (SpETI3), precipitation of previous 3 months (SPI3) and precipitation of the last year (SPI1yr) were the most relevant predictors for AM_{30} estimation. Evapotranspiration was the first-order control on low flow risk for the study period. Distinct long-term shifts in predictive power of variables were apparent. SpETI48 explained most of the variance, but its relevance decreased during the last decades and so did the overall model performance. The importance of the precipitation predictors increased over time. Results indicate changes in the relevant processes or flow paths generating low flows.

Spatial patterns found in a previous study (Thomas et al., 2012) correlated with model performance of the different catchments. Catchments with a more damped discharge behavior showed higher model performance. Several other correlations between catchment properties and performance of the low flow predictors were found and will be valuable to formulate hypotheses being tested in future studies. Both discharge and AM_{30} data was decreasing for most catchments and the lowest flows were observed in the last decades. Also model performance decreased in the last decades. These give evidence that catchment behavior during lower flows became more unique and probably more complex. Geohydrological processes seem to be more important than the meteorological boundary conditions to explain these low flows.

The results are useful to develop low flow monitoring and forecasting tools in order to support water management, in catchments or for specific adaption measures. The low flow predictors can be used to optimize storage allocation rules and to define thresholds for drought alert. Regarding different catchments, the results help to understand in which catchments low flows are more driven by evapotranspiration. In such catchments adaption measures increasing groundwater recharge can be more effective. Additionally, insights from this study are valuable to validate models focusing on low flows. It has to be analyzed if models are able to mimic the relevant time scales for low flow generation and can explain the catchment dissimilarities and long-term shifts in time which were found.

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References

Ahmed, F. (2012). A Hydrologic Model of Kemptville Basin-Calibration and Extended Validation. *Water Resources Management 26*(9), 2583–2604.

Bennet, K. P. and C. Campell (2000). Support Vector Machines: Hype or Hallelujah? *SIGKDD Explorations 2*(2), 1–13.

Blöschl, G., S. Ardoin-Bardin, M. Bonell, M. Dorninger, D. Goodrich, D. Gutknecht, D. Matamoros, B. Merz, P. Shand, and J. Szolgay (2007). At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes 21*, 1241–1247.

Bordi, I., K. Fraedrich, and A. Sutera (2009). Observed drought and wetness trends in Europe: an update. *Hydrology and Earth System Sciences 13*(8), 1519–1530.

Bossard, M., J. Feranec, and J. Otahel (2000). CORINE land cover technical guide - Addendum 2000. Technical report, European Environment Agency.

Conradt, T., H. Koch, F. Hattermann, and F. Wechsung (2012). Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change 12*(3), 633–648.

Demirel, M., M. J. Booij, and A. Hoekstra (2012). Identification of appropriate lags and temporal resolutions for low flow indicators in the River Rhine to forecast low flows with different lead times. *Hydrological Processes published online*, DOI: 10.1002/hyp.9402.

Diomede, T., S. Davolio, C. Marsigli, M. M. Miglietta, A. Moscatello, P. Papetti, T. Paccagnella, A. Buzzi, and P. Malguzzi (2008). Discharge prediction based on multi-model precipitation forecasts. *Meteorology and Atmospheric Physics 101*(3-4), 245–265.

Dogan, S. K., A. Berktay, and V. P. Singh (2012). Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey. *Journal of Hydrology 470-471*, 255–268.

Dwass, M. (1957). Modified Randomization Tests for Nonparametric Hypotheses. *Annals of Mathematical Statistics 28*(1), 181–187.

DWD (2012). German Meteorological Service. http:// www.dwd.de.

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2003). *Hydrological Atlas of Germany 1961-1991 (Hydrologischer Atlas von Deutschland).* http:// www.bmu.de.

Foken, T. (2006). *Angewandte Meteorologie (engl.: applied meteorology).* Springer, Berlin, Heidelberg.

Germer, S., K. Kaiser, O. Bens, and R. Hüttl (2011). Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region - a Review. *Die Erde 142*(1-2), 65–95.

Good, P. (2005). *Permutation, Parametric, and Bootstrap Tests of Hypotheses, third edition.* Springer, New York.

Gudmundsson, L., L. M. Tallaksen, and K. Stahl (2011a). Spatial cross-correlation patterns of European low, mean and high flows. *Hydrological Processes 25*(7), 1034–1045.

Gudmundsson, L., L. M. Tallaksen, K. Stahl, and A. K. Fleig (2011b). Low-frequency variability of European runoff. *Hydrology and Earth System Sciences 15*(9), 2853–2869.

Hannappel, S. and H.-J. Voigt (1997). Beschaffenheitsmuster des Grundwassers im Lockergestein (engl.: Groundwater quality patterns in unconsolidated rock). In J. Matschullat, H. Tobschall, and H.-J. Voigt (Eds.), *Umweltgeochemie (engl.: Environmental geochemistry)*, pp. 360–393. Springer, Heidelberg.

Hisdal, H., K. Stahl, L. M. Tallaksen, and S. Demuth (2001). Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology 21*(3), 317–333.

Holzbecher, E. (2001). The dynamics of subsurface water divides - watersheds of Lake Stechlin and neighbouring lakes. *Hydrological Processes 15*(12), 2297–2304.

IPCC (2007). Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC.

Karatzoglou, A., D. Meyer, and K. Hornik (2006). Support Vector Machines in R. *Journal of Statistical Software 15*(9).

Kinal, J. and G. Stoneman (2012). Disconnection of groundwater from surface water causes a fundamental change in hydrology in a forested catchment in south-western Australia. *Journal of Hydrology 472-473*, 14–24.

Kirchner, J. W. (2006). Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research 42*, W03S04.

Land Surveying Office of the Federal State of Brandenburg (2012). Digital elevation model (1:25000). http://www.geobasis-bb.de.

Li, L. H., H. G. Xu, X. Chen, and S. P. Simonovic (2010). Streamflow Forecast and Reservoir Operation Performance Assessment Under Climate Change. *Water Resources Management 24*(1), 83–104.

Lin, J. Y., C. T. Cheng, and K. W. Chau (2006). Using support vector machines for long-term discharge prediction. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 51*(4), 599–612.

LUGV (2000). Flächendeckende Modellierung von Wasserhaushaltsgrößen für das Land Brandenburg, Studien und Tagungsberichte 27 (engl.: water balance modelling across the whole area of the Federal State of Brandenburg). Technical report, State Office for Environment, Health and Consumer Protection of the Federal State of Brandenburg.

McKee, T. B., N. J. Doesken, and J. Kleist (1993). The Relationship of Drought Frequency and Duration to Time Scales. In *Eighth Conference on Applied Climatology, 17-22 January 1993*.

Merz, C. and A. Pekdeger (2011). Anthropogenic Changes in the Landscape Hydrology of the Berlin-Brandenburg Region. *Die Erde 142*(1-2), 21–39.

Meyer, D., E. Dimitriadou, K. Hornik, A. Weingessel, and F. Leisch (2012). e1071: Misc Functions of the Department of Statistics (e1071), TU Wien, http:// CRAN.R-project.org/package=e1071.

Mishra, A. K. and V. Desai (2005). Drought forecasting using stochastic models. *Stochastic Environmental Research and Risk Assessment 19*(5), 326–339.

Mishra, A. K. and V. P. Singh (2010). A review of drought concepts. *Journal of Hydrology 391*, 202–216.

Modarres, R. (2007). Streamflow drought time series forecasting. *Stochastic Environmental Research and Risk Assessment 21*(3), 223–233.

MUGV (2013). Ministry of Environment, Health and Consumer Protection of Brandenburg, Geo Informations: http:// www.mugv. brandenburg.de.

Österle, H., P.-C. Werner, and F.-W. Gerstengarbe (2006). Qualitätsprüfung, Ergänzung und Homogenisierung der täglichen Datenreihen in Deutschland, 1951-2003: ein neuer Datensatz (engl.: quality checking, gap filling and homogenizing of daily data in Germany, 1951-2003: a new data set). 7. Deutsche Klimatagung, 9. - 11. Oktober 2006, Münich, Germany. http:// www.meteo.physik.uni-muenchen.de/ dkt/ poster.htmll.

Patil, S. and M. Stieglitz (2011). Hydrologic similarity among catchments under variable flow conditions. *Hydrology and Earth System Sciences 15*(3), 989–997.

Piechota, T. C. and J. A. Dracup (1996). Drought and regional hydrologic variation in the United States: Associations with the El Nino Southern Oscillation. *Water Resources Research 32*(5), 1359–1373.

Risley, J., H. Moradkhani, L. Hay, and S. Markstrom (2011). Statistical Comparisons of Watershed-Scale Response to Climate Change in Selected Basins across the United States. *Earth Interactions 15*, 1–26.

Samsudin, R., P. Saad, and A. Shabri (2011). River flow time series using least squares support vector machines. *Hydrology and Earth System Sciences 15*(6), 1835–1852.

Sawicz, K., T. Wagener, M. Sivapalan, P. A. Troch, and G. Carrillo (2011). Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences 15*(9), 2895–2911.

Singh, R., T. Wagener, K. van Werkhoven, M. E. Mann, and R. Crane (2011). A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate - accounting for changing watershed behavior. *Hydrology and Earth System Sciences 15*, 3591–3603.

Sivapalan, M., M. A. Yaeger, C. J. Harman, X. Y. Xu, and P. A. Troch (2011). Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. *Water Resources Research 47*, W02522.

Smakhtin, V. U. (2001). Low flow hydrology: a review. *Journal of Hydrology 240*(3-4), 147–186.

Stahl, K., H. Hisdal, J. Hannaford, L. M. Tallaksen, H. A. J. van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jodar (2010). Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences 14*(12), 2367–2382.

State Office for Mining, Geology and Raw Material of Brandenburg (2012). Hydrogeologic Map of Brandenburg: http://www.geo.brandenburg.de/ hyk50si.

Staudinger, M., K. Stahl, J. Seibert, M. P. Clark, and L. M. Tallaksen (2011). Comparison of hydrological model structures based on recession and low flow simulations. *Hydrology and Earth System Sciences 15*(11), 3447–3459.

Thomas, B., G. Lischeid, J. Steidl, and R. Dannowski (2012). Regional catchment classification with respect to low flow risk in a Pleistocene landscape. *Journal of Hydrology 475*, 392–402.

Tootle, G. A., A. K. Singh, T. C. Piechota, and I. Farnham (2007). Long lead-time forecasting of US streamflow using partial least squares regression. *Journal of Hydrologic Engineering 12*(5), 442–451.

Turc, L. (1961). Evaluation des besoins en eau d'irrigation, Evapotranspiration potentielle. *Ann. Agron. Paris 12*, 13–49.

Van Loon, A. F. and H. A. J. Van Lanen (2012). A process-based typology of hydrological drought. *Hydrology and Earth System Sciences 16*(7), 1915–1946.

Vapnik, V. (1995). *The Nature of Statistical Learning Theory.* Springer, New York.

Vidal, J. P., E. Martin, L. Franchisteguy, F. Habets, J. M. Soubeyroux, M. Blanchard, and M. Baillon (2010). Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite. *Hydrology and Earth System Sciences 14*(3), 459–478.

Wagener, T., M. Sivapalan, P. Troch, and R. Woods (2007). Catchment Classification and Hydrologic Similarity. *Geography Compass 1*(4), 901–931.

Wechsung, F., V. Krysanova, M. Flechsig, and S. Schaphoff (2000). May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? *Landscape and Urban Planning 51*(2-4), 177–189.

Wegehenkel, M. and K. C. Kersebaum (2008). A first assessment of the impact of climate change on discharge and groundwater recharge in a catchment in Northeastern Germany. *Journal of Agrometeorology 10*, 274–281.

Wegehenkel, M. and K. C. Kersebaum (2009). An assessment of the impact of climate change on evapotranspiration, groundwater recharge, and low-flow conditions in a mesoscale catchment in Northeast Germany. *Journal of Plant Nutrition and Soil Science 172*(6), 737–744.

Wendling, U. and J. Müller (1984). Entwicklung eines Verfahrens zur rechnerischen Abschätzung der Verdunstung im Winter (engl.: development of a meathod to calculate evapotranspiration during winter). *Zeitschrift für Meteorologie 34*, 82–85.

6 Synthesis

The research described in Chapter 2 to 5 had the overall aim of analyzing catchment similarity, first-order controls and time scales concerning low flows in order to determine appropriate adaption measures to sustain minimum runoff in small catchments of Brandenburg, Germany. In addition to the results of the single chapters, this chapter synthesizes the results and answers the guiding questions.

6.1 Regional low flow patterns

On the one hand, low flow is a seasonal phenomenon and a result of the annual cycle of precipitation, temperature and evapotranspiration. Two low flow regimes can be found in the mid-latitudes (Gudmundsson et al., 2011b; Laaha and Blöschl, 2006). In northern Europe and the Alps low flow mainly occurs during winter and is determined by snow storage. The other regions show low flows during the summer and autumn months due to higher evaporation demand during the growing season. In Brandenburg the second low flow regime is predominant at all rivers. On the other hand, low flow anomalies and occurrences of streamflow droughts are of particular interest for water management and environmental protection. Small catchments of Brandenburg were compared regarding low flow from a seasonal perspective and its anomalies (Chapter 4 and Chapter 5). Additionally, both chapters investigate the interplay between meteorological forcings and low flow patterns. Catchment properties (climate, land use, soil, water balance, area and geohydrology) were correlated with spatial patterns in order to build hypotheses on governing processes and the first-order controls on low flows. Chapter 4 focuses on spatial patterns whereas Chapter 5 concentrates on temporal anomalies and their explanation by meteorological predictors.

In both studies the contributing catchment areas were unknown. Data were z-normalized or standardized, which allowed analysis of all catchments in one dataset without calculating areal discharge yields. As a consequence, no absolute values but dynamics were analyzed.

6.1.1 Which first-order controls on low flows and related time scales exist? (guiding question 1)

57% of the variance in discharge was explained by the mean discharge behavior of all analyzed catchments (Chapter 4). The mean discharge behavior describes the main temporal variance in the data set. Remaining principal components (PCs) describe differences between catchments, i.e. the spatial variance (43% of total variance). Part of the spatial variance could be explained by two meteorological patterns (21% of spatial variance) and two geohydrologic patterns (15% of spatial variance). The second meteorological and second geohydrologic pattern explained regional low flow patterns. Catchments with a more continental climate in the east and those located east of Berlin (specific geohydrology of this moraine plateau) showed a more pronounced annual cycle with lower flows during late summer and a pronounced low flow period, respectively. Autocorrelation in discharge was higher for the more eastern catchments, and thus base flow is assumed to be more important there. According to the explained variance, the meteorological pattern is slightly more important than the geohydrologic one. The meteorological patterns fit to those found on the European scale (Gudmundsson et al., 2011b; Bordi et al., 2009), but the geohydrologic pattern is due to the unique geohydrology east of Berlin. There is a demand for more sophisticated understanding of the relation between weather patterns and low flows for the studied region. This thesis closes the gap between global or continental studies (e.g. Gudmundsson et al., 2011b; Stahl et al., 2012), where catchment similarity is mainly explained by climate forcing, and studies on small catchment (e.g. Lischeid et al., 2010; Tetzlaff et al., 2011), where landscape and geohydrology are more important to explain patterns.

Chapter 5 focuses on low flow anomalies and meteorological predictors. The potential evapotranspiration sum of the previous 48 months was the most important low flow predictor (AM_{30}, lowest annual 30-day mean flow). Thus, potential evapotranspiration was more important to describe ground water recharge and subsequently baseflow than precipitation. Actual and potential evapotranspiration can differ largely, but the potential evapotranspiration sum of 48 and 3 months was important to explain low flow dynamics. Other studies showed that considering potential evapotranspiration improves drought forecasting, and depending on catchment, it can be more important than precipitation (Vicente-Serrano et al., 2012; Demirel et al., 2012). Risley et al. (2011) showed for catchments all over North America that if the index of dryness (potential evapotranspiration to precipitation ratio) increases, mostly actual evapotranspiration increases, too. In contrast, Conradt et al. (2012) could not find a correlation between monthly area-averaged potential and actual evapotranspiration. Both studies used hydrologic models to calculate the actual evapotranspiration. Short-term (3-monthly) evapotranspiration and precipitation were of minor importance but improved prediction. First-order controls on low flow were not stable over time (Figure 5.5). The long term evapotranspiration was not able to explain AM_{30}s in 15-year windows after 1990. The predictive power of precipitation variables increased slightly during the studied period. These results show that the important temporal scales can change with length of observation and state of the catchment. The long term evapotranspiration especially explained the decrease of low flows around 1990. It described dynamics during 15-year windows well during relatively wet years, but failed at explaining the dynamics during relatively dry periods after 1990. Consequently, the long-term potential evapotranspiration is suitable to describe the long term memory of the groundwater, but other predictors are needed to describe low flow dynamics on shorter time scales.

The combination of Chapter 4 and 5 allows further conclusions beyond those already mentioned. AM_{30}s were modelled with better accuracy in catchments with more damping (geohydrologic pattern) and with lower mean yield (Table 5.4). Damping increases with a more continental climate and according to geohydrology (see autocorelation and power spectrum in Figure 4.4). According to the geohydrologic pattern, damping increases with forest cover and depth to the groundwater table (Table 4.3). In conclusion, the low flow predictors found as well as associated time scales are appropriate to describe low flow dynamics in catchments with higher damping, which is due to a larger vadose zone or less seepage by higher evapotranspiration of forest or less precipitation input. Correlations are rather low, and more research is needed to specify the relationship of damping of discharge with storage and release from the vadose zone, the active groundwater storage, land cover, and meteorological forcing.

Lischeid et al. (2010, 2012) show that the vadose zone serves as a low-pass filter regarding the precipitation input. The damping in groundwater table time-series was mainly explained by the depth of the vadose zone. Damping also explained trends at the respective groundwater gauges. This thesis shows the importance of this concept, which has been applied to groundwater tables, to understand patterns of streamflow on the regional scale (Chapter 4).

Low flow risk is due to the superposition of two discharge patterns resulting in stronger decrease of flows during summer and a prolonged low flow period (Chapter 4). Model residuals suggest that for some catchments AM_{30}s are significantly lower or higher in average (Chapter 5). However, no correlation between these two patterns was found. Mean residuals only correlate with surface catchment area but PCs associated to low flow risk do not. Several authors already pointed out that catchment properties can only describe runoff behavior to a limited extent (Ley et al., 2011; Deckers et al., 2010; Laaha and Blöschl, 2005). To understand processes, the incorporation of catchment properties is one important step, but this is not mandatory for catchment classification regarding water management issues.

The results of both studies support the hypothesis that climatic conditions are mainly responsible for changes in low flows. (i) The 2^{nd} principal component (Chapter 5) was explained by a climate pattern which is also found in studies on the European scale (Gudmundsson et al., 2011b; Bordi et al., 2009) and was described as zonal structure of atmospheric circulation. This pattern is partly explaining the direction and significance of the discharge trends of the different catchments (Table 4.3). (ii) Patterns correlating with land use were not able to explain streamflow trends. This would have served as a space-for-time analogy. Land use changes strongly impact catchment discharge (Nathkin et al., 2012, Chapter 2), but for the catchments and time period analyzed, climatic change seems to be the first-order control. On the one hand, changes in land use could explain part of the trend in the first principal component if all catchments were affected. On the other hand, land use change could be reflected in higher ranked principal components, which were not analyzed in this regional study, if only single catchments were affected. No data on changes in land use was available. The correlation between forest cover, agricultural land use cover and the meteorological pattern can be due to co-evolution of land use and climatic gradient as found in other studies (Brooks et al., 2011). (iii) 46 % of the variability in AM_{30} could be explained by meteorological predictors (Chapter 5). The decrease in AM_{30} around 1990 was mainly explained by long-term potential evapotranspiration (Figure 5.4).

Involved time scales are estimated to be very long because the potential evapotranspiration of the previous 48 months was the most important low flow predictor (Chapter 5). This predictor describes the long-term memory of the groundwater storage. This process is superimposed by processes on shorter time scales as indicated by the other predictors, the potential evapotranspiration and precipitation of the previous 3 months. Demirel et al. (2012) optimized lag times and temporal aggregation of precipitation, potential evapotranspiration and groundwater storage in order to predict low flows of sub-catchments of the river Rhine. They did not investigate time scales larger than one year. Regarding potential evapotranspiration, they obtained a spatial aggregation of more than half a year and about 200 days lag time to predict low flow (7-day flow with 90 days lead time) in non-alpine subcatchments of the river Rhine. Potential evapotranspiration of about 2–3 months and nearly no lag time was the best predictor for reduced lead time (14 days) and temporal aggregation (3 days) of streamflow. Lorenzo-Lacruz et al. (2010) show that standardized precipitation evapotranspiration indices (SPEI, precipitation minus potential evapotranspiration) were able to describe reservoir inflow, storage and outflow. The aggregation lengths found increased distinctly with the storage process (8, 33 and 48 months, respectively). The results are only partly comparable because catchment sizes and landscape differ.

6.1.2 Which are the differences between small catchments regarding low flow vulnerability? (guiding question 2)

Trend analysis and hydrologic modeling using climate change scenarios assume further decrease of runoff and low flows for the next decades (Milly et al., 2005; Wegehenkel and Kersebaum, 2009; Conradt et al., 2012; Menzel and Burger, 2002). Uncertainties in model chains, greenhouse gas emission scenarios and future development of trends hinder a precise estimation of runoff changes. As a consequence, the vulnerability of catchments to climate forcing becomes important to identify those rivers which are affected first and more distinctly. Temperature and consequently potential evapotranspiration are projected to increase in Brandenburg (IPCC, 2007). Annual precipitation is not projected to change substantially, but more precipitation is expected during winter and less during summer months. Catchments where low flows are explained more by evapotranspiration are expected to be more vulnerable. Singh et al. (2011) state that dryer watersheds will be more vulnerable to climate change. The results of the thesis cannot verify this hypotheses. The predictive power of the predictor based on 3-monthly precipitation correlates negatively with mean annual and summer precipitation (Table 5.4) and the predictive power became more important in the last decades when low flows have decreased (Figure 5.5). This suggests that vulnerability of dryer watersheds is related to changes in precipitation which are more uncertain than those of Temperature (and subsequently potential evapotranspiration).

Low flows decreased for most of the catchments (Chapter 5, Figure 5.4). The more pronounced runoff decrease in the south-east of Brandenburg, explained by a meteorological pattern (Chapter 4), shows the higher low flow vulnerability of respective catchments. There are no studies known to the author which describe future changes in the corresponding meteorological pattern. It is also expected that catchments with a high low flow risk (Chapter 4) are more vulnerable to climate change. Low flows in some of those catchments were very low (sometimes even drying of the rivers occurred) during the last decades (Ramelow et al., 2012). This shows that in addition to meteorological patterns, geohydrologic patterns are important to explain local differences in vulnerability. The explanatory power of potential evapotranspiration differs between catchments (Chapter 5, Figure 5.6). Especially for those catchments where long-term potential evapotranspiration explains low flows better, the highest decrease in low flows can be expected. Catchments No. 7, 13 and 14 in Chapter 5 are located east of Berlin in the region with high low flow risk. For catchments 14 and 7 the explanatory power regarding low flows of long term evapotranspiration was highest. In addition to catchments with a high low flow risk, the catchments where potential evapotranspiration explained low flows better have a high vulnerability to climate change. According to the correlations found, these are catchments with positive loadings on a discharge pattern (Chapter 5) describing the damping of discharge caused by geohydrology (Table 5.4). Again, this shows the importance of concept of damping to explain spatial patterns as described before (section 6.1.1).

6.2 Conclusions on adaption measures

In Chapter 2 a qualitative assessment of measures to sustain minimum runoff is given (Table 2.1 and 2.3). Potential adaption measures to sustain minimum runoff during periods of low flows can be classified into three categories: (i) increase of groundwater recharge and subsequent baseflow by land use change, land management and artificial ground water recharge, (ii) increase of water storage with regulated outflow by reservoirs, lakes and wetland water management and (iii) consideration of regional low flow patterns during planning of measures with multiple purposes (urban water management, waste water recycling and inter-basin water transfer). The duration from implementation to the time when measures become effective differs widely. Some of the measures become effective directly, but others, like land use change, can take several decades. In this section conclusions on which of the reviewed measures are appropriate, based on the research on catchment similarity and the first-order controls (Chapter 4 and 5), are provided.

6.2.1 Which adaption measures to sustain minimum runoff in small catchments of Brandenburg are appropriate considering regional low flow patterns? (guiding question 3)

Research on adaption measures to increase minimum runoff is an interdisciplinary or transdisciplinary task. Only conclusions from a regional hydrologic perspective are provided here. This thesis intends to provide the hydrologic background for research in the fields of water management, ecology, socio-economy and others.

Measures increasing groundwater recharge and subsequently baseflow require relatively deep groundwater levels and have to be situated at the recharge areas away from the streams in order to increase potential storage volume and avoid evapotranspiration. Recharge measures have to be located in areas of the catchment where they assure a rise in groundwater heads that is still effective during late summer. As an adverse example, management scenarios of a ditch irrigation system regarding the interaction of groundwater and streamflow during low flows were analyzed (Chapter 3). It was concluded that for an effective sustainment of minimum runoff (i) no water should be directed to the ditches during low flows, (ii) initial water levels in the ditch system should be as high as possible, (iii) numerous of such measures would be needed to considerably increase streamflow in a meso-scale catchment, and (iv) increasing water levels (resulting in higher fluxes to the stream during low flows) is likely to conflict with current land use.

Reservoirs should be dimensioned in a way that as little water as possible is lost by evaporation or seepage and water is still be available when flows are lower than minimum discharge. Deeper reservoirs are probably not feasible because of the low gradients in the landscape. The use of existing structures (e.g. former fishing lakes) is beneficial because no new sites have to be acquired. But the effectiveness to sustain minimum runoff can be lower or objectives can even exclude each other if a measure has several tasks (Chapter 3).

Section 6.1.2 already discusses in which catchments adaption measures are needed first and low flow risk is high. Catchments with a higher low flow risk also have relatively deep groundwater tables. Catchments with a high low flow risk according to the 5$^{\text{th}}$ principal component (Chapter 4) are exposed to lower flows during summer but higher flows during winter months compared to other catchments. Measures increasing groundwater recharge are recommended for these catchments (Figure 4.6). Groundwater levels are relatively low and low flows during summer are due to a stronger decrease in baseflow. The establishment of recharge basins is recommended in the near future, but water probably needs to be pumped to the recharge areas at higher altitudes. In the long run, conversion of coniferous to deciduous forest and land management favouring groundwater recharge should be considered. At catchments with a higher low flow risk, according to the 3$^{\text{rd}}$ principal component, recession during summer months lasts longer, autocorrelation of runoff is higher and the power spectrum shows a damping of higher frequencies in the runoff time-series. No correlation between depth to the groundwater table was found for this component. It has to be decided ad hoc if groundwater recharge is feasible. If this is not the case, the construction or restoration of reservoirs is recommended. For catchments with increased low flow risk according to the 3$^{\text{rd}}$ principal component, the low flow period is not as prolonged as for those catchments with high low flow risk according to the 5$^{\text{th}}$ (Figure 4.4). The required storage volume of reservoirs or in the underground is lower in these catchments. Water storage in smaller decentralized measures as lakes or wetland water management can be promising for such catchments, too.

Long term potential evapotranspiration was the most important predictor to describe the decrease of low flows during the last decades (Chapter 5). It shows that changes in groundwater recharge due to increased evapotranspiration were the main cause for decreasing low flows in the past. For catchments with a high low flow risk the explanatory power of long-term potential evapotranspiration is high (Chapter 4). This indicates that in those catchments groundwater recharge is largely controlled by evapotranspiration processes from the vadose zone. Measures increasing groundwater recharge, especially those reducing evapotranspiration, are recommended for those catchments. Adaption measures are necessary because low flows are expected to stay low or decrease even further (guiding question 2, section 6.1.2).

Ground water recharge stabilizes the seasonal low flow dynamics but cannot be used for the regulation of flows according to water demand and defined minimum runoff. Water storage with regulated outflow would be the first adaption measure in this case. Inter-basin water transfer will only be necessary if anthropogenic impacts on a catchment require a large volume of surplus water which cannot be guaranteed by other measures. One example are streams in Brandenburg affected by the groundwater deficit caused by lignite mining (Pusch and Hoffmann, 2000; Koch et al., 2005). The use of cleaned waste water and water management of settlements do not only aim at sustaining minimum runoff. Instead, the sustainment of minimum runoff must be part of an integrated planning and management of these measures. A detailed assessment is needed to ensure that measures are harmless to the environment and health and measures are accepted by the population (MUGV, 2010). Appropriate institutional structures are necessary to increase the capacity to adapt to climate change (Miller et al., 1997; Ivey et al., 2004). An example on appropriate adaption options for the Canadian water sector is given by de Loe et al. (2001). They demonstrate how stakeholder interests and adaption measures can be merged. The results of this thesis provide the hydrologic background for a similar compilation of adaption measures for Northeast Germany.

6.3 Regionalization and extrapolation

No analyses on regionalization of the patterns found in this thesis have been carried out and only qualitative statements are given here. First, we have to distinguish between meteorological and geohydrologic patterns (Chapter 4). The two meteorological patterns have a distinct spatial gradient which is also found in other studies (Gudmundsson et al., 2011b). The gradients found can be used for regionalization. Geohydrologic patterns did not show spatial gradients. Correlations with catchment properties were relatively low. The mean depth to the groundwater table was the only catchment property correlating with geohydrologic patterns. Uncertainties of a regionalization based on this variable are estimated to be high.

The mean depth to the groundwater table and mean summer potential evapotranspiration correlate with the explanatory power of the long-term potential evapotranspiration (Chapter 5). In areas where these two variables are high, the long-term potential evapotranspiration is useful as low flow indicator. The regression model did not fail at any catchment and performance was higher than $r^2 = 0.4$ for all analyzed catchments (Chapter 5, Figure 5.6). As long as anthropogenic impacts are moderate and catchment properties are within the range of those analyzed (Table 5.3), low flow predictors are expected to be applicable.

Extrapolation of the results to future behavior is only valid in a very narrow range because results of the statistical analyses are based on observed behavior of the past only. Unexpected behavior (black swans) is a specific source of uncertainty. In the context of the thesis, this could be major changes in the hydrologic systems like the decoupling of groundwater from a stream with abrupt changes in runoff behavior (see e.g. Kinal and Stoneman, 2012). Such changes are beyond the scope of the thesis and must be subject to further studies. Additionally, low flows are expected to remain low in the future (Chapter 5). This hypothesis is based on climate projections estimating only minor changes in precipitation amounts compared to potential evapotranspiration.

Models have been used to estimate discharge and other variables of the hydrologic cycle in Brandenburg (e.g. Conradt et al., 2012; Wechsung et al., 2000). In contrast to models, the statistical analyses used in this thesis have the advantage that no assumptions on the involved processes have been made. Models can use the results from this thesis for validation because temporal as well as spatial patterns which were found in the data should be reproduced by a valid model. Particularly, this is the difference in the direction of discharge trends between catchments in the north-west and south-east, the difference in damping behavior of catchments and the more specific discharge of the moraine plateau east of Berlin (Chapter 4) as well as the distinct decrease in low flows around 1990 described by increasing long-term potential evapotranspiration (Chapter 5). This would be a crucial step to test our theories and advance in the field of hydrology in the way claimed by Kirchner (2006).

6.4 Future research needs

Based on the results of the thesis, there is a need of further research on groundwater recharge dynamics and adaption strategies for small catchments of the mid-latitudes. Even though research on groundwater recharge has been carried out for decades, it has to be understood under which states of the system, depending on the history of precipitation, evapotranspiration as well as morphology, soils, vegetation and others, water from a rain event is recharged. Especially, the inclusion of remote sensing data (soil moisture, vegetation and precipitation) is expected to increase knowledge on spatial patterns.

As already pointed out in section 6.1.1 and 6.1.2, research on the causes of damping of discharge is promising. The contribution of meteorology, storage and release from the vadose zone (especially the part accessible to evapotranspiration), deep seepage in the vadose zone and memory of the active groundwater storage to damping has to be understood for different spatial scales. This will help to build valid models considering the governing processes at the scale they are applied to.

Potential evapotranspiration aggregates were useful as low flow predictors, even though the precise understanding on the processes and temporal dynamics remained unknown. More detailed analyses on the relationship between precipitation, potential evapotranspiration, actual evapotranspiration and subsequently low flows is needed in order to generate smarter low flow indicators.

In a cultural landscape like Brandenburg natural processes are superimposed by anthropogenic influences of land use change and water management. Further studies have to include these impacts and evaluate them regarding adaption measures to sustain minimum runoff. Furthermore, existing water management has to be evaluated and water allocation rules have to be adapted to the low flow patterns found in this thesis. Research on adaption measures and strategies in small catchments of the mid-latitudes has to be interdisciplinary and transdisciplinary. In a next step, the socio-economic framework has to be intersected with the hydrologic findings.

6.5 Conclusion

This thesis determines appropriate adaption measures to sustain minimum runoff in small catchments of Brandenburg, Germany, based on (i) catchment similarity during periods of low flows and (ii) the first-order controls on low flows. This thesis advances knowledge in the field of statistical data analysis in order to compare meso-scale catchments in hydrologicly complex landscapes. Surface and subsurface catchments can differ in this landscape. The used methods analyze dynamics rather than absolute values enabling the comparison of catchments without information on the subsurface catchment area. Moreover, results from the statistical analyses are used to determine appropriate adaption measures.

For most analyzed catchments, runoff (between 1991–2006) and low flows (measured as annual 30-day minima, between earliest 1965 and 2006, depending on catchment) decreased. In the south-east of Brandenburg catchments showed a stronger decrease in runoff. The distinct decrease in low flows for most catchments around 1990 was described best by the simultaneous increase in long term potential evapotranspiration.

Discharge decreased faster during the summer months and the low flow season was prolonged in catchments east of Berlin. Consequently, these were the catchments with highest low flow risk and consequently high vulnerability to climate change. It was proven that this was due to the more continental climate and specific geohydrology of this moraine plateau at these catchments.

Long time scales were more important to explain the overall development in low flows. The potential evapotranspiration sum of the previous 48 months was found to be the most important meteorological low flow predictor. This predictor was probably suited best to describe the memory of the catchments. Consequently, evapotranspiration was the first-order control on groundwater recharge and subsequently low flows on this time-scale (1995–2006). This variable was more important to explain low flows in catchments with a high low flow risk. The potential evapotranspiration and precipitation of the previous 3 months were additionally useful to predict low flows on shorter time-scales. The first-order controls on low flows identified support the assumption that low flows will stay low or decrease even further because potential evapotranspiration is projected to increase during climate change. Low flow predictors could describe the low flow dynamics more accurately in catchments with a more dampened discharge and low mean yield.

In combination, the results suggest that catchments east of Berlin with a high low flow risk and in the south-east showing a stronger decrease in runoff should be considered first regarding adaption measures to sustain minimum runoff. Measures increasing groundwater recharge are required to counteract falling groundwater heads and stabilize low flows during the summer month. Recharge has to take place at the recharge areas on higher altitudes away from the streams. In the short term recharge basins are recommended, but forest conversion to mixed or deciduous forests and land management increasing groundwater recharge have to be implemented in the long term. Water reservoirs are additionally useful if groundwater recharge is not feasible (e.g. conflicting with land use or environmental protection), and water demand requires a more precise regulation of streamflow and mitigation of extreme low flow events. The results of this thesis have to be considered in integrated planning and management of measures which do not only aim at sustaining minimum runoff (e.g. waste water management and community water management). Inter-basin transfer of water is only preferable if catchments are largely impacted by anthropogenic activities and water demand is extremely high like in the Lower Lusatian lignite mining district.

The results can serve as one additional source to validate regional hydrologic and catchment models. The different damping behavior of catchments, the specific discharge at the moraine plateau east of Berlin, the differences in discharge trends and the pronounced decrease in low flows around 1990 seems to be appropriate to test the validity of models and consequently advance the hydrologic theories.

References

Bordi, I., K. Fraedrich, and A. Sutera (2009). Observed drought and wetness trends in Europe: an update. *Hydrology and Earth System Sciences 13*(8), 1519–1530.

Brooks, P., P. Troch, M. Durcik, E. Gallo, and M. Schlegel (2011). Quantifying regional scale ecosystem response to changes in precipitation: Not all rain is created equal. *Water Resources Research 47*, W00J08.

Conradt, T., H. Koch, F. Hattermann, and F. Wechsung (2012). Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change 12*(3), 633–648.

de Loe, R., R. Kreutzwiser, and L. Moraru (2001). Adaption Options for the near term: climate change and the Canadian water sector. *Global Environmental Change 11*, 231–245.

Deckers, D. L. E. H., M. J. Booij, T. M. Rientjes, and M. S. Krol (2010). Catchment Variability and Parameter Estimation in Multi-Objective Regionalisation of a Rainfall-Runoff Model. *Water Resources Management 24*(14), 3961–3985.

Demirel, M., M. J. Booij, and A. Hoekstra (2012). Identification of appropriate lags and temporal resolutions for low flow indicators in the River Rhine to forecast low flows with different lead times. *Hydrological Processes published online*, DOI: 10.1002/hyp.9402.

Gudmundsson, L., L. M. Tallaksen, K. Stahl, and A. K. Fleig (2011b). Low-frequency variability of European runoff. *Hydrology and Earth System Sciences 15*(9), 2853–2869.

IPCC (2007). Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC.

Ivey, J. L., J. Smithers, R. C. De Loe, and R. D. Kreutzwiser (2004). Community capacity for adaptation to climate-induced water shortages: Linking institutional complexity and local actors. *Environmental Management 33*(1), 36–47.

Kinal, J. and G. Stoneman (2012). Disconnection of groundwater from surface water causes a fundamental change in hydrology in a forested catchment in south-western Australia. *Journal of Hydrology 472-473*, 14–24.

Kirchner, J. W. (2006). Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research 42*, W03S04.

Koch, H., M. Kaltofen, U. Grunewald, F. Messner, M. Karkuschke, O. Zwirner, and M. Schramm (2005). Scenarios of water resources management in the Lower Lusatian mining district, Germany. *Ecological Engineering 24*(1-2), 49–57.

Laaha, G. and G. Blöschl (2005). Low flow estimates from short stream flow records - a comparison of methods. *Journal of Hydrology 306*(1-4), 264–286.

Laaha, G. and G. Blöschl (2006). Seasonality indices for regionalizing low flows. *Hydrological Processes 20*, 3851–3878.

Ley, R., M. C. Casper, H. Hellebrand, and R. Merz (2011). Catchment classification by runoff behaviour with self-organizing maps (SOM). *Hydrology and Earth System Sciences 15*(9), 2947–2962.

Lischeid, G., M. Natkhin, J. Steidl, O. Dietrich, R. Dannowski, and C. Merz (2010). Assessing coupling between lakes and layered aquifers in a complex Pleistocene landscape based on water level dynamics. *Advances in Water Resources 33*(11), 1331–1339.

Lischeid, G., J. Steidl, and C. Merz (2012). Functional versus trend analysis to assess anthropogenic impacts on groundwater heads. *Grundwasser 17*(2), 79–89.

Lorenzo-Lacruz, J., S. M. Vicente-Serrano, J. I. Lopez-Moreno, S. Begueria, J. Garcia-Ruiz, and J. Cuadrat (2010). The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *Journal of Hydology 386*, 13–26.

Menzel, L. and G. Burger (2002). Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *Journal of Hydrology 267*(1-2), 53–64.

Miller, K. A., S. L. Rhodes, and L. J. Macdonnell (1997). Water allocation in a changing climate: Institutions and adaptation. *Climatic Change 35*(2), 157–177.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature 438*(7066), 347–350.

MUGV (2010). Ministry of Environment, Health and Consumer Protection of the Federal State of Brandenburg. Positionpapier Verwendung von Gereinigtem Abwasser für Maßnahmen zur Statbilisierung des Landschaftswasserhaushalts (engl.: Position Papter Use of Cleaneed Wastewater for Measures to Stabilize the Landscape Water Balance). http:// www.mugv. brandenburg.de/ cms/ detail.php/ bb1.c.291832.de? highlight= positionspapier.

Nathkin, M., J. Steidl, O. Dietrich, R. Dannowski, and G. Lischeid (2012). Differentiating between climate effects and forest growth dynamics effects on decreasing groundwater recharge in a lowland region of Notheast Germany. *Journal of Hydology 448-449*, 245–254.

Pusch, M. and A. Hoffmann (2000). Conservation concept for a river ecosystem (River Spree, Germany) impacted by flow abstraction in a large post-mining area. *Landscape and Urban Planning 51*(2-4), 165–176.

Ramelow, M., S. Böttcher, R. Dannowski, C. Merz, J. Steidl, and B. Thomas (2012). Bausteine eines Transdisziplinären Konzeptes zur Stabilisierung der Abflussverhältnisse am Fredersdorfer Mühlenfließ (Brandenburg) (engl.: Parts of a transdisciplinary concept to stabilize runoff at the Fredersdorfer Mühlenfließ, Brandenburg, Germany). In U. Grünewald, O. Bens, H. Fischer, R. F. Hüttl, K. Kaiser, and A. Knierim (Eds.), *Wasserbezogene Anpassungsmaßnahmen an den Landschafts- und Klimawandel (engl.: water related adaption measures for the landscape and climate change)*, pp. 258–265. Schweizerbart, Stuttgard, Germany.

Risley, J., H. Moradkhani, L. Hay, and S. Markstrom (2011). Statistical Comparisons of Watershed-Scale Response to Climate Change in Selected Basins across the United States. *Earth Interactions 15*, 1–26.

Singh, R., T. Wagener, K. van Werkhoven, M. E. Mann, and R. Crane (2011). A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate - accounting for changing watershed behavior. *Hydrology and Earth System Sciences 15*, 3591–3603.

Stahl, K., L. M. Tallaksen, J. Hannaford, and H. A. J. van Lanen (2012). Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. *Hydrology and Earth System Sciences 16*, 2035–2047.

Tetzlaff, D., C. Soulsby, M. Hrachowitz, and M. Speed (2011). Relative influence of upland and lowland headwaters on the isotope hydrology and transit times of larger catchments. *Journal of Hydrology 400*(3-4), 438–447.

Vicente-Serrano, S. M., S. Begueria, J. Lorenzo-Lacruz, J. J. Camarero, J. I. Lopez-Moreno, C. Azorin-Molina, J. Revuelto, E. Moran-Tejeda, and A. Sanchez-Lorenzo (2012). Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications. *Earth Interactions 16*.

Wechsung, F., V. Krysanova, M. Flechsig, and S. Schaphoff (2000). May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? *Landscape and Urban Planning 51*(2-4), 177–189.

Wegehenkel, M. and K. C. Kersebaum (2009). An assessment of the impact of climate change on evapotranspiration, groundwater recharge, and low-flow conditions in a mesoscale catchment in Northeast Germany. *Journal of Plant Nutrition and Soil Science 172*(6), 737–744.

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Author's declaration

I prepared this dissertation myself and without illegal assistance. The work is original except where indicated by references in the text and no part of the dissertation has been submitted for any other degree.

This dissertation has not been presented to any other university for examination, neither in Germany nor in any other country.

Berlin, June 23$^{\text{rd}}$, 2013

(Björn Daniel Thomas)