Chapter 1

General introduction
1.1 Climate change impacts on the hydrological cycle

Climate change is predicted to lead to an increase of global temperature and to changes in the global water cycle. The Intergovernmental Panel on Climate Change (IPCC) developed six climate projections and associated storylines which range from very rapid economic growth and introduction of new and more (resource-efficient) technologies (A1F1, A1T, A1B, B1) to slow and fragmented economic growth and (diverse) technological changes (A2, B2). The associated likely global temperature increase ranges from 1.1°C to 6.4°C in 2090-2099, compared to 1980-1999 (IPCC 2007; 4th assessment report). The likely temperature increase in 2050 ranges from 0.4°C to 2.6 °C in 2050, compared to 1990 (IPCC 2013). Associated changes in the global hydrological cycle include an increase in mean annual precipitation in the tropics and high latitudes and a decrease in the subtropics (Alexander et al. 2006). Also seasonal precipitation patterns are likely to change. It is projected that the duration of dry periods will increase and that these will be alternated with more extreme rainfall events, even in regions where the mean precipitation will decrease (Alexander et al. 2006, Rajczak et al. 2013). Furthermore, decreases in summer precipitation are likely to co-occur with increased autumn, winter and spring precipitation (Rajczak et al. 2013, van Haren et al. 2013, Vautard et al. 2014). In seasonal climates, all these changes can lead to an increased flooding risk in spring, due to an increase in soil surface saturation and associated surface run-off, and increased rates of groundwater discharge in streams (Arnell and Gosling 2013, Rajczak et al. 2013). Additionally, summer droughts are also likely to occur more often, especially in combination with higher summer temperatures (Bakker and Bessembinder 2007, Briffa et al. 2009, Zolina et al. 2013). This temperature increase will also lead to an increase of potential evapotranspiration. Combined with less precipitation in summer, this may lead to lower groundwater tables and reduced groundwater discharge which amplifies the impacts of summer drought on groundwater dependent ecosystems (IPCC 2013). Summarizing, this means that water availability, water table fluctuations and groundwater discharge fluxes are likely to change severely.

The Royal Netherlands Meteorological Institute (KNMI) downscaled the IPCC projections for the Netherlands. The KNMI developed four climate change scenarios for the year 2050 (2036-2065), compared to 1990 (1976-2005). These scenarios are based on the global climate change scenarios (A1B, A2, B1) as developed by the IPCC (IPCC 2007). The Dutch scenarios differ from one another by the presumed global
temperature increase (1°C or 2°C) and by changes in air circulation patterns which means that eastern winds will prevail in summer, instead of western winds, increasing summer temperature and drought (van den Hurk et al. 2006). In 2009, the 2006 KNMI scenarios were updated according to new scientific findings (Klein Tank and Lenderink 2009). The KNMI concluded that a global temperature increase of 2°C is more likely than 1°C increase. Furthermore, the regional differences in extreme precipitation events are likely to increase. Also in the Netherlands, summer temperature and the intensity of summer rain events will increase, which increases both the risk of summer drought and of summer inundations (van den Hurk et al. 2006).

1.2 Plants and their need for water

The changes in climatic conditions and especially in the hydrological cycle are likely to affect plant communities. Plants are sessile organisms and therefore depend on the local environmental conditions to ensure their survival and reproduction success. As a result of spatiotemporal variation in environmental conditions, different plant communities occur at different sites or - upon changing conditions - over time. One of the most important environmental conditions that shapes vegetation communities is water availability (Silvertown et al. 1999, Weltzin et al. 2003, Wright et al. 2005a, Ordoñez et al. 2010a, Ordoñez et al. 2010b, Bartholomeus et al. 2011, Douma et al. 2012a, Douma et al. 2012b). Changes in the hydrological cycle are thus expected to have major impacts on plant community distributions. The hydrological conditions influence vegetation communities in three ways, through: (i) water availability, (ii) stability or fluctuations in water levels and (iii) water chemistry.

Water availability is an essential factor that determines plant survival and reproduction. Both water shortage and water surplus affect plant survival, where droughts hamper water uptake and thus photosynthesis. A surplus of water on the other hand can lead to anoxic soil conditions, depending on local soil properties, limiting oxygen availability to the roots and leads to reduced respiration and root activity and accumulation of toxic substances that are normally reduced under aerobic conditions (Blom and Voesenek 1996).

The fluctuation in water availability is also important in shaping vegetation communities as it requires a high degree of morphological and physiological plasticity to tolerate these fluctuations. The survival ability of plants under these
changing circumstances is not dependent on one plant organ but instead relies on the entire plant (Crawford 1996). Plant tolerance to these changing conditions differs among plant species. Changes in water level fluctuations thus lead to changes in species distribution and composition (Leyer 2005, Zou et al. 2014). Especially endangered plant species, which are already under threat, are sensitive to changes in water level fluctuations (Bartholomeus et al. 2011). Furthermore, plant species richness is higher around streams with intermittent flow, than at streams with ephemeral or perennial flow (Katz et al. 2012). Maintaining water level fluctuations is therefore important for the conservation of particular vegetation communities.

Also water chemistry, which is often very different for regional groundwater discharge than for local groundwater discharge and groundwater recharge, shapes plant species composition (Wassen et al. 1990a, Tahvanainen 2004, Lucassen et al. 2006, Marini et al. 2008, Kuglerová et al. 2014). Species richness is for example substantially higher at regional groundwater discharge sites than at groundwater recharge sites where rainwater influence is dominant (Wassen et al. 1990a, McNamara et al. 1992, Lucassen et al. 2006, Kuglerová et al. 2014). The differences in water chemistry between these sites contribute to the formation of the local abiotic conditions and thus to the occurrence of different vegetation communities.

1.3 Climate adaptation measures at a catchment scale

Climate change will likely affect all three abovementioned water conditions. To mitigate potential negative effects of changes in water availability, fluctuations and chemistry on vegetation patterns, climate adaptation measures can be implemented. In regions where shifts in precipitation over the year are expected, these measures can be used to store water in times of water surpluses and use that in times of drought. This can buffer expected changes in water availability, water table fluctuations and water chemistry (i.e. groundwater discharge fluxes).

In order to implement such measures successfully, it is essential to consider the entire catchment (Capon et al. 2013). That is, upstream measures to store water surpluses affect also the downstream area of the catchment. Adaptation measures may positively affect the conditions at one location, such as increased water availability, while decreasing or increasing water availability elsewhere, which can have a negative effect for that specific location. Especially when considering groundwater flow and groundwater discharge, which may connect locations over hundreds of meters to kilometres apart, a regional scale approach is essential for
correctly testing the suitability of climate adaptation measures. This PhD research focuses therefore on an entire catchment to ensure that all effects, upstream and downstream, are taken into account when implementing climate adaptation measures.

There are several adaptation strategies that can be implemented at the catchment scale, such as: (i) upstream storage in the subsurface of cover-sands and glacial ridges (Aquifer Storage and Recovery, ASR), (ii) headwater storage by placing dams that temporarily hold the water, (iii) decrease discharge capacity by stream re-meandering to increase resilience and allow downstream inundations (storage in stream) and (iv) increase of groundwater recharge through changes in vegetation or crops. Upstream storage is used to store water surplus and use that in times of drought. This measure is implemented at locations with a low groundwater table where (i) it does not lead to waterlogging, and (ii) there is a sufficient subsurface volume present to store the water. However, this approach can increase the groundwater discharge flux to elsewhere which needs to be taken into account when implementing this measure. Headwater storage is another option which especially increases water availability upstream. This obviously has consequences for the water availability downstream, which may decrease as a result. Stream re-meandering is implemented in streams which have been canalised in the past. Re-meandering increases the stream length and resilience which means that water is stored for a longer time in the stream. This increases water availability in the close proximity of the stream and increases the stream capacity to store water surpluses after heavy precipitation events. Finally, changes in land use (in vegetation type, or vegetation vs. agriculture) influences the local recharge. A pine forest for example has a higher evapotranspiration rate and intercepts more precipitation than a grassland, which decreases groundwater recharge and thus the groundwater table. Which of these measures is best applicable depends on the local and regional conditions of the catchment.

1.4 Stream valley catchments as a case study
Due to their dependence on precipitation and their high ecosystem diversity (Higler and Verdonschot 1993), stream valleys catchments are suitable model systems to evaluate the effects of climate adaptation measures at catchment scales. Streams discharges and groundwater tables in the catchment follow, albeit delayed, precipitation patterns and are thus influenced by it. Changes in precipitation
amounts and its spatiotemporal dynamics will therefore likely influence stream valley functioning. Furthermore, ecosystems that depend on precipitation as water source are most likely to be influenced by climate change compared to ecosystems that are not (Witte et al. 2012). Stream valley catchments, and especially riparian ecosystems (Capon et al. 2013), may thus require climate adaptation measures to ensure their current functioning in a future climate. Because of their diverse nature, they also provide a good example of how and where to implement climate adaptation measures.

Which of the aforementioned climate adaptation strategies are applicable, however, depends on the local and regional characteristics of the catchment. The focus of this research is therefore on a stream valley catchment in the Pleistocene part of Netherlands, where streams are mainly fed by rainwater. Undisturbed streams are meandering and have an asymmetric cross profile (Higler and Verdonschot 1993). This in turn provides a wide gradient of water availability, water level fluctuations, water chemistry (i.e. groundwater discharge or recharge) and soil properties across the catchment. As a consequence of this large variety of environmental gradients, stream valley catchments are generally species-rich environments (Grootjans et al. 2002) and worth protecting in the future climate.

In the Netherlands, man has cultivated the stream valley catchment landscape from 3000 BP onwards, disturbing its natural discharge and vegetation patterns. Especially from 1920 onwards, when mechanisation in agriculture started, stream valley systems were drained and overall heavily disturbed. Upper course drainage led to more groundwater fluctuations which reduced peat formation and increased desiccation of nature areas. Next to more groundwater fluctuations, upper course drainage also reduced upstream recharge and as a consequence groundwater discharge. That led to a reduction of the buffering capacity of groundwater discharge areas, leading to acidification of these locations and of the deterioration of local vegetation communities (Grootjans et al. 2002).

The canalisation of streams increased stream velocity and stream discharge, which (i) decreased the number of inundation events, leading to a decline of inundation specific vegetation and reduced flora dispersal, (2) deteriorated stream morphology (deep and straight streams instead of meandering, branched, braided rivers), including a reduction of the number of biological structures such as branches, trees and leaves entering the streams, and (3) increased the sharp distinction between aquatic and terrestrial vegetation, instead of having a smooth transition between the two. Finally, upstream fertilization led to eutrophication of
the groundwater and fertilizers from surrounding agricultural fields led to surface water eutrophication (Aggenbach et al. 2009). Because of these altered environmental conditions, the number of plant species declined rapidly in stream valley catchments and many plant species have become endangered (Grootjans et al. 2002). These processes have continued for many years and have had a great impact on the ecological functioning of stream valley catchment.

The water-vegetation system in a stream valley catchment that has endured year-long deterioration may not be resilient enough to cope with climatic changes that can deteriorate the system even further. They therefore provide a suitable case study for implementing and testing the suitability of climate adaptation measures.

1.5 Challenges, knowledge gaps and approaches
To assess the effects of climate change on stream valley catchments and to implement suitable climate adaptation measures, a hydrological modelling approach is required. With this modelling approach, the effects on water availability, water level fluctuations and water chemistry can be studied for an entire catchment. Furthermore, by coupling these results to a vegetation model, the effects of aforementioned changes on the whole water-vegetation system can be assessed.

First, the climate change effects on the hydrology and vegetation patterns in a stream valley catchment need to be evaluated. The climate adaptation measures are then implemented to test if these can buffer the negative effects of climate change.

However, the current hydrology and vegetation models are not capable of taking the effects of extreme hydrological events into account, because the effects of such events on plant species functioning is unknown. Additional knowledge about how plant species respond to hydrological extremes is therefore required in order to successfully model the effects of climate extremes on vegetation communities.

Furthermore, the endangered vegetation communities in stream valley catchments depend on specific hydrological conditions, which is the upwards flow of groundwater, to ensure their existence. Despite previous research which has used plant species as indicators for groundwater discharge sites (Klijn and Witte 1999, Rosenberry et al. 2000, Batelaan et al. 2003), it is not clear why these species occur mostly there. In order to fully grasp the effects of climate change and climate adaptation measures on the water-vegetation system, these mechanisms need to be
researched and taken into account, i.e. what are the plant characteristics that are required to be present at such a site?

The abiotic conditions at such sites are different from groundwater recharge and local discharge sites, due to the long contact of the water with the subsurface. In order to predict suitable habitats for characteristic groundwater discharge species it is essential to distinguish between local and regional groundwater discharge sites. However, the current hydrological models only distinguish between groundwater recharge and groundwater discharge sites. This requires the development of a new model tool that is able to distinguish between local and regional groundwater discharge sites, which can thus be used to indicate suitable sites for the characteristic vegetation. Additionally, the tool can also be used to evaluate the effects of climate change on these groundwater fluxes.

Furthermore, climate change and adaptation measures will not only affect vegetation patterns but other land uses as well. Agriculture for example is also dependent on water availability and is thus likely to be affected by changes in precipitation patterns and water adaptation measures. This may lead to different agricultural practices or other land use changes. These in turn may affect hydrology and thus vegetation patterns, and are therefore important to take into account.

The aforementioned challenges that need to be tackled require different approaches. The following approaches have been applied to fill these knowledge gaps. The first water-vegetation modelling study will serve as a starting point to evaluate if stream valley catchments are under threat.

To understand the effects of extreme fluctuating water availability on plant species and to understand the mechanism behind the abundance of indicator species at groundwater discharge sites, plant characteristics, or plant traits have been used. Plant traits are “any morphological, physiological or phenological feature measurable at the individual level (...)” (Violle et al. 2007). Traits within a plant community are selected based on the abiotic conditions at a site; the abiotic conditions act as a filter that select the appropriate plant traits and thus the fittest species (Keddy 1999). Plant traits are therefore directly linked to the abiotic environment. This makes them useful in: (i) assessing the effects of changing water availability and water level fluctuations on vegetation communities and (ii) identifying traits that are essential for species which are most abundant at groundwater discharge sites.

Distinguishing between local and regional groundwater discharge fluxes and simulating land use changes requires a new modelling concept. This modelling concept needs to simulate changes in hydrology, vegetation and land use. This
requires the use of three models, one for each discipline. The hydrological model (IBRAHYM, (Vermeulen et al. 2007)) simulates the saturated and unsaturated zone and generates output of, amongst others, groundwater tables and fluxes. The latter were used to distinguish between local and regional groundwater discharge fluxes. The vegetation model (PROBE (Witte et al. 2007, Douma et al. 2012a, Witte et al. 2014)) uses a trait-based approach to simulate vegetation communities. Abiotic input data and mean plot trait values, based on field data, are used to simulate vegetation types. Such a model is therefore highly suitable to model the effects of hydrological changes on vegetation communities. New insights gained from the plant trait approach can be implemented in this trait-based model. To simulate changes in agricultural land use, an Agent Based Model (RULEX (Bakker et al. 2015b)) was used. This model is used to simulate an agent’s (i.e. a farmer’s) behaviour with data on socio-economic properties and abiotic conditions. All challenges and approaches are summarised in Box 1.

**Box 1. Main challenges, knowledge gaps and approaches**

I. What are the effects of climate change and climate adaptation measures on hydrology and vegetation patterns?
*Approach: coupled hydrology-vegetation model*

II. How do plant species respond to extreme hydrological events?
*Approach: trait-based greenhouse experiment*

III. Which plant characteristics are associated with regional groundwater discharge sites?
*Approach: trait-based database research*

IV. Can a hydrology model distinguish between local and regional groundwater discharge fluxes?
*Approach: model different fluxes and compare with field data*

V. Does land use change affect hydrology and vegetation patterns?
*Approach: coupled land use - hydrology - vegetation model*
1.6 Aims and outline of this thesis

The aim of this research is therefore to investigate how to configure the spatial arrangement of landscape elements in stream valley catchments to optimize biodiversity under various scenarios of climate change and climate adaptation measures, using a modelling approach as outlined above (Figure 1).

Chapter two starts with a modelling study to simulate the effects of climate change and climate adaptation measures on hydrology and vegetation communities. This provides the current state-of-the-art of the hydrology-vegetation modelling and evaluates the vulnerability of stream valley catchments.

In the following chapters, the aforementioned knowledge gaps are researched. The effects of extreme drought and inundation events on plant performance and plant traits are studied in chapter three. This has been done by conducting a greenhouse experiment to mimic changes in water availability and thereby in water level fluctuations. Plant species responses to these changes were recorded.

In chapter four, a trait-based approach has been applied to distinguish between plant species that occur mainly at regional groundwater discharge sites and species that occur at wet groundwater recharge sites. This generated an overview of plant traits that are required for species that are most abundant at regional groundwater discharge sites.

In the fifth chapter, the level of detail of the groundwater flux modelling has been improved. A groundwater model was used to locate infiltration sites and local and regional groundwater discharge sites. These results were tested with data collected in the field. Additionally, four climate change scenarios were run to test how these regional groundwater discharge patterns may change in a future climate.

The effects of climate and socio-economic change, climate adaptation measures and policy legislation on agricultural land use changes are evaluated in chapter six. The subsequent effects on hydrological patterns and vegetation communities were also evaluated.

This thesis concludes with a general discussion and conclusion in chapter seven.
Figure 1. Schematic overview of the five research chapters. Chapter 2 focuses on climate change and climate adaptation effects on hydrology and vegetation. In chapter 3 the effects of hydrological extremes on riparian vegetation were tested. Plant trait differences between species growing at regional groundwater discharge sites (B) and at wet groundwater recharge sites (or local groundwater discharge sites) (A) were evaluated in chapter 4. Chapter 5 focused on differentiating between local (A) and regional groundwater discharge (B) sites both in the field and through a modelling approach. Additional climate change scenarios were implemented to see if these patterns were likely to change in the future. In chapter 6, land use changes were incorporated into the hydrology-vegetation modelling approach. These models were used to simulate the effects of climate and socio-economic change, climate adaptation measures and policy legislation on land use, hydrology and vegetation patterns.