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Effects of climate and land use change on the Tarland catchment

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Abstract

Potential changes in climate, land use and water demand may affect the distribution and availability of Scotland's water resources. Understanding the resilience of these resources is important to ensure that policy-makers make informed choices regarding land use planning, climate change adaptation and effective water management.

This research project aims to quantify the impacts of climate change and land use change on water resources in the Tarland catchment for two future periods, the near future (2041-2070) and the far future (2071-2100). The study area chosen is a sub-catchment of the Dee, an important environment for wildlife and used for domestic water supply for over half of Aberdeenshire. This sub-catchment lies between a national park and the valley floor, making it ideal for both woodland and arable land expansion.

Climate change simulations were derived from the outputs of the UKCP09 Weather Generator and bias corrected by applying the delta change method. Projections for land use change were taken from a series of scenarios created by a stochastic software tool, LandSFACTS, integrating both top-down and bottom-up causes of land-use change. Flows, actual evapotranspiration (AET) and soil moisture were then calculated using a semi-distributed watershed-scale rainfall-runoff model, PERSiST.

Climate change in this area will lead to an increase of mean yearly temperatures of 2°C for the near future and 3°C for the far future. At a yearly scale precipitation is expected to remain the same. However intra-seasonal variations will occur, leading to a decrease in the summer (-15% to -18%) and an increase in the winter (+9% to +11%). AET will increase, as the result of a combined temperature increase and increase in ET rates due to land use changes driven both by policies and biophysical changes; in parallel, hydrologically effective rainfall (HER) will decrease. These changes will severely impact streamflow, causing a decrease of 23% to 33% for the near future, and of 32% to 40% for the far future. Furthermore, soil moisture is also expected to decrease significantly, from 36% to 43% for the near future and up to 56% for the far future, depending on the evolution of land use. This will likely lead to changes in land management and possibly irrigation requirements. Finally, demographic changes will lead to an increase in freshwater demand, further stressing the available water resources.

Keywords: climate change, land use change, hydrological modelling

Foreword

This report is the result of a 5-month internship carried out at the James Hutton Institute in Aberdeen, Scotland, under the master's degree in Sciences of the Universe, Environment and Ecology at the Pierre and Marie Curie University. The research project undertaken takes place within the framework of the "Water Futures" work package commissioned by the Scottish Government, which will use a scenario-based approach to provide a broad assessment of the resilience of Scotland's water resources to potential future changes.

The James Hutton Institute is an international research center based in Scotland whose aim is to deliver evidence-based solutions to the global challenges facing land and natural resource use both now and in the future.

The training took place within the Environmental and Biochemical Sciences research unit under the research theme Biochemistry and Hydrology under the supervision of James Sample.

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*Si tu tiens à ta chair,
Bénis l'eau qui t'ennuie
Et qui glace ta chair ;
Car c'est grâce à la pluie
Que le pain n'est pas cher.*

Jean RICHEPIN (1849-1926) : excerpt from Ce que dit la pluie

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Introduction

Projections of population growth in the coming years estimate the Earth's population will exceed 9 billion by 2050. Meeting human needs for food and energy while minimally impacting the environment will therefore pose a significant challenge. To face this challenge, we must first understand the complex interactions between food, energy and water. The production of food and energy is directly linked to water resources: agriculture is the largest consumer of water, and the generation of electricity requires great amounts of water as well, whether used directly or indirectly (Finley & Seiber, 2014). In addition, global warming is intimately linked to land use and water quantity and quality. Overall, it is clear that governmental and international policy-makers need to develop an integrated strategy for dealing with the stresses generated by a growing population, their energy and food needs, water resource variations and the ways in which these elements interact with global warming.

The aim of the present research project is to quantify the impact of changes in climate, land use and water demand on a vulnerable resource zone, the Tarland catchment, for two future periods: the near future (2041-2070) and the far future (2071-2100). Land use changes, driven by policies such as the Scottish Land Use Strategy, may lead to decreases in natural runoff (for example through increased afforestation) or to increased demand for water abstraction (for example through agricultural intensification). In parallel, demographic changes may alter the demand for domestic water, and climate change may affect the magnitude and timing of rainfall and evapotranspiration.

In general, impact studies aiming to quantify water resource variations under climate change stresses require a series of specific steps. First, it is necessary to simulate future climate conditions with a global climate model (GCM) based on a greenhouse gas emissions scenario for the XXI century. As the scale at which GCMs are designed to operate is greater than that required for most impact studies, these simulations must be downscaled and bias-corrected. Furthermore, estimating only climate variations may prove insufficient: changes in land use, by impacting evapotranspiration (ET) rates and water retention properties, also have an impact on hydrological flows (Qi et al., 2009). Therefore, better understanding of land use change, driven both by policy and climate variations, is an important step in developing integrated scenarios to improve the decision making process. Finally, in order to quantify the interactions between climate and land use change on water resources, we use hydrological models, following calibration of the parameters involved.

This report begins with a literature review summarizing the results from a few national scale studies performed in Scotland. Then, a description of the climate simulations and land use scenarios considered is given, followed by an explanation on the functioning of the hydrological model used and the parameter calibration performed. Finally, model outputs are analyzed for each scenario considered and an assessment for the future of this zone's water resources is presented.

I) Literature review: context in the UK and Scotland

Climate and land use are intimately linked to both the quantity and quality of water resources. National scale studies allow us to have a broad vision of how climate and land use will evolve in the upcoming years, as well as the impact these changes might have on Scotland's water resources. This first estimate, though providing a scenario outline for policy making and water resource management, should be complemented with smaller scale studies to allow an integrated and better adapted decision making process.

I.1. Climate change

Simulating future climate generally follows a top-down approach: greenhouse gas emission scenarios, produced by the IPCC, are introduced into climate models, which are then downscaled and bias-corrected. In the UK, the leading source of climate change information, integrating these different steps, is UK Climate Projections 2009 (UKCP09) (UK Climate Projections, 2014).

I.1.1. UK Climate Projections 2009 (UKCP09)

UKCP09 is a climate analysis tool providing probabilistic projections of climate change for the UK. UKCP09 was produced in 2009 and funded by a number of agencies led by Defra, the Department for Environment, Food & Rural Affairs. It is based on sophisticated scientific methods provided by the Met Office, with input from over 30 contributing organisations (UK Climate Projections, 2014). Three IPCC greenhouse gas emission scenarios are used in UKCP09, taken from the Special Report on Emissions Scenarios (SRES; IPCC, 2000):

- A1FI ("high"): the A1 storyline assumes very rapid economic growth, a population peaking mid-century and rapid introduction of new technologies. A1FI more particularly describes fossil energy intensive technological advancements.
- A1B ("medium"): also part of the A1 storyline, scenario A1B considers a balance between fossil and non-fossil energy resources.
- B1 ("low"): population growth in B1 resembles that of A1, but considers rapid changes in economic structures toward a service and information economy.

Greenhouse gas emissions scenarios are inputted into three dimensional global climate models (GCMs). GCMs are models describing the behaviour of the components of the climate (atmosphere, ocean, cryosphere and land surface) and the interactions between them. Typically, GCMs represent the climate by using a three dimensional grid dividing the atmosphere and ocean into layers (about 270 km wide and 39 km deep). Then, at each grid point, a number of equations derived from laws of physics is solved for all time steps to describe the large-scale evolution of the system (Murphy et al., 2010).

Compared to the resolution of most impact studies, the resolution of these models is often too coarse. To provide projections at a finer spatial scale, the outputs of GCMs must therefore be downscaled. In order to downscale GCM outputs to a 25 km scale, the UKCP09 methodology uses the Met Office regional climate model (RCM). Regression relationships are developed between changes simulated by the RCM and changes simulated at nearby grid points in the GCM. This method resembles a traditional statistical downscaling approach, in

which a set of large-scale *predictor* variables are used to obtain values of localized *predictand* variables, using relationships trained on historical observations. However such methods assume that historical relationships persist into the future. In this case, that assumption is avoided as the relationships are trained using changes in the *predictor* and *predictand* variables simulated by the GCM and RCM extending to larger parts of the parameter space than those existing in the historical observations (Murphy et al., 2010).

Uncertainty linked to these models can be assessed by using an ensemble approach (e.g. CMIP3, Meehl et al., 2007; CMIP5, Taylor et al., 2012). Multi-model ensembles, constructed by pooling projections from several GCMs developed at different modelling centres, provide an indication of the range of the uncertainty associated to climate projections: if projections from different models agree with each other, then the confidence associated with these results increases. In this case however a single GCM model is utilised, the slab model configuration of the third Met Office coupled ocean-atmosphere model (HadCM3), known as HadSM3, which considers the ocean as a uniform slab. Here another way of creating a simulation ensemble was applied: studying different configurations of a single model, developed by altering the values of certain parameters. By considering the multiple variants of the Met Office Climate model it is possible to render probabilistic projections, sampling major known uncertainties in relevant climate system processes. However it is important to distinguish the different existing uncertainty sources: uncertainty due to natural variability, and model uncertainty, which can be further subdivided into three categories:

- Parameter error
- Initial and boundary condition errors
- Structural errors

Running an ensemble simulation with a single model can only address the first two bullet points. To consider structural error it is necessary to compare different models, thus sampling to some extent the effects of variations in basic structural assumptions such as choice of model grid and numerical integration scheme or the fundamental physical assumptions made (Murphy et al., 2010). Moreover, different downscaling methods do not provide exactly the same results: there is uncertainty associated with downscaling and bias-correcting. By applying different downscaling models, it has been observed that for precipitation, annual averages are quite similar, but the spatial distribution varies. For temperatures, there are significant differences, especially in summer (Quintana Seguí et al., 2010).

I.1.2. Results

The outputs of UKCP09 allow us to infer the following trend for future climate in Scotland and the rest of the UK:

- All areas of the United Kingdom will be warmer, more so in the summer than the winter. The temperature increase, at a 50% probability level, for the near future (2041-2070) will be between 1.6 °C (North West Scotland) and 2.8 °C (Southern England), and in the far future (2071-2100) between 2.2 °C and up to 3.6 °C (with the same spatial pattern) (fig. 1)
- Central estimates of annual precipitation show very little change everywhere at the 50% probability level for both future periods. However this disguises the change in

annual distribution of precipitations — winter precipitations showing a net increase (by +9% to +17% in the near future and +11% to +23% in the far future), and summer precipitations decreasing (by -11% to -20% for the near future and -12% to -24% for the far future). The least affected zone is North West Scotland, and the most is South East England.

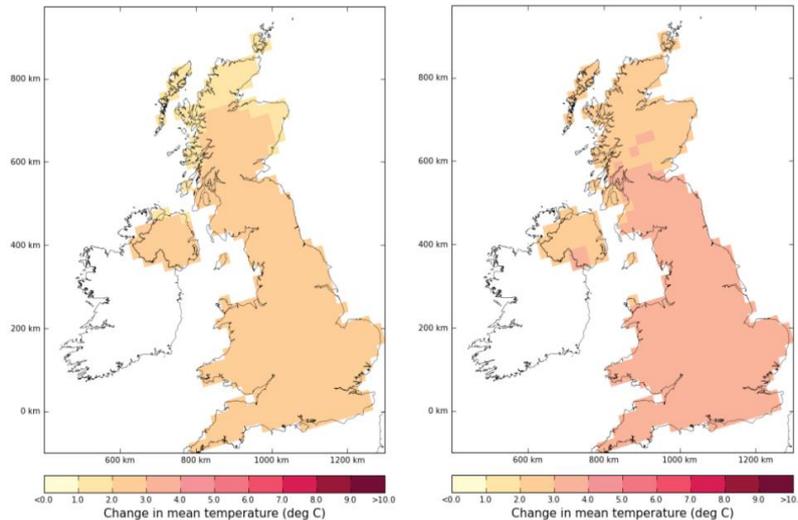


Figure 1: Projected change in temperature for 2041-2070 (left) and 2071-2100 (right) for the Medium emissions scenario according to the HadCM3 model (UK Climate Projections, 2014-a)

In brief, for both temperature and precipitation variations Scotland is the least affected region. These changes are however still likely to impact water resources, particularly if we consider interactions between increased evapotranspiration rates due to the temperature increase and variations in precipitation. To fully assess the possible range of change in Scotland’s hydrological flows, another factor — land use change — is to be considered, for it is likely to impact evapotranspiration rates, as well as runoff and infiltration.

I.2. Land use change

Different land uses imply different moisture requirements, vegetation types and evapotranspiration rates. Water resources are therefore directly influenced by land use, whether it is through differing management practices linked to agricultural exploitation of the land, or the indirect effect of ET rates intrinsic to the land cover type (Sample et al., 2011). Indeed, agricultural expansion involves an increase in the amount of water needed for irrigation, while forests are associated with substantially higher rates of evapotranspiration than other land cover types (Sample et al., 2012).

In the coming years, a number of factors will lead to changes in Scotland’s landscapes (Dunn et al., 2012). On one hand, indirect changes such as temperature and precipitation variations induced by climate change will modify the biophysical constraints to which land is subjected, therefore altering its productivity and flexibility (Brown et al., 2008). On the other hand, political and social factors, influenced by both global drivers (e.g. population growth and an increasing need for climate change mitigation) and local drivers (e.g. market forces and local skills), will lead to a change in land use management (Brown & Castellazzi, 2014). Indeed, retaining high levels of agricultural production whilst maintaining water quality and

limiting greenhouse emissions are at the heart of Scotland’s environmental policy for the upcoming century (e.g. Climate Change Act 2009; Land Use Strategy; Food and Drink Policy; Forestry Strategy).

I.2.1. Climate change driven land use change

a. Land Capability Systems

As mentioned above, temperature and precipitation variations impact land use by altering the biophysical constraints to which the land is subjected. One way to quantify the influence of climate variations on land use is to classify the areas of interest based on the intrinsic biophysical limitations of the land, which act as a constraint to use. This enables the grading of land quality (higher quality land being more adaptable to varying land uses), and allows us to link climatic constraints and land use: as climatic constraints evolve, the optimal land use, and consequently the actual land use, will evolve as well. This approach is known as a Land Capability system, whose aim is to identify the capacity of an area for different uses and the optimal use from a biophysical perspective, excluding socio-economic factors (MLURI, 2014).

The Land Use Capability system was first adapted for agriculture in Scotland in 1969 (Bibby & Mackney) and further developed into the Land Capability for Agriculture (LCA) classification (Bibby et al., 1982). The purpose of the LCA classification was to rank land on the basis of its potential productivity and flexibility by estimating climate and soil properties along with gradient and soil-climate interactions (soil wetness, erosion...). The original LCA system is still firmly embedded within land-use planning in Scotland, serving as the official agricultural classification system used by agriculturists, planners, estate agents and others as a basis of land valuation (MLURI, 2014).

The LCA is a seven class system, four of whose classes are further divided into subdivisions. Class 1 represents the land with the highest potential flexibility, whereas Class 7 is of limited agricultural value. These seven classes can be simplified into four categories broadly representative of land’s agricultural capability (tab. 1).

LCA classes	Biophysical limitations	Potential land use
Arable agriculture <i>Class 1 to 3.1</i>	None to Moderate	Often referred to as “prime” agricultural land, these land classes are capable of being used for a wide variety of crops. The factors contributing to this are favourable climate, gentle slopes and thick well drained soils.
Mixed agriculture <i>Class 3.2 to 4.2</i>	Moderate to Moderately severe	Land in these classes is capable of being used for a smaller amount of crops, primarily cereals, forage crops and grass. Climate is less favourable, slopes are higher and soils less well drained.
Improved grassland <i>Class 5.1 to 5.3</i>	Severe	These can be permanent or part of a rotation. They have been modified specifically for agriculture by addition of organic and inorganic fertilisers and herbicides, aiming to generate a maximum yield for grazing, silage production or hay production.
Rough grazing <i>Class 6.1 to 7</i>	Very severe to Extremely severe	This type of land has severe limitations, such as poor draining, acid or shallow soils or more extreme climates. This type of soils can however still be of high value on ecological terms, by storing carbon or supporting rare habitats.

Table 1: LCA classes for Scotland and associated land uses

A major limitation in the LCA system, as noted by Brown et al. (2008), is that it assumes a static, rather than temporally dynamic, climatic state. It therefore lacks an evaluation of the impact of long-term climatic trends and the potential changes in agricultural land classes which may ensue. However climatic constraints play a key role in determining land capability. Indeed, climate can restrict ecological processes such as plant growth, or limit management activities like harvesting and sowing. A change in climate therefore implies either new opportunities or risks in land use, the flexibility in land-use options either increasing or decreasing.

b. Land Capability under climate change

In Brown's study (2008), the LCA system was updated to investigate the influence of future climate change on land use potential for the 2050s. To do so, climate change scenarios derived from the HadRM3 climate model were used, downscaled using a simple interpolation (delta-change method). Changes in LCA "prime" land and maximum potential soil moisture deficit (MPSMD) were evaluated. These two factors are of great importance in the determination of water resource variations as a result of land use change. Expansion of prime arable land indicates a change in evapotranspiration and potentially an increase in water abstraction for irrigation purposes. Soil moisture variations and "prime" land expansion are also linked, for persisting drier or wetter conditions can alter a land's productivity and flexibility. Furthermore, soil moisture is a good indicator of possible irrigation requirements because water abstraction needs cannot be directly deduced from land use. Irrigation requirements will be further discussed in I.4.1.

Changes in MPSMD

Figure 2 shows the projected changes in MPSMD for the reference scenario. In eastern and southern Scotland soil moisture deficits are projected to increase by 50 to 150 mm, contrasting with the west where MPSMD changes are smaller, ranging from about -25 mm to +25 mm. As a result, the West will retain its predominantly wet conditions whilst the drier areas in the east will become even drier.

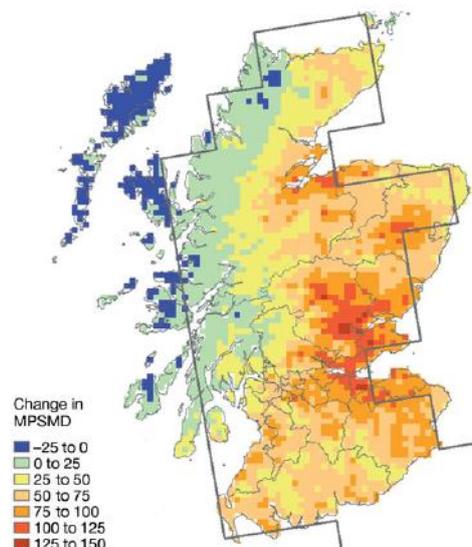


Figure 2: MPSMD changes (in mm) from 1981-2000 to the 2050s obtained by using HadRM3 model forced by a Medium-High Emissions scenario (Brown et al., 2008)

Changes in land use

As a result of climate change induced soil moisture variations, the current expansion of available “prime” land in the East (fig. 3) is likely to be substantially modified. As the predicted temperature increase is quite homogeneous, MPSMD becomes the dominant factor influencing spatial variation in the expansion of “prime” arable land.

Figure 3 illustrates the impact of the observed decrease in MPSMD, resulting in new opportunities for agriculture in eastern Scotland, where the decrease in MPSMD is most important, and the marginal areas fringing the uplands. Western areas however exhibit little new “prime” land potential despite the temperature increase, which can be attributed to continuing wet conditions and low MPSMD values. This observation is of great importance, for the vast majority of Scotland’s existing intensive agriculture is located in the East, and some of these areas already have significant water quality issues (Dunn et al., 2012). Potential future expansion would therefore increase the pressure on these areas which are already at risk.

Furthermore, the expansion of arable land, mainly at the expense of lower-graded “marginal” land (i.e. Improved Grassland and Rough Grazing), is expected to have a strong environmental impact. This type of land, though of lower agricultural value, plays an important role in buffering water supplies and maintaining biodiversity (Brown et al., 2008).

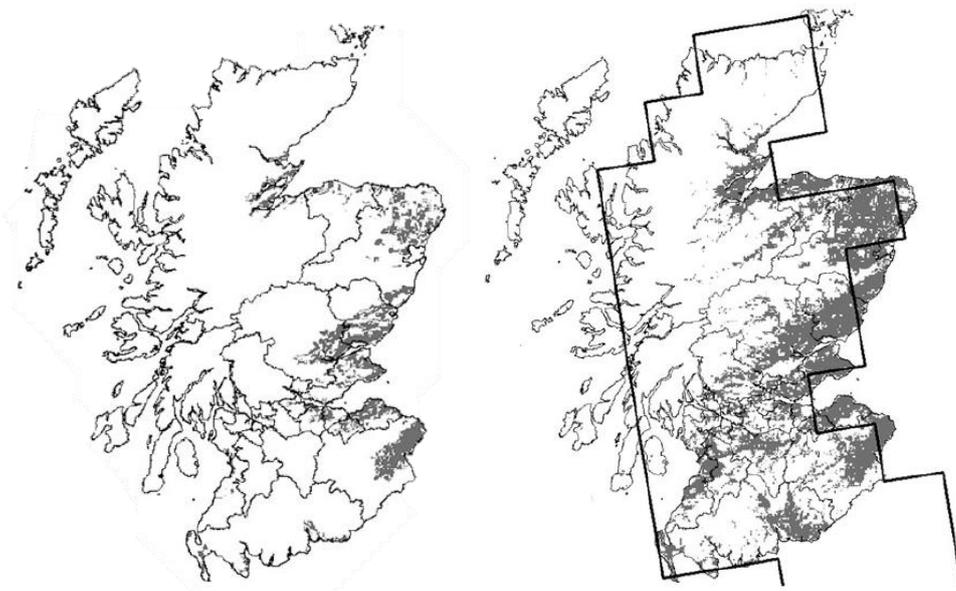


Figure 3: Areas of “prime” land in Scotland for 1981-2000 (left), and for the 2050s obtained by using HadRM3 model forced by a Medium-High Emissions scenario (right) (Brown et al., 2008)

Overall, this study showed that, in the face of climate change, the potential for arable land expansion will become greater. However, considering only the impact of climate change on land use, i.e. downscaling large-scale scenarios to obtain a mechanistic determination of land-use change, may be limiting. Indeed, land-use patterns are influenced by both top-down and bottom-up factors (Brown & Castellazzi, 2014). Complimentary “bottom-up” and fine-grained approaches incorporate social and cultural factors influencing land-use behaviour, for it is ultimately the land owners/managers and policy makers who will decide how land is used (Baudry & Thenail, 2004).

I.2.2. Policy driven land use change

a. Land Use Strategy

In order to approach the challenges facing land use in Scotland, the Scottish government set out a series of objectives regarding land use relating to the economy, environment and communities. The aim is to contribute to greenhouse-gas emission reduction and adapt to the existing climate change all while getting the best out of Scottish lands. These objectives are mainly defined within the Land Use Strategy (Scottish Government, 2011) and should allow a sustainable and optimal exploitation of land resources. The Land Use Strategy provides a broad context for planning authorities on Government policies relevant to all land use. Amongst the different land uses considered, some types have particular value in delivering benefits of key strategic importance (i.e. “prime” arable land and woodland), for which particular policies were defined.

It is important to note that our study area is located within the Aberdeenshire council area which figures amongst one of the two pilot projects set out to test regional Land Use Frameworks (Scottish Government, 2015). These projects guide future decisions on how the land is used in these areas, concluding with the first review of the Land Use Strategy in 2016.

b. Other strategies

The Scottish Land Use Strategy is amongst a series of projects which will impact land use patterns and therefore water quantity and quality, a few of which are described below.

Scotland’s National Food and Drink Policy (Scottish Government, 2009) aims to promote sustainable economic growth of the food and drink industry, addressing food security and sustainability issues while considering changes in Scotland’s demographics. “Prime” agricultural land should therefore retain its capacity for food production.

The Scottish Forestry Strategy is a framework designed to expand woodlands throughout Scotland in order to benefit from the different services forestry can provide, such as carbon sequestration, biomass production or biodiversity preservation. By the second half of the 21st century the Scottish government has proposed to increase forest area from about 17% to 25% of Scottish land area (Scottish Government, 2006), but this without regional differentiation. “Prime” agricultural land (tab. 1) is excluded from this afforestation objective (Scottish Government, 2011). Indeed, concerns over global food affordability and supply, combined with poor harvests in major arable cropping regions and the emergence of biofuels, have lead farmland prices to be at a historic high (Forestry Commission Scotland, 2009). This implies that marginal agricultural landscapes in the upland fringes will be prioritized, although these possess a higher biodiversity value than existing farmland (Brown & Castellazzi, 2014). Within this context the aim is to focus of woodland creation on land where the benefits offered by forests are likely to outweigh the potential for agricultural production, especially lower quality agricultural land.

Another issue of concern is the type of woodland which would be prioritised to reach the afforestation objective. Different wood types offer different benefits. Native woodland, generally broad-leaved, has a high biodiversity and historic value (Brown & Castellazzi, 2014). Coniferous trees are of higher economic value, and are generally preferred for use as

timber. The choice of woodland utilised therefore depends on the priority given to nature preservation over economic gain.

These are the main policies driving land use change, but other factors may also exert an influence, albeit to a lesser extent, such as measures implemented by the Floods Directive (e.g. river restoration for Natural Flood Management), the Water Framework Directive (e.g. measures for diffuse pollution control) or the Habitats Directive (furthering protection of certain species, such as salmonids and their natural spawning habitat).

I.3. Water resource variations

Several national scale studies of the evolution of Scotland's water resources under varying pressures have been carried out.

I.3.1. Runoff

Dunn et al. (2012) undertook a national scale study designed to explore the relationships between climate, water resources and land use by analysing changes in ET, precipitation and runoff. Climate simulations were based on two models from the GCM-RCM (Global Climate Model-Regional Climate Model) Perturbed Physics Ensemble (PPE) developed by the UK Met Office Hadley Centre. Future precipitation and PET were evaluated through modification of the 1961-1990 observed dataset by applying monthly delta-change weighting factors. Future land use patterns were determined by comparing baseline land use data (the Land Cover Map of Scotland 1988) to a future scenario considering biophysical changes, impacting crop growth, as well as socioeconomic factors, notably an increase in the importance granted to food security in the future. The water balance model used estimates water storage and drainage from the soil to ground and surface water bodies by calculating soil moisture conditions at each time-step.

The results for the 2050s are as follows:

- Strong geographic gradients in climate were highlighted. The main driver of these changes is precipitation variability, since PET rates present a much lower spatial variability.
- Yearly changes in runoff were more difficult to assess, since the results obtained from the two different climatic models showed opposing trends (one decreasing and the other increasing). At a smaller time-scale changes are however observable. In autumn months the increase in precipitations is expected to cause an increase in runoff of up to 30%, with the decrease in precipitations in the summer causing a reduction of 9% to 32%.

I.3.2. Streamflow

Prudhomme et al. (2013), studied stream flow variations for all of the UK. Climate simulations were also based on the PPE, downscaled and bias-corrected following a quantile-mapping method. Three types of hydrological models were used (regionalised, catchment, and hybrid), which employ three different methods of calibration on different parts of the flow regime.

In this study, changes in mean annual flow were mainly within a +/-20% range, large areas suggesting little to no change. Small increases in stream flow were projected for the south and the east of the UK, while the West shows a tendency to the reduction of annual flows. In Scotland, simulations suggest a reduction in annual flow. Changes in Q10 (exceeded 10% of the time) suggest little change for most of the UK (except for the midlands and East Anglia). Q10 changes across most of Scotland remain within the +/-5% range, except for two scenarios (out of 11) where projections suggest a 20% increase.

Summer changes show a more pronounced trend with decreases of up to 80% in the north and west of Great Britain.

Winter patterns are more mixed, showing tendencies towards both an increase and a decrease amongst the different climate model realisations. In Scotland flows show a small increase or decrease, still within the +/- 20% range with changes in the east reaching up to +40%.

To summarize, this study showed little changes in the overall water balance, however disguising important regional and temporal variations. This highlights the importance of a catchment scale analysis, where the relationships between water supply, demand and storage can be explored based upon local land use patterns.

I.4. Changes in water abstraction needs

There has been a substantial amount of research concerning *supply* of water resources in the face of climate change (e.g. Prudhomme et al., 2013; Sample et al., 2012). Fewer studies have addressed water *demand* issues (Brown et al., 2012) even though determining the balance between water supply and water demand is key in developing sustainable resource use.

Indeed, in addition to the impact that climate change and land use change may have on Scotland's water resources, an increase in demand is expected to occur and therefore alter the water balance through increased water abstraction. On one hand, a projected population increase (Scottish Water, 2009) implies greater household requirements. On the other hand, agricultural intensification driven by food security policies, combined with climate driven changes in soil moisture, will likely impact water abstraction needs for irrigation.

I.4.1. Water abstraction for irrigation

Although in Scotland agriculture is a relatively minor component of water demand compared to industrial and household demand (Brown et al., 2012), this component is projected to increase as requirements for produce grow and climate change stress on crops (as a result of evapotranspiration losses) becomes greater. Furthermore, water abstraction needs are greatest in summer, when resources are at their lowest.

Brown et al. (2012) compared water supply and demand at a national scale. Cropping patterns were divided into 3 groups according to irrigation requirements: (i) potato-like (ii) cereal-like and (iii) grassland-like. Water demand was obtained by comparing local soil's hydrological properties (i.e. storage capacity or available water capacity, fig. 4) to the local climatic component, as defined by potential soil moisture deficit (PSMD). Soil Moisture

Deficit is the difference between field capacity (FC), when the soil is fully saturated and the surplus has drained off, and the amount of water actually held by the soil (Defra, 2003; fig. 4). SMD can be decreased through rain or irrigation, or increased as a consequence of evaporation from the soil and leaf surfaces and transpiration from the leaves.

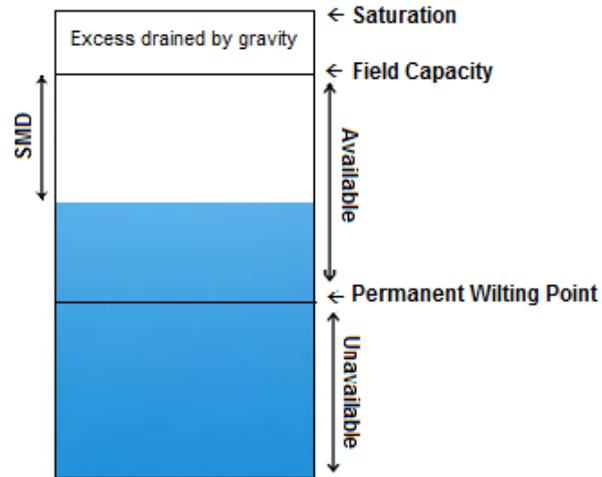


Figure 4: Soil water content

PSMD was then used to obtain irrigation values using a regression-based method developed by Knox et al. (2007). This method requires first determining irrigation needs at specific sites by using an irrigation scheduling computer model (Irrigation Water Requirements or IWR; Knox et al., 1996); the outputs of this model are then used to develop a correlation between irrigation needs and PSMD using linear regression. Finally spatialized irrigation needs (in mm) are multiplied by the surface occupied by currently irrigated crops (i.e. potato-like) to obtain final volumetric irrigation demand (See Figure 5).

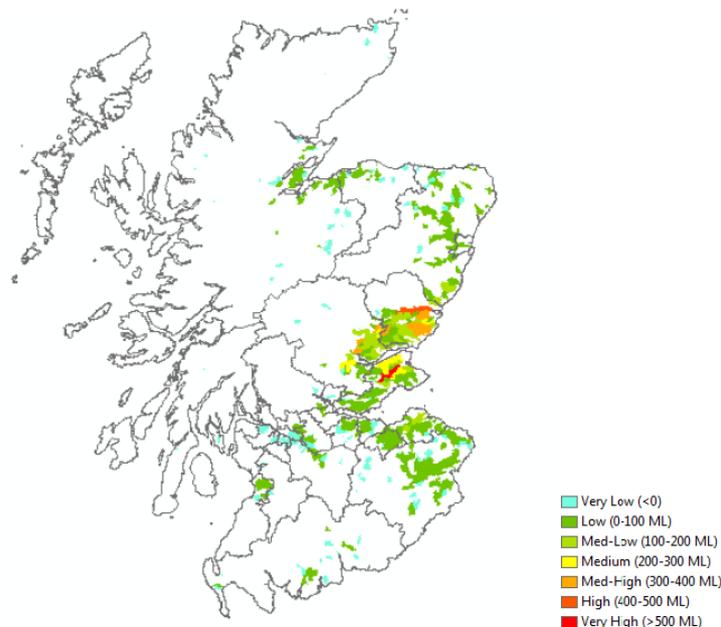


Figure 5: 2050s change in Irrigation Demand (ML/km²) (Brown et al., 2012)

Assuming that both land use patterns and the defined area of irrigated crops remain the same as at present, the methodology used in this project suggests an increase in irrigation

volumes by the 2050s with climate change of about 30% with important spatial variations. Note that the spatial distribution of the increase in irrigation requirements closely resembles the distribution of MPSMD shown in Figure 2.

Overall, the method developed in this study seems appropriate for determining large scale variations in irrigation requirements. However, it does not account for possible changes in land use and cropping patterns, which are predicted to change substantially. Furthermore, this method cannot be applied at a small scale, for it requires precise knowledge of cropping patterns and their evolution; also uncertainty at this scale may exceed the range in variation.

I.4.2. Water abstraction for household demand

Another element to be taken into account is a projected increase in population, leading to an increase in industrial and household demand. Scotland's population has continued to increase in recent years due mainly to net immigration (Scottish Water, 2009). Looking at the historic trend, the population has increased by 0.5% over the last 20 years; however population variations are unevenly distributed.

Furthermore, although Scotland is a water rich country, due to the geography and large numbers of small communities Scotland has over 200 water resource zones scattered around the country. This is a unique water supply system with 70% of the zones accounting for just 1% of the population (Scottish Water, 2009).

Assessing the ability of water management authorities to fulfil the increase in water demand requires considering the three elements limiting water exploitation:

- The yield of the source defined as the amount of water which can be reliably exploited up to a 1 in 40 year drought event by Scottish Water (Scottish Water, 2009)
- Controlled Activities Regulations (CAR) abstraction licence limits. The aim of these regulations is to protect, improve and promote sustainable use of Scotland's water environment (SEPA, 2014).
- Water Treatment Works Capacity (WTWC). In most water resource zones, the deployable output is limited by WTWC. Table 2 shows a first estimation of the supply-demand evolution for the different water resource zones comprised within Aberdeenshire. Yield and CAR regulations are assumed constant.

Figure 6 illustrates the different water resource zones used for drinking water abstraction in Aberdeenshire, where our study area is located.

For all water resources zones (except for Clatto, Lintrathen & Whitehillocks) demand is expected to increase (tab. 2). According Scottish Water, WTW capacity will remain the limiting factor to freshwater availability. This projection however fails to consider long-term impacts of climate and land use change on deployable outputs. Scottish Water has set out to better determine long-term yield variations (Scottish Water, 2009). Furthermore, demand projections only extend to 2039, so comparison with our resource variation projections (for 2041-2070 and 2071-2100) proved difficult.

	2020 (Projected)		2039 (Projected)	
	Demand variation (%)	Limiting Factor	Demand variation (%)	Limiting Factor
Craighouse	28.8	WTW	27.0	WTW
Ballater	10.1	WTW	12.9	WTW
Braemar	35.2	WTW	36.8	WTW
Crathie	53.8	WTW	46.2	WTW
Invercarnie & Mannofield	10.0	WTW	9.4	WTW
Herricks	10.8	WTW	13.0	WTW
Lumsden	28.3	CAR	31.3	CAR
Turriff, Gallowhill, Forehill & Rochomie	6.3	WTW	6.4	WTW
Clatto, Lintrathen & Whitehillocks	-1.7	Yield	-4.0	Yield

Table 2: Current and projected supply-demand balance as estimated by Scottish Water (2013)

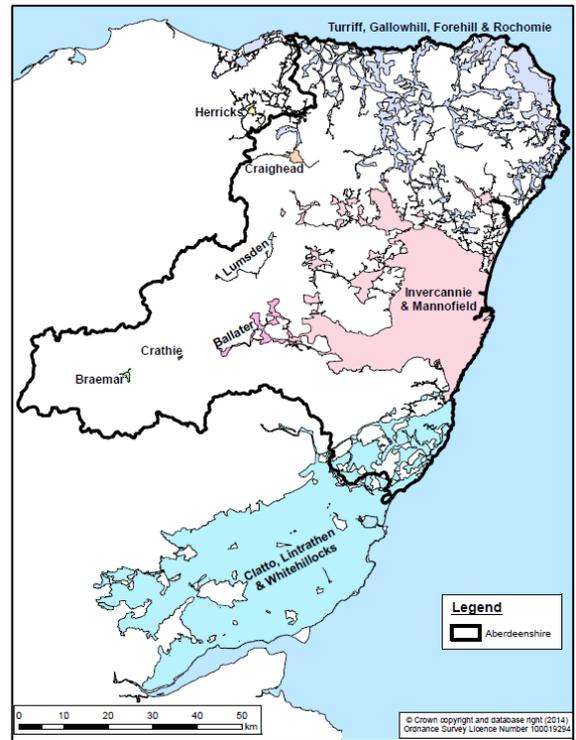


Figure 6: Aberdeenshire's Water Resource Zones

Overall, we observe that demand is projected to increase, at a growing rate. An increase in demand combined with a decrease of available resources could affect freshwater availability in the long-term.

1.5. Overview

To summarize, several changes are expected to occur at a national scale:

- A temperature increase ranging from 1.6 °C to 2.8 °C for the 2041-2070 period and between 2.2 °C to 3.6 °C for the 2071-2100 period.
- Seasonal precipitation variations. An increase in winter precipitations (+9% to +17% in the near future and +11% to +23% in the far future) and a decrease in summer precipitations (by -11% to -20% for the near future and -12% to -24% for the far future). Runoff impacted by precipitation changes, increasing in the fall and winter and decreasing in the summer.
- A tendency towards a reduction of annual flows. A pronounced decrease in summer months, and mixed tendencies in the winter.
- Drier conditions in Eastern Scotland leading to an expansion of arable land. Increased irrigation requirements proportional to the increase in SMD.
- Policy driven woodland and arable land expansion at the expense of semi-natural environments.
- Demographic changes leading to increased freshwater requirements

Although these results give a broad overview of the potential changes occurring on both biophysical and socio-economic perspectives, spatial heterogeneity and uncertainty of these results highlight the need to perform smaller scale assessments of the impact of climate and land use change. Ultimately, this should allow policy-makers to measure the efficiency of the strategies undertaken and improve the decision-making process.

II) Material and methods

II.1. Climate change: UKCP09 Weather Generator data

II.1.1. Climate simulations

In order to simulate the impact of climate change on Scotland's water resources we first must obtain climate projections for the relevant periods: 2041-2070, the near future, and 2071-2100, the far future. In our case, we used what is called a Weather Generator (WG). Weather generators are models that replicate the statistical attributes of a local climate variable (Wilby et al., 2004) allowing us to obtain a *synthetic* time series of temperature and precipitation consistent with the underlying climate projections (Jones et al., 2009).

The UKCP09 Weather Generator is based around a stochastic rainfall model that simulates future rainfall sequences. Other variables, such as temperature and sunshine, will be generated according to the rainfall state by determining their mathematical/statistical relationships with rainfall (or *inter-variable relationships*, IVRs). The first step is to generate a baseline climate by calibrating the WG with observed data. To simulate future climate, change factors at the monthly time scale for each grid are taken from the UKCP09 probabilistic projections (see I.1) to define the range of possible climate change. The stochastic model is then refitted using the perturbed future rainfall statistics, and finally the other weather variables are generated from the rainfall series.

Compared to the UKCP09 probabilistic projections alone, using a WG data has many advantages. Indeed, the 25 by 25 km UCKP09 grid box may not provide the resolution needed for certain impact assessments, or a compatible time scale. Using the WG approach can provide high resolution time series at a 5 by 5 km grid resolution. Furthermore, when assessing changes in the severity and frequency of extreme events, observational records are often insufficient, presenting small sample numbers of the most important extremes. WG allow estimation of extremes by generating long, stationary series to provide large statistical samples. In total 100 WG simulations of baseline and 100 simulations of 2041-2070 and 2071-2100 climates were generated.

II.1.2. Bias correction

Comparing the WG baseline to the historic observed weather data provided by the Met Office, a slight discrepancy was observed, the WG data not fully representing the frequency in extreme values. Although WG predictions for the baseline period are derived from statistical indicators based on observed data, the WG output is nevertheless biased. To account for this, we performed a simple bias correction for which we assumed that the relative difference between the model baseline and the model future is realistic, despite any bias (Jackson-Blake et al., 2014). The following assumptions are therefore made:

$$Sim_F/Sim_B = Obs_F/Obs_B \text{ (Multiplicative)} \quad (1)$$

$$Sim_F - Sim_B = Obs_F - Obs_B \text{ (Additive)} \quad (2)$$

The obtained change factors (Δ) to apply to baseline observations are therefore Sim_F/Sim_B or $Sim_F - Sim_B$, and were calculated from the average of monthly mean values

over each 30 year period for each WG simulation. The daily observed data was then perturbed using these change factors; multiplicative change factors were used for rainfall and additive for temperature:

$$Obs_F = \Delta * Obs_B \text{ (Multiplicative)} \quad (3)$$

$$Obs_F = \Delta + Obs_B \text{ (Additive)} \quad (4)$$

The main limitation of this method is that it considers only mean climate change. Additive deltas shift only the mean, preserving the same distribution on a daily and interannual scale: possible changes in distribution at these scales are overlooked (Ducharne et al., 2009).

II.2. Land use change: LandSFACTS

As stated in part I.2, land use patterns are influenced by both top-down (i.e. climate change, globalisation) and bottom-up (political and social) factors, with interactions varying over space and time. Nowadays, land-use change scenarios are often derived exclusively from ‘top-down’ downscaling of larger scale scenarios based upon macro-drivers and policy priorities, therefore neglecting key social or cultural factors.

To fully assess the possible changes occurring in land-use patterns, Brown & Castelazzi (2014) developed a flexible stochastic software tool (LandSFACTS) which relies on cross-scale scenarios based upon the IPCC Special Report on Emission Scenarios (IPCC, 2000) framework, integrating both top-down and bottom-up causes of land-use change. Local land-use changes were considered at the land-use parcel (field) scale. The stochastic aspect of the tool ensures spatiotemporal coherence of land-use allocation simulations. Simulation drivers were divided into three key components: biophysical constraints, socio-economic factors and the current land-use patterns (fig. 7).

To determine current land use patterns at a large scale (e.g. the Dee river basin) coarse land-use data was based on the UK Land Cover Map 2000 (LCM2000, Fuller et al., 2002). For smaller scale (e.g. catchment) simulations, actual land-use data was used (derived from the European Commission’s Integrated Administration and Control System, IACS, cross-referenced with Ordnance Survey’s Mastermap database).

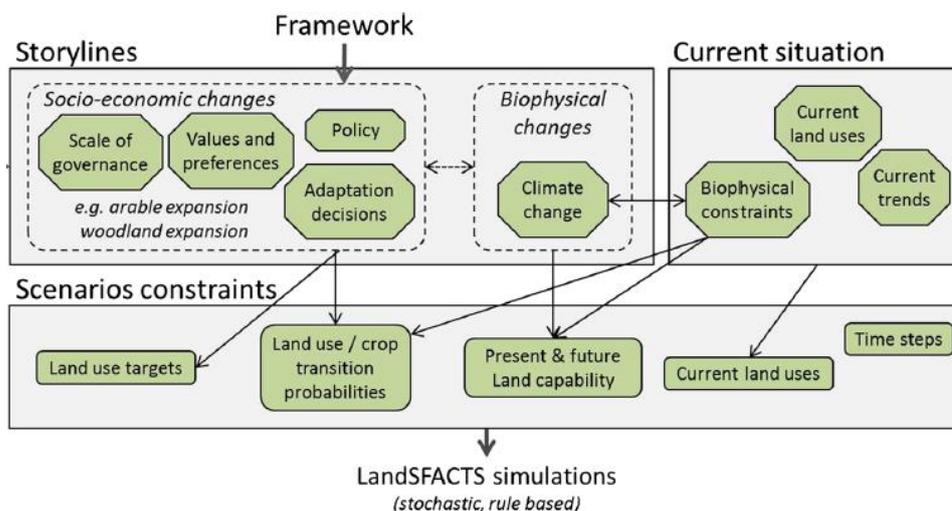


Figure 7: Conversion of biophysical, socio-economic and current land-use trends from storylines into simulations, adapted from Brown & Castelazzi (2014)

Biophysical limitations were characterised by using the Land Capability approach (tab. 1). Future changes in land capability were derived from a medium-high emissions projection for the 2050s combined with soils and topography data references against a 1981-2000 baseline (Brown et al., 2008; see I.2.1).

The scenario for the 2050s was applied to both future periods.

Socio-economic factors are determined by global drivers, policy targets (see I.2.2) or local preferences. Global drivers were derived from the IPCC SRES framework and divided into 4 categories of governance ranging from pro-economy to pro-environment with a global or local dominance (fig. 8). Policy targets, such as Scotland’s afforestation policy (Scottish Government, 2006), were compared to a series of rules identified for each storyline in order to capture the key characteristics of the scenario. Results showed that the policy objective for woodland expansion couldn’t always be met, since competing pressures such as food security don’t allow for the expansion of woodland at the expense of farmland. In this case, progressively lower % values were implemented until the target was achievable by 2050.

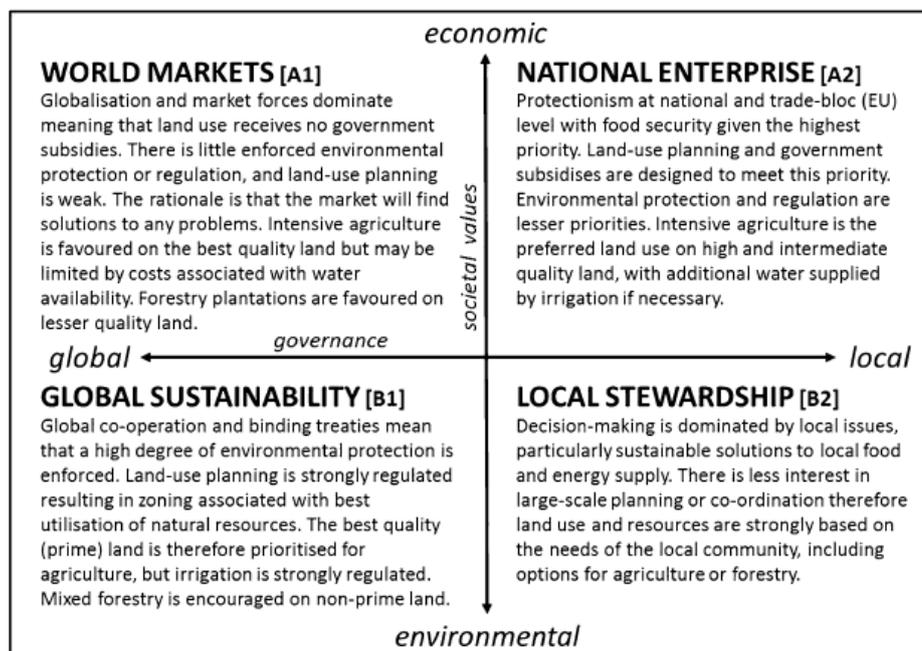


Figure 8: Socio-economic categories of governance considered in LandSFACTS (Brown & Castelazzi, 2014)

Targets and constraints derived from each of the four scenarios are as follows:

- World Markets (WM): Future prime land reserved for intensive arable production, limiting woodland expansion to 22% (rather than 25%) over the whole Dee catchment. Agricultural expansion in drought risk areas is limited as irrigation is reserved for high-value produce. In marginal areas forestry production (preferably coniferous for its higher economic value) is preferred to improved grassland.
- National Enterprise (NE): Woodland expansion (again preferably coniferous) is also limited to 22% due to prime land being reserved to agriculture. Irrigation is not regulated, and the expansion of intensive agriculture is limited only by land quality.

- Global Sustainability (GS): The 25% woodland expansion objective is met preferably using native or deciduous trees. Prime land cannot expand into drought risk areas due to regulated irrigation.
- Local Stewardship (LS): Agricultural production is concentrated on prime land in order to provide a local food supply and low-intensity agriculture is emphasised. Woodland expansion (preferably native) is allowed upland for energy and recreation.

II.3. Study area choice

The Tarland Burn is situated in NE Scotland (fig. 9), and is the uppermost tributary of the Dee. The River Dee is an internationally important environment for wildlife and is designated a Special Area of Conservation (SAC) for supporting populations of Atlantic salmon, otter and freshwater pearl mussel. Furthermore, the River Dee and its tributaries provide domestic water supply for the whole of Aberdeen City and over half of Aberdeenshire (Dee catchment partnership, 2015). It lies between the Cairngorms National Park, a stronghold for British wildlife, and the valley floor, therefore presenting the potential for both arable expansion and intensification and new forestry. Overall, monitoring changes in water quality and quantity of the Dee is interesting from both economic and environmental perspectives.

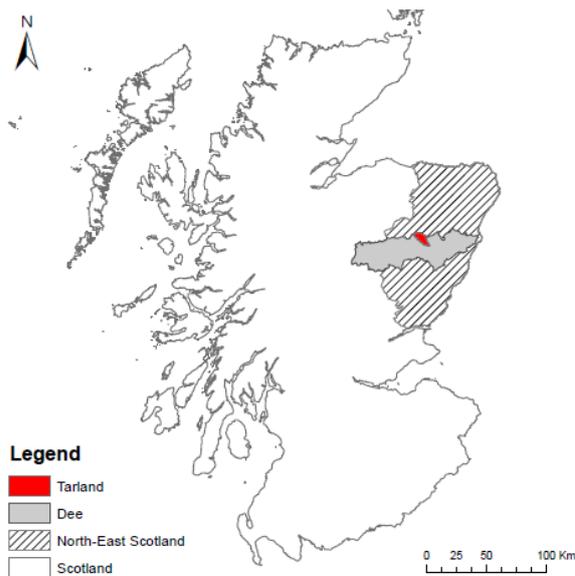


Figure 9: Location of the case study area within the greater Dee catchment in NE Scotland

Table 3: Physical characteristics of the Tarland Catchment

Catchment area (km ²)		70.8
Mean elevation (m)		249
Elevation range (m)		137-620
Mean annual rainfall (mm)		800
Coull current land use distribution (50.6 km ²)	Arable (%)	21
	Coniferous (%)	14
	Deciduous (%)	5
	Other (%)	60
Aboyne current land use distribution (20.2 km ²)	Arable (%)	9
	Coniferous (%)	36
	Deciduous (%)	5
	Other (%)	50

The Tarland drains the most Westerly area of intensive agriculture of the river Dee catchment (fig. 10). It is the first entering point of nutrient-impacted waters into the oligotrophic main river. Rainfall is approximately 800 mm/yr with long periods of winter snow. The Tarland catchment can be subdivided into two sub-catchments (fig. 10): Coull and Aboyne. Each sub-catchment is composed of a series of different land uses shown in Figure 10, which were subsequently simplified into three land uses, Arable, Woodland and “Other” (regrouping semi-natural environments and improved grassland, see Annex 1). Table 3 summarizes the principal physical characteristics of the Tarland catchment. More details on the Tarland catchment are available in Annex 3.

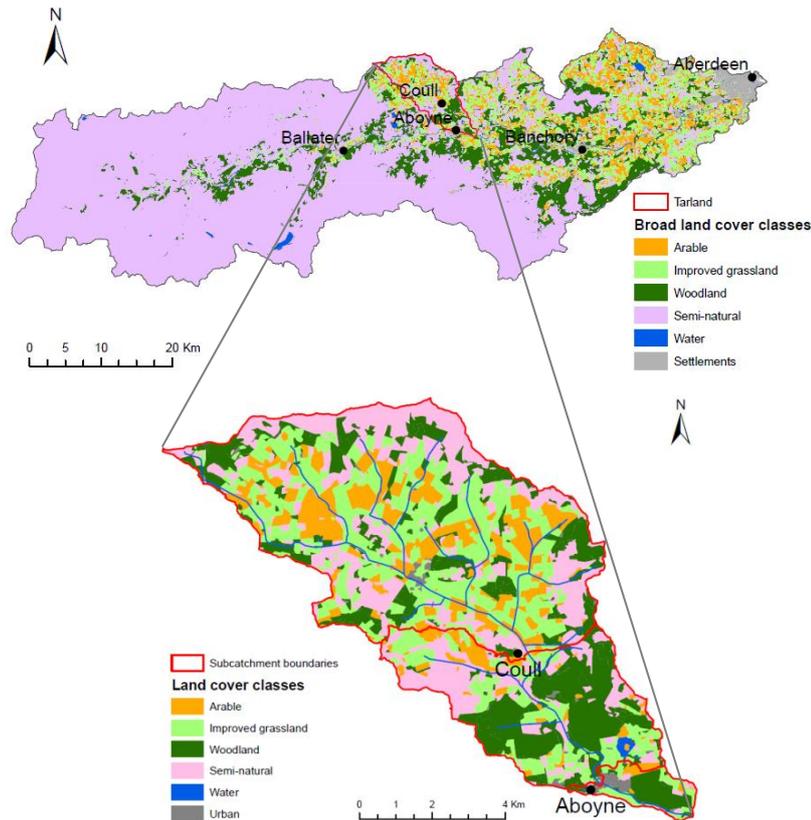


Figure 10: Location of the Tarland catchment within the larger Dee catchment and broad current land cover (upper) and close-up of the case study area (lower)

In brief, the Tarland catchment was chosen as a case study area for its following characteristics:

- i. It is a well-studied research catchment with a long record of high-frequency monitoring data.
- ii. Drinking water is supplied primarily by surface water abstractions
- iii. There is potential for agricultural expansion and/or afforestation
- iv. There is potential for population growth

II.4. Hydrological model: PERSiST

II.4.1. Model description

PERSiST (Precipitation, Evapotranspiration, and Runoff Simulator for Solute Transport), developed by Futter et al. in 2014, is a semi-distributed watershed-scale bucket-type rainfall-runoff model. Watersheds (level 1, Fig. 11) are represented as an ensemble of sub-catchments (level 2) made up of one or more landscape units (level 3). Within each landscape unit there are a series of connected water stores or buckets, which receive, store or transmit water (level 4). Our study area was divided in two sub-catchments (Coull and Aboyne) each composed of 3 hydrological response units: arable, forest, and other. Within each hydrological response unit, 3 water stores were defined: quick, soil and groundwater. A small number of land usages was necessary to reduce the number of dimensions in the parameter space when performing a calibration (details in II.4.2). Indeed, previous studies (Perrin et al., 2001) have

proven that increasing model complexity improves the fit of observed data in calibration mode (in comparison to more restricted models), but often degrades the performance at the verification stage. This observation is all the more important if we aim to evaluate impacts of climate and land use change, where robustness of model performance is paramount.

PERSiST has been primarily designed for single catchment simulations at gauged basins. Indeed, it requires a calibration against streamflow measured at one or more points in the river. The calibration can be based on several indicators: Pearson’s correlation (R^2), Nash-Sutcliffe statistics (Nash & Sutcliffe, 1970) for untransformed (NS) and log-transformed (logNS) series, mean absolute error (MAE) and root mean square error (RMSE). Parameters can be calibrated manually or by using an algorithm (see II.4.2).

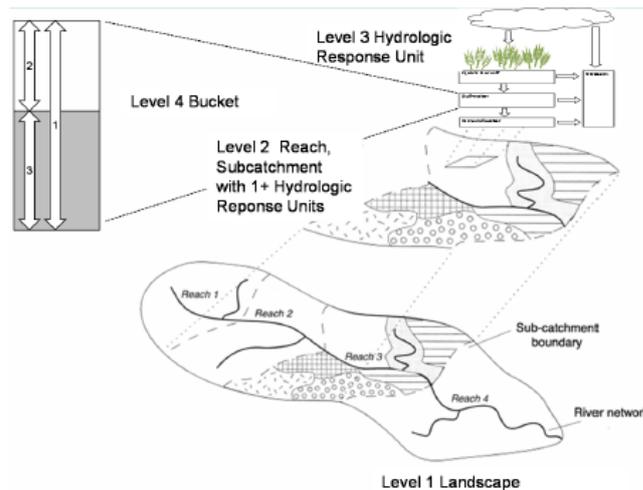


Figure 11: Conceptual representation of the landscape in PERSiST (Futter et al., 2014)

The model requires daily time series of air temperature and precipitation from one or more sites as driving data. PERSiST can also be used for projecting possible future patterns of runoff by using downscaled temperature and precipitation time series from regional or global climate models.

There are a number of parameters which control the hydrologic response type of the model. These parameters are applied at a subcatchment, reach, hydrologic response (corresponding to the different land uses) or bucket level (tab. 4).

Hydrological response units

The amount of water inputted into the model is controlled by precipitation and ET at the land-use scale. Parameters include snow-threshold temperature (h_1 in $^{\circ}\text{C}$), and snowfall and rainfall multipliers (h_2 and h_3). When temperatures are below the snow threshold, it is assumed precipitation falls as snow. Depth of rainfall and snowfall are calculated by multiplying observed precipitation by snowfall and rainfall multipliers. ET is calculated using a degree day evapotranspiration parameter (h_5) which defines the maximum ET when air temperatures are above the growing degree threshold (h_6 , $^{\circ}\text{C}$). The total amount of ET ($\text{mm}\cdot\text{d}^{-1}$) is calculated as the difference between observed air temperature (T) and the growing degree threshold (h_6) multiplied by the degree day ET parameter (h_5):

$$ET = (T - h_6) \cdot h_5 \quad (5)$$

ID	Name	Description	Unit	Min	Max
h1*	Snow threshold	Threshold temperature above which snow pack melts	°C	-1	1
h2*	Snow multiplier	Adjustment factor relating precipitation observations at the meteorological station to depth of snow actually falling on the land use	-	0.8	1.2
h3*	Rain multiplier	Adjustment factor relating measured precipitation to estimated rainfall	-	0.8	1.2
h4*	Degree day melt factor	Depth of water melted from the snow pack for every degree Celsius above snow melt threshold	mm. °C ⁻¹	1	2.5
h5	Degree day ET	Depth of water lost due to ET per degree per day, when temperature exceeds the growing degree threshold	mm. °C ⁻¹	See Table 5	
h6*	Growing degree threshold	Threshold temperature above which ET can occur	°C	-2	2
b1	Max capacity	Maximum depth of water that can be held in the bucket	mm	See Table 6	See Table 6
b2	Retained water depth	Depth below which water no longer freely drains	mm	Table 6	Table 6
b3*	Runoff time constant	Characteristic time constant for water drainage	d	Quick: 1 Soil: 3 GW: 40	Quick: 3 Soil: 10 GW: 120
b4	Relative ET	The fraction of total evapotranspiration in a landscape unit occurring in a given bucket	-	1 in Soil 0 elsewhere	
b5	ET adjustment	Exponent for limiting evapotranspiration	-	10	
b6	Infiltration	The maximum depth of water that may infiltrate into a bucket from any source	mm	1000 in Quick and Soil 480 in GW	
b7*	Drought runoff fraction	The fraction of incoming precipitation contributing null to runoff when the soil water will not freely drain	-	0	0.2 in Soil
b8	Relative area index	Fraction of surface area covered by bucket	-	1	
r1	Area	Subcatchment area	km ²	56.2	
r2	Length	Length of the main stem of the reach	m	Coull: 9300 Aboyne: 5400	
r3	Width	Width of the main stem of the reach	m	Coull: 2 Aboyne: 3	
r4	a	Flow velocity multiplier	-	0.565	
r5	b	Flow velocity exponent	-	0.241	

Table 4: Model parameters applicable at a hydrological response type (h_1 - h_6), bucket (b_1 - b_{10}) and reach (r_1 - r_5) level. Parameters having been calibrated when using the MCMC tool are marked with a *. The min and max represent the range within which these parameters were calibrated.

The values for the degree day evapotranspiration parameter were based on literature values. To quantify the effect of land use on hydrology, its link with the ET regime must be considered. Therefore, it is necessary to assess evapotranspiration rates as a function of the vegetation type and the soil moisture conditions. This was done in Dunn & Mackay's study on a southern Scottish catchment similar to our study area (1995) by combining two

equations. The Penman-Monteith formula (Monteith, 1965) accounts for the influence of vegetation on the evapotranspiration regime, and was combined with the Rutter interception model (Rutter et al., 1971) to provide a complete model of the interception, drainage and evapotranspiration processes. To obtain the total annual evapotranspiration loss for different land uses, a time series input of meteorological data combined with vegetation specific data was used. Table 5 gives the results in $\text{mm}\cdot\text{year}^{-1}$ averaged over 5 years.

To transform these values into degree day ET, we divided the annual ET loss estimated in Dunn & Mackay’s study (1995) by the sum of temperatures above $0\text{ }^{\circ}\text{C}$ averaged over several years from a sample of our observed meteorological data.

The “forest” hydrological response unit considers both coniferous/evergreen and broadleaf/deciduous trees, the total degree day ET having been calculated by applying an area weight to each. Other hydrological response units were given an average value of $475\text{ mm}\cdot\text{year}^{-1}$.

	Arable	Deciduous	Evergreen	Bracken	Conurbations	Felled	Grass	Heather
Annual ET loss	554	633	766	411	438	338	475	473
Degree day ET ($\text{mm}\cdot^{\circ}\text{C}^{-1}$)	0.19	0.22	0.26	0.16				
		Current LU: 0.25 WM: 0.26 NE: 0.26 GS: 0.24 LS: 0.24						

Table 5: Total evapotranspiration losses ($\text{mm}\cdot\text{y}^{-1}$) for different land uses and the corresponding degree day ET

Buckets

A hydrologic response type consists of one or more buckets linked together in a user specified manner. Buckets allow the routing of water by either storing it or transferring it to other buckets or to surface waters. Within each bucket water is divided into stagnant and freely draining fractions. The bucket can be partitioned as follows (Fig. 12): the maximum depth of water in a bucket (A; b_1 in Table 4) can be partitioned into freely draining water (B) and water that may contribute to ET but not drainage (C; b_2 in Table 4).

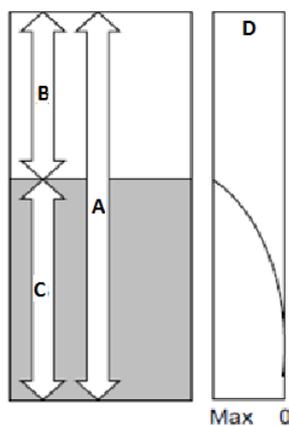


Figure 12: Generic bucket structure (left) and relative evapotranspiration rate as a function of water depth (right). A is the maximum depth of water in a bucket; B is the freely draining water; C is water that may contribute to ET but not drainage; D is the rate of ET (Futter et al., 2014)

The rate of ET (D) is not constrained when there is freely draining water in the bucket. If the water depth (z) drops below the freely draining depth (b_2) then ET is limited as a power function of water depth at a user defined rate (b_5) as follows:

$$ET = \left(\frac{z}{b_2}\right)^{b_5} \cdot ET \quad (6)$$

Retained water depths for each hydrological response type were set according to literature values. Firstly, the dominant soil types per land use were determined. Then, an area weighted average was calculated for field capacity (retained water depth) and saturation (maximum capacity) from the HOST database (Boorman et al., 1995; table 6).

The rate at which water drains from a bucket is controlled by a characteristic time constant (b_3). The depth of water draining on day t ($\Delta Z = z_{t-1} - z_t$) is calculated as follows:

$$\Delta Z = \frac{z_{t-1} - b_2}{b_3} \quad (7)$$

In many cases, rainfall during dry conditions is assumed to contribute only to recharge of the soil and groundwater. However, a small fraction of the rain may contribute to streamflow (Futter et al., 2014). This phenomenon is simulated by a drought runoff fraction (b_7), the fraction of total input contributing to streamflow when the water level is below retained water depth.

	Soil	% of dominant soils	FC (mm)	Saturation (mm)	PWP (mm)
ARABLE	Tarves	62.9	335	471	59
	Countesswells	37.1	320	455	45
		Weighted average	329.4	465.1	54
FOREST	Countesswells	100	320	455	84.9

	Land Use	% in "Other"					
OTHER	Heath	22.9	Pressendye	12.0	361	497	81.0
			Countesswells	10.9	320	455	84.9
	Improved Grassland	52.1	Tarves	32.1	335	471	58.9
			Countesswells	20.0	320	455	44.5
	Rough grazing	22.6	Countesswells	15.1	320	455	84.9
			Tarves	7.5	335	471	66.3
	Urban	1.9	Corby	1.2	124	259	70.0
			Undif alluvium	0.7	181.7	252.8	77.1
	Waterbodies	0.5	Countesswells	0.5	320	455	84.9
				Weighted average	327.5	462.6	66.4

Table 6: Dominant soils by land-use with their corresponding hydrological properties and area percentages (FC= Field Capacity, PWP= Permanent Wilting Point)

In the context of our study, we defined three buckets: quick, soil and groundwater. Quick-flow buckets simulate surface processes, receiving inputs of rainfall and snowmelt. Saturation excess flow generated by other buckets is routed through the quick bucket to the adjacent

reach. The soil and groundwater buckets were designed to represent the hydrological behaviour of these type of reservoirs.

The incoming amount of water draining into a bucket is limited by the infiltration rate (b_6) or the difference between the maximum and current water depth (b_1-z). However to avoid exceeding the box's storage capacity and create "saturation excess" (flows going back from soil box to quick box) we have set very high infiltration rates in the soil and quick box.

Flows of water between buckets are described using a square matrix (tab. 7). Elements (i,i) of the square matrix represent the fraction of water leaving the bucket that is directly routed to the stream. Elements (i,j) represent the fraction of water transferred from bucket i to j.

	Quick (Q)	Soil (S)	Groundwater (G)
Quick (Q)	Q to stream = 0	Q to S = 1	Q to G = 0
Soil (S)	S to Q = saturation excess (0)	S to stream = 0.4	S to G = 0.6
Groundwater (G)	G to Q = saturation excess (0)	G to S = saturation excess (0)	G to stream = 1

Table 7: Square matrix defined for the Tarland PERSiST application

Soil to groundwater infiltration, which we equate here to Base Flow Index (BFI), can be defined by performing a hydrograph separation. Here we used a mean value derived from BFI values for different Dee gauging stations available in the HOST database (Boorman et al., 1995). Soil to stream fluxes are equal to the remaining fraction of water ($1 - 0.6$).

Outputs

The final outputs obtained once a PERSiST simulation is run are:

- Streamflow; streamflow is estimated in upstream reaches first. While progressing downstream, flow is calculated based on streamflow from upstream reaches and inputs from the local sub-catchment. Runoff is estimated within these sub-catchments for each hydrologic response type. First rainfall and snowmelt are calculated using measured temperature and precipitation (i). Then they are routed through the uppermost bucket (ii), ET is subtracted (iii) and finally the outflow is estimated (iv). Steps (i)-(iv) are repeated for each bucket in the hydrological response type.

Reach parameters including length (r_2), width (r_3) (measured) and the parameters necessary to determine flow velocity as a function of flow (flow velocity multiplier and exponent, deducted) must be specified.

$$v = r_4 Q^{r_5} \quad (8)$$

Linking discharge to velocity allows us to infer how the flow out of the reach changes over time as input fluxes vary.

- Soil Moisture Deficit (SMD); this is calculated by determining the difference between depth of water in a bucket (z , mm) and bucket maximum water-holding capacity (b_1 ; mm)
- Hydrologically Effective Rainfall (HER); HER is an estimate of the precipitation entering a watershed which contributes to runoff (i.e. precipitation minus

interception and ET). HER is estimated by working backwards through time series of ET and precipitation inputs: starting from the last day of simulation actual ET is accumulated and precipitation for that day is subtracted and HER is obtained (unless the difference is negative, then HER is set to 0).

II.4.2. Model calibration and performance assessment

The calibration of hydrological models, i.e. the optimization of parameters from a set of observed data over a calibration period, aims to improve (or rather allow) the performance of these models in future simulations under climate change. To do so, an indicator of the model's performance is chosen, for instance the Nash-Sutcliffe coefficient (1970). A common problem encountered in model calibration, especially when there are a large number of parameters, is the equifinality of parameters (Beven, 2006). Equifinality refers to different parameter sets achieving similar results, implying that there are several acceptable representations of reality that cannot easily be dismissed and should be considered in the evaluation of uncertainty. Furthermore, if one or several optimal parameter sets is obtained for a given period, it is not guaranteed that the model performance will be maintained for a different period. This is of great importance when it comes to studies on climate change impacts: we know climate will be different, but we cannot judge the ability of our models to simulate future flows. To fully assess the uncertainty associated with calibration, and to test the model's robustness regarding climate variations, we first generated a large ensemble of parameter sets by performing a Markov Chain Monte Carlo (MCMC) calibration, which were subsequently tested using a split-sample test.

a. Markov Chain Monte Carlo (MCMC)

To evaluate uncertainty associated with calibration, one method is to produce a large amount of acceptable parameter sets by performing an autocalibration. Autocalibration increases reproducibility, reduces calibration time, takes into account equifinality and allows us to estimate parameter uncertainty. Futter et al. (2014) developed, alongside PERSiST, an MCMC tool to identify credible parameter sets, assess parameter sensitivity and generate ensembles of model predictions. The MCMC code was based on the Metropolis-Hastings algorithm (Metropolis et al., 1953; Hastings, 1970). The Metropolis-Hastings algorithm is a method of obtaining a sequence of random samples from a probability distribution.

When running an MCMC calibration, multiple Markov chains sample parameter proposals from distributions that are tuned during chain evolution. Proposal likelihoods are evaluated and compared to the previous iteration, the more likely proposals being accepted. The distribution of the next sample is dependent only on the current sample value. In brief, as described in the paper by Futter et al. (2014), the different steps taken by the MCMC sampler are as follows:

- (i) First, one must perform a manual calibration to provide a basis for identifying credible parameter ranges to be sampled during the MCMC analysis. The parameter set from the manual calibration initializes the system, setting the best model performance (BMP) and parameter set. Performance is estimated using Nash-Sutcliffe

statistics (Nash & Sutcliffe, 1970) for untransformed (NS) and log-transformed (logNS) flow time series: $\sum((NS - 1) + (\log NS - 1))$

- (ii) A random starting point is drawn from the parameter space and model performance is recorded. If model performance is better than the BMP, the starting point is accepted and the BMP and parameter set are updated. If on the contrary it is worse, the ratio between the two is calculated and compared to a random number between 0 and 1. If the ratio exceeds the random threshold, the starting point is accepted. Otherwise a new starting point is drawn and model performance evaluated.
- (iii) The parameter set is then perturbed by applying a jump. Model performance using the new parameter set is evaluated; if it is better the jump is repeated. If it is better than the BMP, the parameter set and BMP are updated. If it is worse, the ratio between the new and old model performance is compared to a random number between 0 and 1, either rejecting the jump or accepting it. If it is rejected, a counter is incremented; if the authorised number of rejection is reached, the process goes back to (ii). The process is repeated until no further improvement is achieved.

Once we obtained an ensemble of parameter sets, performance indicators on the calibration period were also outputted. Interpreting these indicators allows us to assess model performance, since they indicate how well the fit is between observed and simulated data for streamflow as well as for the logarithm of streamflow (which focuses on low flows). One of the indicators outputted is the Nash-Sutcliffe criterion (Nash & Sutcliffe, 1970), which indicates how well the plot of observed versus simulated data fits the 1:1 line. Nash-Sutcliffe efficiencies (NSE) range from $-\infty$ to 1. Essentially, the closer to 1, the more accurate the model is. Values <0 indicate the model performance is worse than the mean observed value, indicating unacceptable performance (Moriassi & Arnold, 2007). According to Moriassi & Arnold (2007), model performance is deemed satisfactory if $NSE > 0.5$, good if $NSE > 0.65$ and very good if $NSE > 0.75$.

b. Split-sample test

Klemeš (1986) defined a calibration/validation protocol to assess model performance in a rigorous manner: the split-sample test. This method consists in dividing the calibration period into several sub-periods, performing a calibration on one of the sub-periods and comparing the results with another sub-period. If the performance on the calibration period is similar to that on the validation period then the model is deemed robust. Choosing climatically contrasted period gives further indication of the model's robustness under different conditions; in this case it is a differential split-sample test.

For our study we divided the available flow logs into two sub-periods: the calibration period (07/03/2003-31/07/2007), which was inputted into the MCMC tool to obtain a parameter set ensemble, and a validation period (01/08/2007-31/12/2010) used to test the robustness of said parameter set ensemble. As the available log of observed flows was limited, the validation period chosen neighbours the calibration period, hindering the possibility of performing a differential split-sample test (and therefore estimating the model's robustness in the face of climate change). Slight climatic differences are however present

amongst these two periods (Annex 2) so the test offers to a certain extent an indication of the robustness of this model under changing climate.

II.5. Hydrological and climatic descriptors

After obtaining a set of climatic and hydrological datasets for each scenario considered, we calculated a series of indicators allowing us to better understand the evolution of climate and water resources in our research zone.

II.5.1. Climate descriptors

Climate descriptors allowing us to describe changes in climatic variables were calculated by comparing the simulated baseline and the simulated future for each WG scenario, multiplicative for precipitation and ET and additive for temperature.

$$\text{Precipitation \& ET: } \Delta P = (P_{sim}^F - P_{sim}^B)/P_{sim}^B \text{ and } \Delta ET = (ET_{sim}^F - ET_{sim}^B)/ET_{sim}^B \quad (9)$$

$$\text{Temperature: } \Delta T = T_{sim}^F - T_{sim}^B \quad (10)$$

The ^B and ^F exponents refer to Future and Baseline.

II.5.2. Hydrological descriptors

a. Streamflow

Changes in flows and Soil Moisture Deficit were also calculated using multiplicative change factors. Simulated future flows and SMD were not compared with observed data, but with a simulated baseline created by inputting climate data from the control period into the hydrological model. This eliminates part of the bias potentially created when there are differences between the *actual* data and the data outputted by the model.

$$\Delta Q = Q_{sim}^F/Q_{sim}^B \quad (11)$$

$$\Delta SMD = SMD_{sim}^F/SMD_{sim}^B \quad (12)$$

Q_{sim}^F and SMD_{sim}^F refer to the variables simulated by inputting the bias-corrected 100 climate simulations and using 100 parameter sets, and Q_{sim}^B and SMD_{sim}^B refer to the simulated baseline created by inputting Met Office climate data for the control period (1961-1990) also using 100 parameter sets. Other indicators calculated allowed us to analyze changes in extreme flows. For this we calculated the Q10 (exceeded 10% of the time) for daily flows, which characterize high flows, and the Q80 (exceeded 80% of the time) for monthly flows.

b. Irrigation requirements

A suitable way of determining the amount of water necessary for irrigation is by estimating soil moisture deficit (SMD), the difference between field capacity (FC, i.e. maximum amount of water held by the soil when excess has drained off) and the actual water content of the soil (fig. 4). Indeed, SMD and crop growth and quality are intimately linked. When ET becomes greater as a result of a temperature increase or greater ET rates, the soil's water content is depleted, and plants' capacity to extract the water decreases. When a plant can no longer extract water from a soil, the Permanent Wilting Point (PWP) has been reached. The yield and quality of a crop however can be affected from when the soil's water reserves have

attained approximately 35 to 55% of a soil’s available water reserves (FC – PWP). The point at which this happens is known as the Critical SMD (CSMD). Exceeding Critical SMD may imply the need to irrigate in order to preserve crop quality and quantity. In reality however CSMD also depends on rooting depths (and therefore crop type).

As irrigation requirements and SMD can be linked using a linear relationship (Knox et al., 2007), we assume change factors obtained for SMD are very similar to irrigation requirement change factors. Multiplicative change factors were therefore calculated for SMD, as well as a series of indicators relating to variations in SMD over time (tab. 8).

Dry Soil Days (days)	Count of days where the soil is at or below the permanent wilting point
Maximum SMD (mm)	Lowest soil water level expressed as a deficit from field capacity
Maximum SMD Day (day of year)	First occurrence of the maximum soil water deficit
Critical SMD period (day of year)	Period during which soil moisture is below critical SMD
Critical SMD period length (days)	Duration of the critical SMD period
Non-CSMD period length (days)	Count of days where SMD is below critical SMD

Table 8: Soil indicators

III) Results and discussion

III.1. Model performance and robustness

Table 9 summarizes the results of the performance and robustness assessment, obtained by analysing Nash-Sutcliffe efficiencies and performing a split-sample test.

	Calibration		Validation	
	NS(Q)—Coull	NS(Q)—Aboyne	NS(Q)—Coull	NS(Q)—Aboyne
10% Quantile	0.65	0.75	0.66	0.60
Median	0.67	0.77	0.69	0.63
90% Quantile	0.69	0.78	0.72	0.66

	NS(logQ)—Coull	NS(logQ)—Aboyne	NS(logQ)—Coull	NS(logQ)—Aboyne
	10% Quantile	0.66	0.80	0.75
Median	0.68	0.82	0.78	0.79
90% Quantile	0.70	0.84	0.80	0.81

Table 9: Model robustness evaluated by calculating the Nash-Sutcliffe criterion on streamflow and the logarithm of streamflow for each sub-catchment; quantiles shown represent the uncertainty within the 100 parameter set ensemble

NS efficiencies on the calibration period are greater than 0.65, which indicates a good performance (Moriasi & Arnold, 2007), more so for the Aboyne sub-catchment than for Coull. NS efficiencies for the logarithm of streamflow are better than those for streamflow, which indicates performance is improved in the absence of high flows. This can be seen in Figure 13: flow peaks aren’t properly simulated. Although projections for high flows will be given, these are to be considered qualitatively. However, the fit between simulated and observed low flows is satisfying, which increases our confidence in low flow projections and inferred tendencies for mean annual and seasonal streamflow changes.

Furthermore, results for the validation period are quite similar to those for the calibration period, increasing our confidence in the parameter set ensemble and model performance.

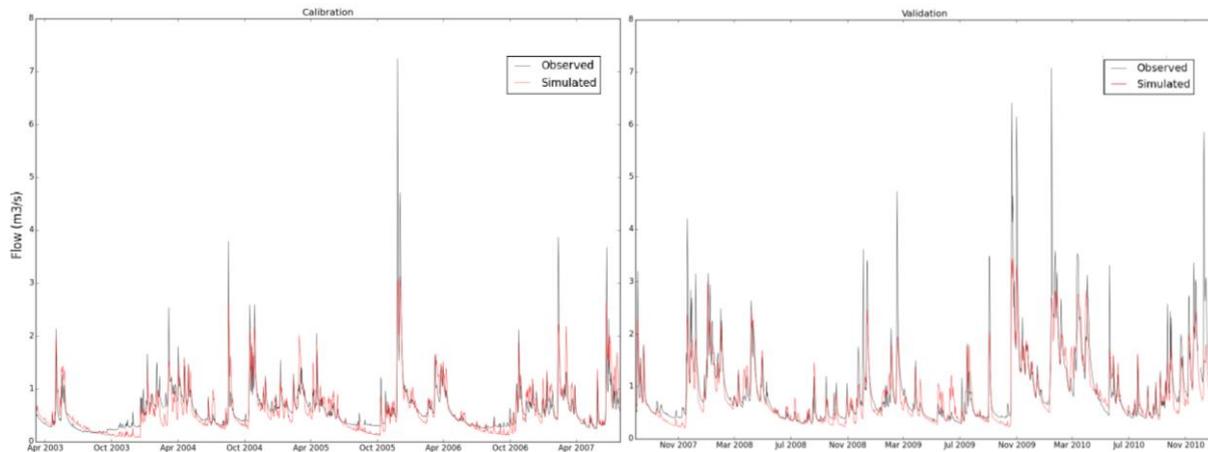


Figure 13: Fit between simulated and observed flows for the calibration (left) and validation (right) period for the Coull sub-catchment

III.2. Impact of climate change

III.2.1. Temperature, ET and precipitations

a. Precipitation

The results obtained by calculating the difference between baseline simulations and future simulations show little to no change in precipitation at a yearly scale for both periods (tab. 10). Furthermore, the uncertainty amongst different WG simulations hinders the possibility to infer major trends with certainty: confidence intervals are large (fig. 14), ranging from negative to positive variations. The table in Annex 4 shows the confidence intervals for precipitation, temperature.

Precipitation	2041-2070	2071-2100
Spring	1	2
Summer	-15	-18
Fall	5	5
Winter	11	9
YEAR	0	0

Table 10: Projected future precipitation change (in %) between baseline and future simulations (median value amongst WG simulations)

2041-2070: At a seasonal scale slight variations are observable (tab. 10), the most important changes occurring in summer and winter months. Summer precipitations are projected to decrease by about 15%, opposite to winter months where the projected change is about +11%. Spring and fall months show changes lower or equal to 5%.

2071-2100: For the far future the observed trends are similar but of different intensity (tab. 10). Winter precipitations are expected to increase by 9% and summer precipitations are projected to decrease by 18%. Spring and fall months would also remain very close to present day.

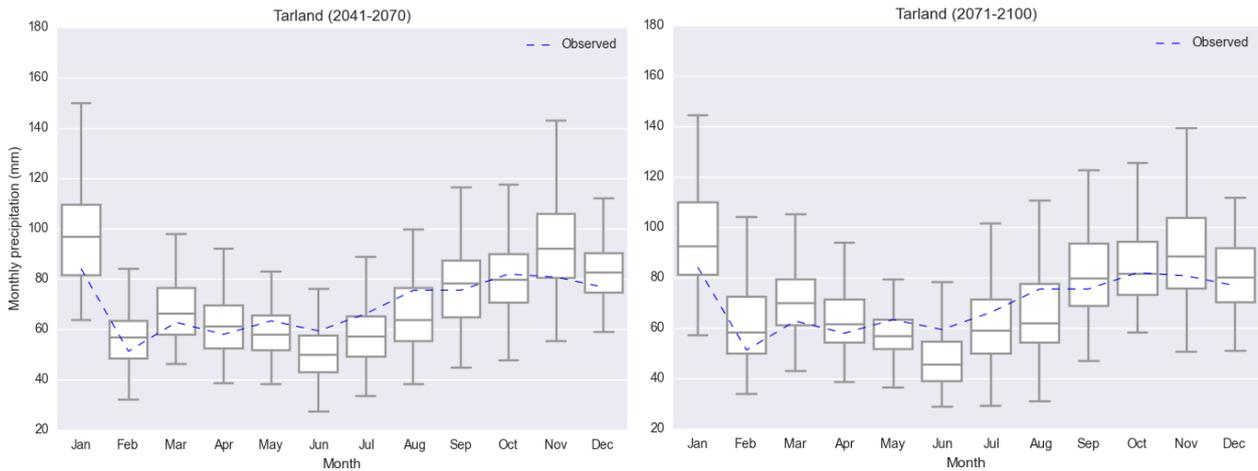


Figure 14: Monthly precipitations averaged, per month, over each 30 year period. Future precipitations are shown as boxplots representing the range of variation amongst the 100 WG simulations for the 2041-2070 (left) and 2071-2100 (right) periods; the centre of the boxplots shows the median value, the outlines the quartile range, and the whiskers the 10% and 90% quantiles. Observed precipitations are represented as a dashed line.

It is important to note that these estimations are approximate. As can be observed in 14 and 4, projected changes vary from negative to positive, and often observed precipitations are contained within the quartile range of future precipitations.

b. Temperature

Contrary to precipitations, temperature variations are clearer and unidirectional, showing a year-long increase (fig. 15). The range in WG projections is however still quite large.

Temperature	2041-2070	2071-2100
Spring	1	2
Summer	2	4
Fall	3	3
Winter	2	2
YEAR	2	3

Table 11: Projected future temperature change (in °C) between baseline and future simulations (median value amongst WG simulations)

2041-2070: For the near future, mean yearly temperatures are projected to increase by 2°C on average. The greatest seasonal increase, of 3°C, would occur in fall. The least important variation would occur in spring months, with a 1°C increase (tab. 14).

2071-2100: In the far future, the temperature increase is greater. At a yearly scale temperatures are expected to increase by 3°C. Again, summer months show the greatest increase (4°C), opposite to winter and spring months where the increase is of 2°C.

The increase in temperature alone is likely to impact biodiversity by increasing water temperatures, threatening the survival of cold-water fish species such as Brown trout and Atlantic salmon.

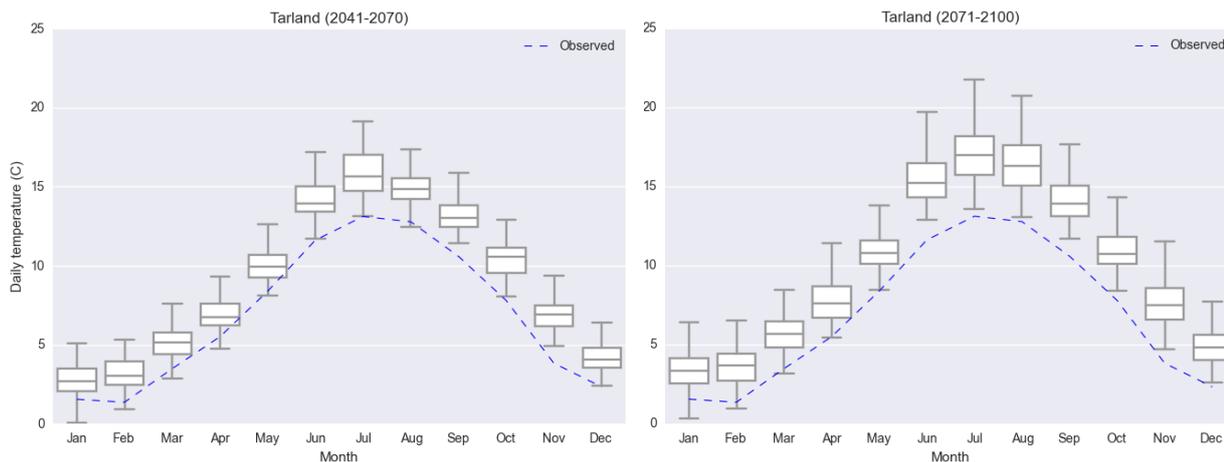


Figure 15: Daily temperatures averaged, per month, over each 30 year period. Future temperatures are shown as boxplots representing the range of variation amongst the 100 WG simulations for the 2041-2070 (left) and 2071-2100 (right) periods. Observed temperatures are represented as a dashed line.

c. Actual Evapotranspiration and Hydrologically Effective Rainfall

PERSiST outputs hydrologically effective rainfall (HER; precipitation entering a watershed eventually contributing to runoff, Futter et al., 2014) and we know how much precipitation is inputted, so we were able to deduce actual evapotranspiration (AET), equal to precipitation minus HER and interception (which was set to 0). AET is different from potential evapotranspiration (PET). PET is the amount of water one expects to be evaporated in the absence of moisture limitations, following the same pattern as temperature; AET is influenced by both temperature and precipitation inputs.

	AET		HER	
	2041-2070	2071-2100	2041-2070	2071-2100
Spring	22	30	-22	-32
Summer	-9	-10	-19	-26
Fall	9	8	-20	-24
Winter	37	48	-23	-37
YEAR	13	17	-26	-33

Table 12: Projected future AET and HER change (in %) between baseline and future simulations (median value amongst WG simulations and parameter set configurations)

2041-2070: AET changes show a different trend than temperature variations and are therefore seemingly impacted not only by the temperature rise but also by changes in precipitation. At a yearly scale, AET is projected to increase by 13%, most likely due to temperature (for precipitation variations at this scale are close to 0%). We observe great disparity amongst seasons, better explained by intra-seasonal precipitation variations. In summer, AET would diminish by 9% regardless of the 2°C temperature increase: the precipitation decrease (of 15%) appears to be the dominant factor. Contrariwise, spring, fall and winter AET would increase. We suppose here that the combination of larger amounts of water available (i.e. an increase in precipitation) and rising temperatures is responsible for stronger AET.

As the temperature increase alters the balance between total water evaporated and total water contributing to runoff and infiltration, HER, opposite to AET, is expected to decrease; the estimated decrease is weakest in summer, for rising temperatures are counterbalanced by the precipitation increase.

2071-2100: The same trends occurring in the 2041-2070 period are observable: an increase in mean yearly AET (+17%), greater spring and winter and fall AET (+25%, +42% and +15% respectively). We also observe a summer decrease of 13%, again most likely driven by the precipitation decrease.

III.2.2. Water resources

As noted above, climate change will lead to a warmer climate and seasonal precipitation variations. As a result of these changes, the balance between AET and HER will be altered, and the overall amount of water inputted into the system will decrease. Here we show the impact of these changes on river discharge and soil moisture.

a. River discharge

Streamflow	2041-2070	2071-2100
Spring	-12	-18
Summer	-25	-32
Fall	-33	-38
Winter	-4	-15
YEAR	-20	-29

Table 13: Projected future streamflow change (in %) between simulated flow baseline and simulated future flow (median value amongst WG simulations and parameter set configurations)

2041-2070: Flow projections for the near future show a decrease in mean annual flows of 20%. The greatest mean seasonal decrease would be during fall and summer, by 25% and 33%, and winter month variations would be the weakest by less than 5% (tab. 13).

Low flows, as represented by the Q80, are projected to decrease by about 30% in the near future. This decrease can be associated with a high level of confidence, for the 10% and 90% quantile values are respectively -42% and -29%. High flow variations are minor, the projected change being of about -3%, the confidence interval being [-12%, 6%].

2071-2100: Projections for the far future also show a net reduction in flows. Mean annual streamflow is projected to decrease by 29%. The strongest seasonal decrease would also occur in summer and fall months, by 32% and 38%. Winter months are the least affected, with discharge variations of -15%.

Low flows are projected to decrease further as climate change intensifies. For the far future period the projected decrease is of about 40%, with a confidence interval of [-51%, -24%]. High flows also show very little change (-8%) with a confidence interval of [-16%, 0.5%].

b. Soil moisture

Determining changes in soil moisture should allow us to infer future trends in irrigation requirements. Indeed, as described in I.2.1., irrigation needs can be linked to SMD by using a linear regression. This relationship however implies that cropping patterns along with the

extent of irrigated surface remain the same, which isn't the case. Therefore, the following projections are to be considered qualitatively.

SMD	2041-2070	2071-2100
Spring	17	27
Summer	25	35
Fall	29	38
Winter	22	34
YEAR	25	37

Table 14: Projected future SMD change (in %) between simulated SMD baseline and simulated future SMD (median value amongst WG simulations and parameter set configurations)

2041-2070: Climate simulations show a pronounced tendency towards drier soils, with SMD projected to increase year-long (tab. 14). At a yearly scale this increase is estimated to be about 25%. The increase would be greatest in the fall (about 29%) and least important in spring (17%), although seasonal differences aren't very pronounced (tab. 14).

2071-2100: As temperatures increase further, the increase in SMD would become more severe. The average yearly increase would be of 37%, approaching 40% in the fall and about 27% in the spring.

Overall, variations in SMD show that increasing temperatures will likely lead to an increase in irrigation requirements, therefore further stressing the region's available water resources. To better understand the impact of the projected increase in SMD on land use management, it is necessary to determine when the critical SMD will be reached (see II.5.2).

SMD indicators

Changes in intensity and timing of SMD variations are expected to occur. Further analysis of SMD variations can allow us to better comprehend how crop systems will be impacted. Figure 16 shows the shift in yearly distribution of SMD relative to the critical SMD, which, if exceeded, is expected to affect crop quality. As most arable land is concentrated in the Coull catchment (tab. 3, fig. 10) this analysis will focus on this sub-catchment.

	Present	2041-2071	2071-2100
Dry Soil Days (days)	0	0	0
Maximum SMD (mm)	112	141	182
Maximum SMD Day (day of year)	240	212	242
Critical SMD period (day of year)	-	-	188-286
Critical SMD period length (days)	0	0	98
Non-CSMD period length (days)	365	365	267

Table 15: SMD indicators for the control period and the two climate change scenarios considered

Present day SMD in average doesn't exceed critical SMD. However, as temperatures rise, SMD is projected to increase year-round (tab. 14 and fig. 16). For the near future, median SMD remains below the critical threshold for all seasons, although during drier years this threshold is likely to be exceeded. For the far future irrigation requirements may become significant. As we can observe in Figure 16, SMD is expected to exceed the critical threshold for over three months per year on average, from the beginning of July to mid-October (tab.

15). As crop quality is impacted when this occurs, it is likely that a change in crop management will be necessary, particularly for vegetables whose growth period occurs during these months (e.g. cabbage, radish...), all the more so if we consider increasing requirements for high-quality produce from agriculture and horticulture (Brown et al., 2012).

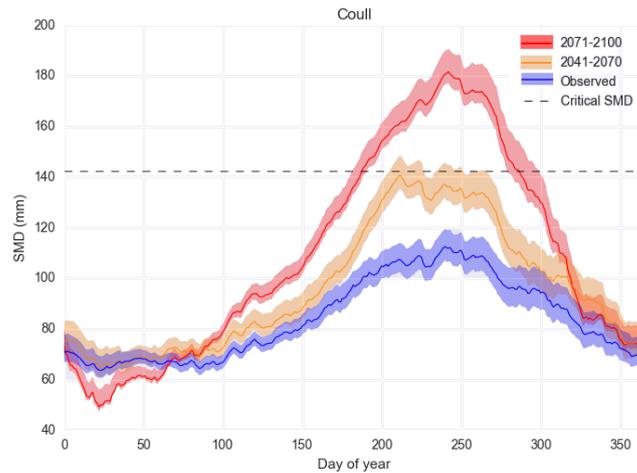


Figure 16: SMD averaged over each 30 year period to show inter-annual variations for the Coull sub-catchment; coloured lines indicate the median value amongst parameter sets used and shading shows the 10th and 90th percentiles

III.3. Impact of land use change

III.3.1. Scenario results

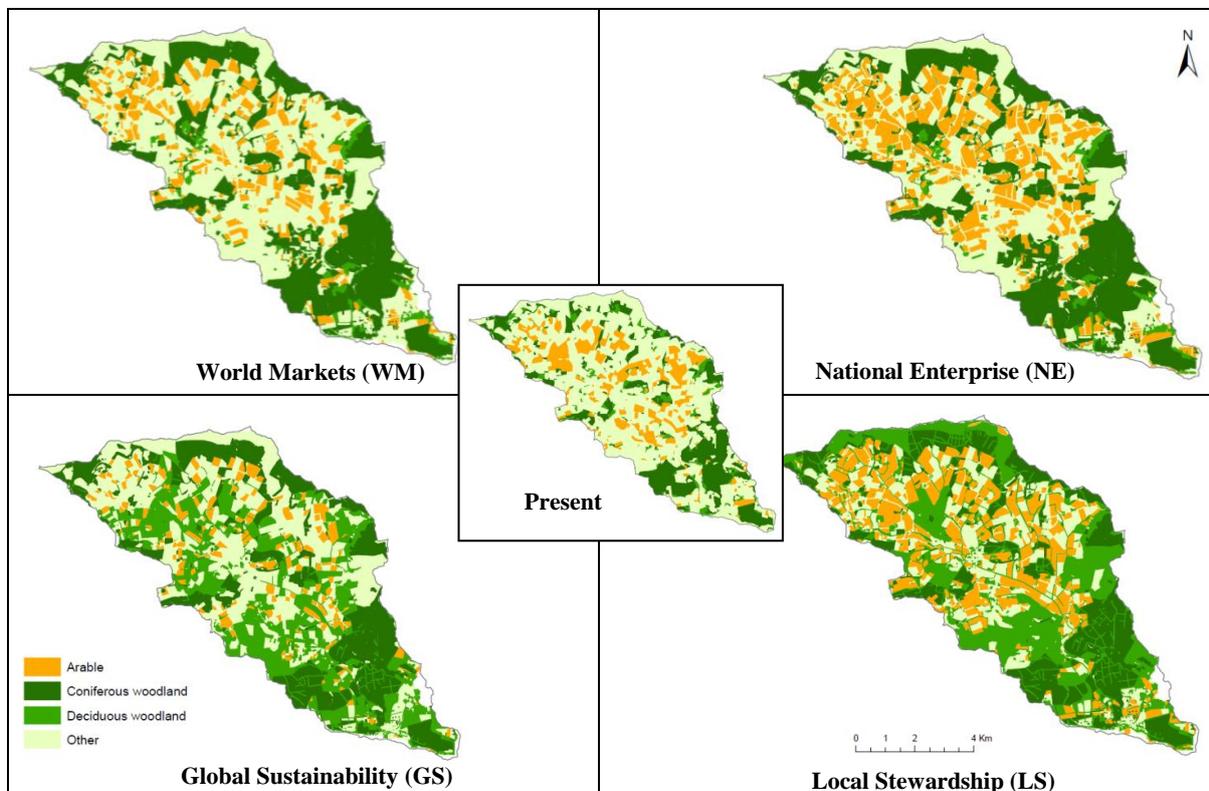


Figure 17: LandSFACTS land use scenario simulations for World Markets (WM), National Enterprise (NE), Global Sustainability (GS) and Local Stewardship (LS); land uses considered in “Other” are detailed in Annex 1

Land use changes obtained for the Tarland, divided by sub-catchments, are summed up in the following table:

		PRESENT	WM	NE	GS	LS
COULL	Arable (%)	21	23	37	15	36
	Coniferous (%)	14	22	21	20	20
	Deciduous (%)	5	2	2	20	20
	Other (%)	60	53	39	46	24
ABOYNE	Arable (%)	9	10	17	7	13
	Coniferous (%)	36	46	49	39	39
	Deciduous (%)	5	4	4	32	30
	Other (%)	50	39	30	22	18

Table 16: Current land use and projected changes in distribution for each land use scenario simulations, World Markets (WM), National Enterprise (NE), Global Sustainability (GS) and Local Stewardship (LS)

The obtained distribution of land use reflects the type of governance and societal values prioritized, as defined in Figure 8 for each scenario. All scenarios incorporate an increase in woodland cover, consistent with the Land Use Strategy for Scotland (2011), although the amount and type vary for each separate storyline. Scenarios with a dominance of economy over environment (WM and NE) show an important expansion in coniferous woodland limited by the extent of “prime” arable land; if environment dominates then the preferred woodland is deciduous. When local governance is applied (LS and NE), arable land is greatly expanded at the expense of semi-natural environments and grassland.

III.3.2. Changes in AET and HER

A first estimation of the impact of land use change on water resources without the impact of climate change was performed. For this the proportion of the different land uses considered was varied, each possessing characteristic AET rates and water retention properties. Climate variables inputted belong to the control period (1961-1990).

By solely varying the proportions of each land use, the balance between AET and HER is altered. Results are shown in Table 17.

	AET				HER			
	WM	NE	GS	LS	WM	NE	GS	LS
Spring (%)	8	12	15	16	-9	-13	-19	-20
Summer (%)	1	2	3	3	-4	-6	-8	-9
Fall (%)	0	1	0	0	-3	-5	-6	-8
Winter (%)	10	14	17	18	-11	-17	-26	-27
Yearly (%)	4	6	8	8	-7	-11	-16	-18

Table 17: Projected future AET and HER change (in %) between simulated AET and HER baseline and simulated future AET and HER for the different LandFACTS scenarios (median value amongst parameter set configurations)

At a yearly scale, we observe that every scenario considered projects an increase in AET and therefore a decrease in HER. This can be explained by the fact that all scenarios comprise a decrease in the surface of semi-natural and improved grassland environments, characterised by lower ET rates (tab. 3).

We also observe that regardless of the scenario considered, the greatest changes would occur in winter and spring, whereas summer and fall months show little to no change. This could be explained, similarly to what was observed as a result of climate change, by AET being constrained by the amount of water available, which implies that an increase in the ET rates or temperature would be irrelevant.

The increase observed is weakest for the WM simulation and greatest for the LS simulation. Since forests have greater ET rates than arable and semi-natural lands, then it is expected that the scenarios with the greatest afforestation objectives would result in stronger ET. This however is not the only factor influencing water resources as a result of land use change: water retention properties (e.g. field capacity, saturation...; tab. 6) vary as well, and will therefore have an impact on soil moisture and river discharges.

III.3.3. Water resources

a. River discharge

When observing the outputs of PERSiST regarding streamflow, we observe that there would be an overall very slight yearly decrease for most scenarios, except WM. The observed decrease would be strongest in the summer. Finally, the same hierarchy, in which WM is the least affected and LS the most, is observed. These changes are however equal or inferior to 10%, and the uncertainty range is very large (Annex 4), so inferring actual trends from these projections proves difficult. Note however the important difference in projected streamflow variations between the LS scenario and the WM scenario.

	WM	NE	GS	LS
Spring (%)	0	-3	-5	-8
Summer (%)	-6	-9	-10	-15
Fall (%)	2	-4	-3	-13
Winter (%)	-1	-3	-4	-9
Yearly (%)	3	-2	-3	-10

Table 18: Projected future streamflow change (in %) between simulated flow baseline and simulated future flow for the different LandSFACTS scenarios (median value amongst parameter set configurations)

Regarding low flows (tab. 19), these are strongly impacted by land use change, almost as much as by climate change. The decrease ranges between 8% for the NE scenario, down to 35% for the LS scenario. High flows on the other hand aren't quite as impacted as changes range from +6% to -2%.

	WM	NE	GS	LS
Q80 (%)	-24 [-37;-10]	-8 [-24;+11]	-29 [-45;-9]	-35 [-57;-9]
Q10 (%)	6 [-6;+20]	-3 [-11;+19]	1 [-15;+23]	-2 [-22;+23]

Table 19: Flow and high flow projection changes for each land use scenario considered and confidence intervals amongst different parameter set configurations

Overall, the greatest impact would result from the GS and LS scenarios, forming part of the scenario category where environment is prioritized. These scenarios envisage more environmentally friendly land management by preferring non-intensive agriculture and

expanding native woodland; this would decrease the amount of diffuse pollution entering the system and allow the development of biodiversity. However, this analysis shows that these approaches might also have a negative effect on aquatic ecosystems (salmonid spawning etc...) due to the strong decrease of low flows.

b. Soil Moisture

	WM	NE	GS	LS
Spring (%)	3	4	1	1
Summer (%)	6	9	9	10
Fall (%)	8	12	15	15
Winter (%)	7	10	6	6
Yearly (%)	8	11	11	12

Table 20: Projected future SMD change (in %) between simulated SMD baseline and simulated future SMD for the different LandSFACTS scenarios (median value amongst parameter set configurations)

Land use simulations show a mild tendency (<15%) towards drier soils, with SMD projected to increase year-long. Compared to the impact of climate change, land use changes would have a much lesser impact.

Scenarios where environmental objectives are prioritized (GS and LS) show the greatest increase in SMD, due to the expansion of woodland characterized by higher ET rates. However, depending on the spatial distribution of SMD, greater values might be concentrated in woodland areas, possessing deeper roots which can therefore access deeper soil water stores.

SMD indicators

	Obs	WM	NE	GS	LS
Dry Soil Days (days)	0	0	0	0	0
Maximum SMD (mm)	112	117	119	120	125
Maximum SMD Day (day of year)	240	240	240	240	240
Critical SMD period (day of year)	-	-	-	-	-
Critical SMD period length (days)	0	0	0	0	0
Non-CSMD period length (days)	365	365	365	365	365

Table 21: SMD indicators for the control period and the different LandSFACTS scenario simulations

Concerning the average yearly variations of SMD, we observe that regardless of the scenario considered critical SMD is never reached (fig. 18; tab. 21). This shows the robustness of Tarland’s water resources regarding land use changes, quantitatively speaking. Changes in diffuse pollution mustn’t however be overlooked; previous studies (Dunn et al., 2012) showed that under certain scenarios of high priority for food security, changes in land use are more important in determining changes in diffuse pollution than direct hydrological effects caused by climate change. For the Tarland catchment more particularly, land use change simulations estimated nitrate concentrations to almost double (from 2mg.l⁻¹ to 3.8 mg.l⁻¹).

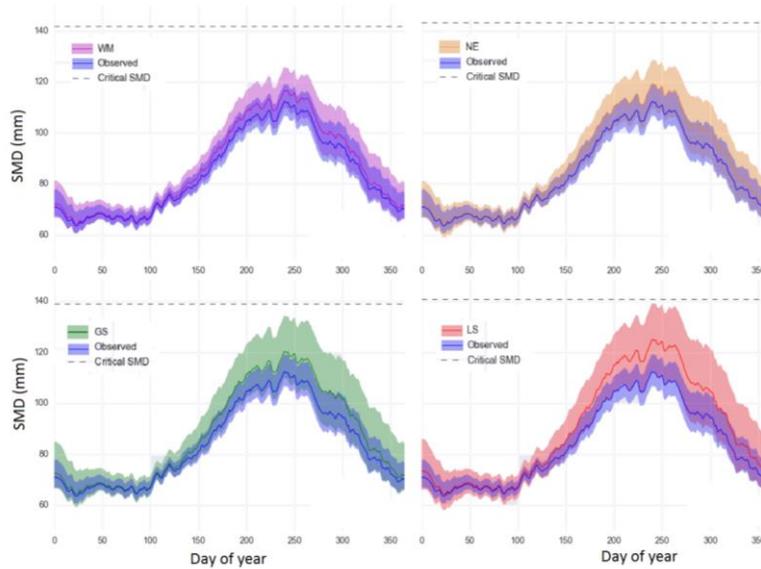


Figure 18: SMD averaged over each 30 year period to show inter-annual variations for the Coull sub-catchment; coloured lines indicate the median value amongst parameter sets used to simulate SMD and shading shows the 10th and 90th percentiles

III.4. Impact of climate change and land use change

The final scenario evaluated is one that combines both the impacts of climate and land use change. Here only the two most extreme land use scenarios will be evaluated, World Markets and Local Stewardship; this reduces the number of combinations of different scenarios while still constraining the range of variation. Overall, we dispose of eight scenarios, consisting of each possible combination of time period considered and land use scenario.

III.4.1. Changes in AET and HER

	AET				HER			
	2041-2070		2071-2100		2041-2070		2071-2100	
	WM	LS	WM	LS	WM	LS	WM	LS
Spring (%)	28	33	34	39	-30	-40	-38	-47
Summer (%)	-9	-8	-10	-9	-23	-28	-29	-34
Fall (%)	9	8	8	8	-22	-24	-25	-27
Winter (%)	44	50	54	60	-30	-42	-42	-50
Yearly (%)	16	19	20	23	-30	-34	-36	-40

Table 22: Projected future AET and HER change (in %) between simulated AET and HER baseline and simulated future AET and HER for the LandSFACTS and WG scenario simulations (median value amongst parameter set configurations and WG simulations)

2041-2070: All future scenarios predict both an increase in AET and a decrease in HER. The LS scenario considers the most severe changes, although differences between land use scenarios are less important than differences amongst periods considered.

Mean yearly AET is expected to increase by 16% to 19% under the combined influence of a temperature increase and greater ET rates due to changes in land use. As a result of the AET increase, HER would decrease by 30% to 34% as the overall distribution between water evaporated water and water routed through the system would be altered.

Intra-seasonal variations are significant for AET changes, least important in the summer (-9% to -8%) and greatest in winter (+44% to +50%), following the same pattern than precipitation variations. Moreover, fall and summer changes remain very similar to changes under climate change alone, regardless of the addition of land use change stresses, as precipitation inputs act as a limiting factor. HER on the contrary would decrease year-long and projected intra-seasonal variations are less important.

2071-2100: Projections for the far future show that warmer temperatures and changes in seasonal precipitations would intensify the trends observed for the near future. The range of variation between the WM and LS scenario remains the same.

AET would increase by 20% to 24% and HER would decrease by 36% to 40%, which should greatly impact river discharge as the total amount of water entering the system will be greatly decreased. Furthermore, seasonal changes should also reflect on streamflow distribution, especially in the months where AET is constrained by the amount of water available (i.e. summer and fall months).

III.4.2. Water resources

a. River discharge

	2041-2070		2071-2100	
	WM	LS	WM	LS
Spring (%)	-16	-25	-22	-31
Summer (%)	-27	-34	-33	-39
Fall (%)	-34	-39	-39	-42
Winter (%)	-8	-19	-19	-31
Yearly (%)	-23	-33	-32	-40

Table 23: Projected future flow change (in %) between simulated flow baseline and simulated future flow for the LandSFACTS and climate change scenarios (median value amongst parameter set configurations and WG simulations)

2041-2070: Concerning streamflow, all scenarios consider a significant decrease in mean yearly discharge. The decrease would be generalized across all seasons, strongest in the summer and fall (27% to 34% and 34% to 39% respectively) and weakest in the winter (8% to 19%). The impact of changes in land use on streamflow is quite important: depending on the scenario chosen, land use management could have an equal impact on flows than a temperature increase. Indeed, the decrease in streamflow projected for the LS scenario in the near future is equivalent to that projected for the WM scenario in the far future.

2071-2100: Mean yearly streamflow changes for the far future vary from -32% to -40%; as for the near future, these changes would be greater in summer and fall (-33% to -39% and -39% to -42% respectively) and least important in winter (-19% to -40%).

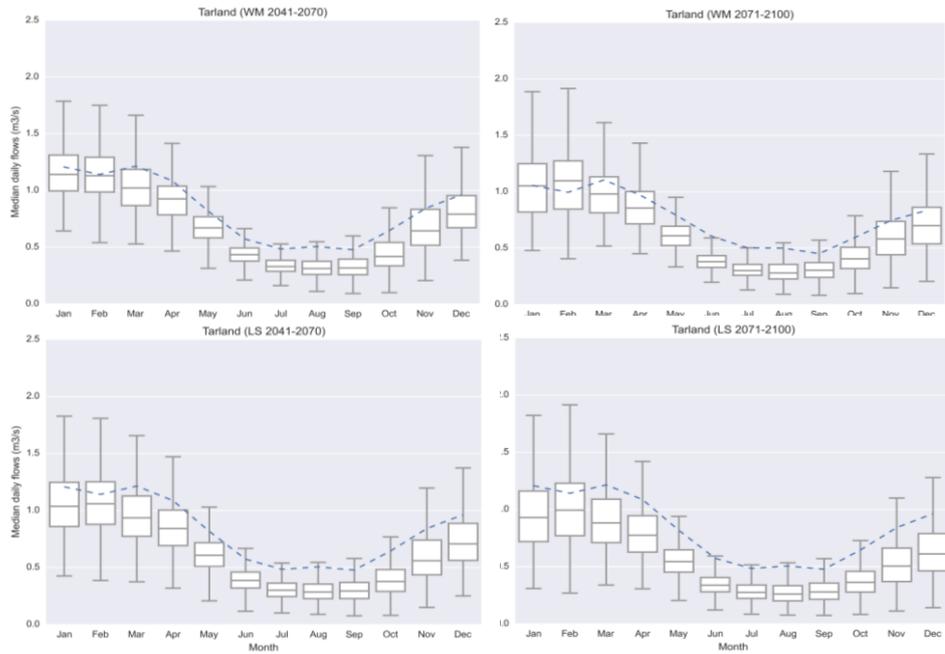


Figure 19: Daily flows averaged, per month, over each 30 year period. Future flows are shown as boxplots representing the range of variation amongst the 100 WG simulations and parameter set configurations for the 2041-2070 (left) and 2071-2100 (right) periods. Simulated baseline flows are represented as a dashed line.

In general, woodland expansion at the expense of semi-natural environments and improved grassland combined with greater temperatures could lead to a strong decrease in streamflow. Woodland would be responsible for faster restitution of precipitation into the atmosphere, and rising temperatures would increase the total amount of water evaporated.

Low flows would decrease significantly as well (tab. 24); confidence intervals support this affirmation. As for mean seasonal and yearly streamflow variations, the greatest decrease would occur under the LS scenario. High flow variations however don't show a clear tendency for the near future, confidence intervals ranging from positive to negative values, suggesting these would remain close to present day high flows. Far future high flows show a more pronounced tendency towards a decrease.

	2041-2070		2071-2100	
	WM	LS	WM	LS
Q80 (%)	-31 [-44;-19]	-41 [-61;-18]	-40 [-52;-27]	-48 [-67;-26]
Q10 (%)	-5 [-15;+5]	-15 [-32;+9]	-12 [-20;-2]	-21 [-38;+1]

Table 24: Flow and high flow projection changes for each land use and climate change scenario combination considered and confidence intervals amongst different parameter set configurations and WG simulations

The important decrease in streamflow predicted could have severe consequences on several fronts; slower flows and less water mean shallower, warmer, less oxygenated water, which could be damaging for ecology. Diminished flows also imply there will be less water available for abstraction, and the ability to dilute effluent inputs from sewage treatment works and septic tanks will be lower, impacting water quality.

These consequences could potentially be widespread across the river Dee catchment, damaging and internationally important habitat, and causing problems for the city of Aberdeen, which is almost entirely supplied by the river Dee.

b. Irrigation requirements

	2041-2070		2071-2100	
	WM	LS	WM	LS
Spring (%)	23	23	36	37
Summer (%)	32	38	43	50
Fall (%)	37	45	46	54
Winter (%)	33	40	47	56
Yearly (%)	36	43	47	56

Table 25: Projected future SMD change (in %) between simulated SMD baseline and simulated future SMD (median value amongst parameter set configurations and WG simulations)

The combined impact of climate and land use change will likely lead to a sharp increase of mean yearly SMD, ranging from 36% to 43% in the near future, and from 47% up to 56% for the far future. Although the choices in land use management can alter the intensity of this phenomenon, the main driver is the temperature increase.

	Obs	2041-2070		2071-2100	
		WM	LS	WM	LS
Dry Soil Days (days)	0	91	132	140	159
Maximum SMD (mm)	112	196	206	238	248
Maximum SMD Day (day of year)	240	263	263	242	242
Critical SMD period (day of year)	-	179-328	169-343	157-325	151-334
Critical SMD period length (days)	0	149	174	168	183
Non-CSMD period length (days)	365	216	191	197	182

Table 26: SMD indicators for the control period and the different LandSFACTS and climate scenario simulations

Finally, we observe that all future scenarios project SMD to exceed critical SMD at some point; the length and magnitude of this exceedance period depends on the land use scenario chosen and the intensity of the projected change in climate. The most severe drying occurs under the LS scenario, although, as previously mentioned, if the increase in SMD is localized in woodland areas then arable land irrigation requirements might be null. However, if SMD changes are driven by climate change then they are generalised over the entire catchment and affect all land usages equally.

Overall, for all scenarios considered the critical period extends from May-June to September for 5 to 6 months, which will most likely severely impact crops grown during this period, leading to either changes in crop rotations or the use of irrigation.

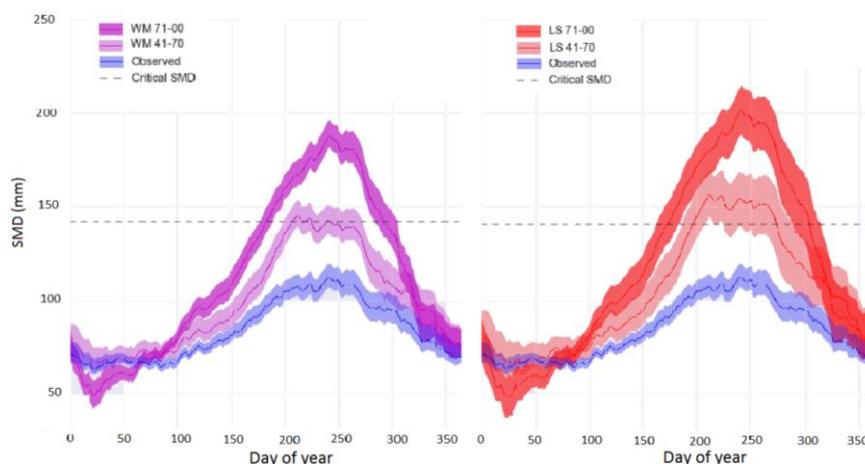


Figure 20: SMD averaged over each 30 year period to show inter-annual variations for the Coull sub-catchment; coloured lines indicate the median value amongst parameter sets used to simulate SMD and shading shows the 10th and 90th percentiles

Conclusion

This study has allowed us to draw preliminary conclusions concerning the evolution of climate, streamflow and other hydrological variables for two future periods under varying stresses.

Results show a temperature increase ranging from 1° C to 3°C for the near future and from 1°C to 5°C for the far future (2°C and 3°C respectively at the 50% probability level). Mean yearly precipitations are expected to remain the same with seasonal variations, i.e. a decrease in the summer (15% to 18%) and an increase in the winter (9% to 11%).

Projected land use changes include woodland expansion for all scenarios, although the amount and type vary for each separate storyline. Arable land changes are dependent on the importance granted to food security ranging from a slight decrease to a significant increase. The surface granted to semi-natural environments and improved grassland would decrease significantly to allow the expansion of woodland and arable land; more so for the environmentally driven scenarios. Climate change will have greater consequences on most hydrological variables than land use change, although changes projected under the LS scenario resemble changes under near future climate conditions. Low flows are equally impacted by both land use and climate change.

Overall, increasing temperatures combined with the expansion of land uses characterized by higher ET rates will have several consequences. First, AET will increase significantly, leading to a sharp decrease in HER, meaning the total amount of water being routed into the different hydrological compartments will be greatly reduced. Months possessing initially low inputs (i.e. summer and fall) will be most impacted.

Proportionally to HER and AET variations, yearly mean streamflow will be severely reduced, by 23% to 33% for the near future, and by 32% to 40% for the far future. This decrease, although generalised throughout all seasons, is most intense in summer and fall, winter flows being the least impacted.

Soil moisture deficits are expected to become much greater, from 36% to 43% in the near future and from 47% to 56% in the far future. All scenarios combining climate and land use change project an exceedance of the critical threshold for several months during summer and the beginning of fall. This could lead either to changes in crop rotations or if high-quality produce is grown, to increased irrigation requirements, which, if obtained through surface abstractions will increase stress the on region's water resources.

The Tarland is a fairly typical Northern European "marginal" agricultural catchment and the issues identified in this study are therefore likely illustrative of pressures faced elsewhere in Scotland, as well as in parts of e.g. Scandinavia. This research project is a first step in allowing policy makers to better understand the consequences of the Scottish Government's Land Use Strategy, by highlighting key trade-offs between sometimes conflicting policy objectives. Most importantly, this study emphasises the strong potential impact of afforestation on water resources. For example, some of the more "environmentally friendly" land use scenarios considered are predicted to cause reductions in low flows that could be harmful to aquatic ecology.

Further research should focus on integrating other water-related services such as drinking water provision, hydropower and flood risk management. Also, quantifying the link between SMD and irrigation needs through better understanding of cropping patterns and water requirements of the produce grown is necessary. Finally, properly constraining all uncertainty sources (from greenhouse gas emission scenarios to downscaling methods) as well as reducing uncertainty linked to the hydrological model's parameterization is an important step in increasing confidence and trust in this and other impact studies.

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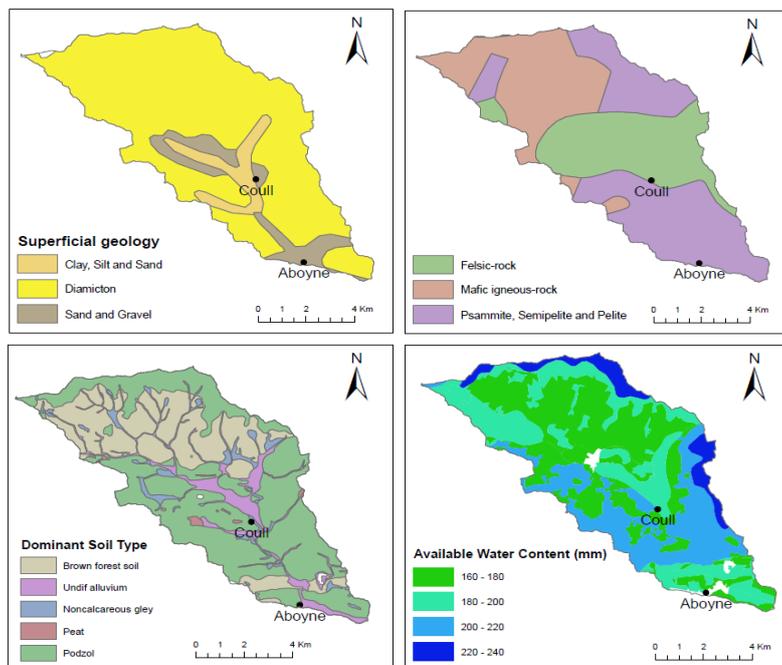
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Annexes

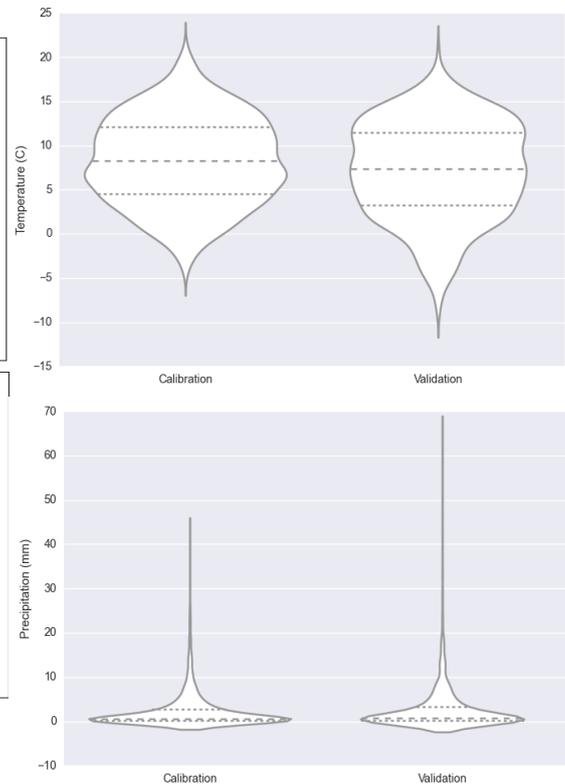
Detailed LandFACTS classes	Broad land cover classes	Simplified classes
Arable Silage For Stock Feed	Arable	Arable
Build Up	Urban	Other
Coniferous Trees	Semi-Nat	Coniferous
Fallow	Arable	Arable
Grass Over 5 Years	Improved Grass	Other
Grass Under 5 Years	Improved Grass	Other
Heather	Semi-Nat	Other
Inland Water	Water	Other
Land, Natural (Non Fields)	Rough Grazing	Other
Marsh Reed, Saltmarshes	Semi-Nat	Other
Mixed Natural	Rough Grazing	Other
Multi Surface (Backyards & Gardens)	Urban	Other
New Woodland	Semi-Nat	Depends on scenario
Nonconiferous Trees	Semi-Nat	Deciduous
Normal Setaside - Bare Fallow	Arable	Arable
Normal Setaside - Nat Regen (After C)	Arable	Arable
Normal Setaside - Sown Grass Cover	Arable	Arable
Other Crops For Stock Feed	Arable	Arable

Rape For Stock Feed	Arable	Arable
Roads, Path And Roadside	Semi-Nat	Other
Rock, Boulders	Semi-Nat	Other
Rough Grassland	Rough Grazing	Other
Rough Grazing	Rough Grazing	Other
Scrub	Rough Grazing	Other
Seed Potatoes	Arable	Arable
Spring Barley	Arable	Arable
Spring Oats	Arable	Arable
Spring Oilseed Rape	Arable	Arable
Spring Wheat	Arable	Arable
Turnips/Swedes For Stock Feed	Arable	Arable
Unclassified	Improved Grass	Other
Unknown	Improved Grass	Other
Winter Barley	Arable	Arable
Winter Oilseed Rape Energy	Arable	Arable
Winter Wheat	Arable </td <td>Arable</td>	Arable

Annex 1: Detailed land cover classes used for the LandFACTS scenario analysis and subsequent simplifications



Annex 3: Geological, pedological and hydrological description of the Tarland catchment



Annex 2: Temperature and precipitation distribution for the calibration and validation period used for the split-sample test

Annex 4: Tables summarizing climate and hydrological changes and the uncertainty ranges associated

		2041-2070			2071-2100		
		10%	Median	90%	10%	Median	90%
Precipitation (relative deltas, %)	Spring	-20	1	29	-19	2	31
	Summer	-36	-15	16	-40	-18	19
	Fall	-19	5	40	-20	5	41
	Winter	-15	11	40	-17	9	47
	YEAR	-22	0	31	-24	0	34

Temperature (absolute deltas, °C)	Spring	0	1	3	1	2	4
	Summer	1	2	4	2	4	6
	Fall	1	3	4	2	3	5
	Winter	0	2	3	0	2	4
	YEAR	1	2	3	1	3	5

		2041-2070						2071-2100					
		WM			LS			WM			LS		
		10%	Median	90%	10%	Median	90%	10%	Median	90%	10%	Median	90%
AET relative deltas, %	Spring	-59	28	131	-56	33	142	-52	34	146	-50	39	155
	Summer	-66	-9	109	-65	-8	111	-68	-10	114	-67	-9	115
	Fall	-68	9	120	-68	8	124	-66	8	126	-66	8	128
	Winter	-58	44	220	-57	50	229	-50	54	233	-49	60	241
	YEAR	-61	16	166	-60	19	170	-58	20	173	-57	23	177

HER relative deltas, (%)	Spring	-76	-30	91	-80	-40	87	-78	-38	70	-82	-47	64
	Summer	-65	-23	55	-72	-28	52	-68	-29	42	-75	-34	42
	Fall	-67	-22	101	-72	-24	86	-69	-25	79	-74	-27	76
	Winter	-82	-30	113	-85	-42	105	-85	-42	95	-87	-50	84
	YEAR	-74	-30	150	-78	-34	126	-76	-36	121	-80	-40	95

Flow relative deltas, %	Spring	-69	-16	73	-74	-25	68	-72	-22	65	59	-31	8
	Summer	-65	-27	52	-70	-34	39	-68	-33	34	24	-39	-8
	Fall	-71	-34	121	-74	-39	91	-73	-39	98	70	-42	0
	Winter	-76	-8	92	-80	-19	86	-81	-19	85	78	-31	25
	YEAR	-74	-23	138	-76	-33	125	-76	-32	123	109	-40	6

SMD relative deltas, %	Spring	-14	23	109	-15	23	129	-11	36	127	-12	37	147
	Summer	-9	32	79	-8	38	88	1	43	90	2	50	99
	Fall	-11	37	77	-8	45	85	-4	46	87	-1	54	95
	Winter	-23	33	127	-25	40	143	-20	47	145	-22	56	160
	YEAR	-32	36	112	-33	43	123	-28	47	125	-30	56	136

Résumé

Les changements potentiels du climat, de l'usage du sol et de la demande en eau auront pour effet de modifier la distribution et la disponibilité des ressources en eau en Ecosse. Comprendre la résistance de ces ressources face à ces changements est important afin de s'assurer que les décideurs fassent des choix éclairés en matière de planification de l'utilisation des terres, d'adaptation au changement climatique et de gestion efficace de l'eau.

Ce projet de recherche a pour objectif de quantifier les impacts du changement climatique et du changement d'usage du sol sur les ressources en eau du bassin versant du Tarland pour deux périodes, le futur proche (2041-2070) et le futur lointain (2070-2100).

La zone d'étude choisie est un sous-bassin versant du Dee, un environnement de grande importance écologique pourvoyant plus de la moitié de l'Aberdeenshire en eau potable. Ce sous-bassin se situe entre un parc national et des plaines alluviales, pouvant ainsi donner lieu à l'extension de forêts ou de terres arables.

Les simulations du changement climatique ont été dérivées des extrants du Weather Generator UKCP09, un générateur stochastique de conditions météo, et débiaisées en appliquant la méthode des deltas. Les projections de changement d'usage du sol ont été générées préalablement avec un logiciel stochastique, LandSFACTS, intégrant à la fois les causes « top-down » et « bottom-up » du changement d'usage du sol. Les débits, l'évapotranspiration réelle (ETR) et l'humidité du sol ont ensuite été calculés en utilisant un modèle pluie-débit semi-distribué, PERSiST.

Le changement climatique aura pour effet d'augmenter les températures moyennes annuelles de 2°C pour le futur proche et de 3°C pour le futur lointain. À l'échelle annuelle les variations de précipitation seront nulles. Cependant des variations intra-saisonniers auront lieu, une diminution en été (de -15% à -18%) et une augmentation en hiver (de +9% à +11%). L'ETR augmentera du fait de l'augmentation de la température combinée à l'augmentation des taux d'évapotranspiration due aux changements d'usage du sol causés par les politiques gouvernementales et les changements biophysiques ; parallèlement la pluie efficace va diminuer significativement. Ces changements impacteront les débits en provoquant une baisse marquée des débits moyens annuels de 23% à 33% pour le futur proche, et de 32% à 40% pour le futur lointain. De plus, il est prévu que l'humidité du sol diminue fortement, provoquant ainsi des changements dans la gestion des terres et, éventuellement, à une augmentation des besoins en irrigation. Finalement, les changements démographiques entraîneront une augmentation de la demande d'eau douce, le tout augmentant la pression exercée sur les ressources en eau disponibles.

Mots-clefs : changement climatique, usage du sol, modélisation hydrologique