BASE

BOTTOM-UP CLIMATE ADAPTATION STRATEGIES TOWARDS A SUSTAINABLE EUROPE

Title: Report on the model developments in the sectoral assessments

Summary: This deliverable reports the advancements of the work accomplished by WP3 under Tasks 3.3: Quantitative analysis of adaptation priorities in key social economic contexts. The Deliverable includes 10 parts. Chapter 1 includes an introduction and the modelling approach in the context of BASE. Chapters 2 to 8 describe the advances in the models developed in BASE, including a critical discussion of their use for evaluating risks and opportunities and adaptation strategies. Chapter 9 outlines the modelling linkages to the continental economic model, among sectors, and between sectoral models and the case studies, and provides a strategy for integration of model outputs and cross validation of the information provided in the Case Studies. Chapter 10 outlines the conclusions.

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1 Introduction

1.1 Objective

The Objective of this Deliverable D3.2 is to describe the models developed in BASE that is, the experimental setup for the sectoral modelling. The model development described in this deliverable will then be implemented in the adaptation and economic analysis in WP6 in order to integrate adaptation into the economic assessments. At the same time, the models will link to the case studies in two ways. First, they use the data in the case studies for model validation and then they provide information to inform stakeholders on adaptation strategies.

Therefore, Deliverable 3.2 aims to address three main questions:

How to address climate adaptation options with the sectoral bottom-up models?

- This includes a quantification of the costs of adaptation with the sectoral models, in monetary terms or in other measures of costs. The benefits in this framework will be the avoided damages, therefore a measure of impacts is necessary.
- How are models linked to the economic model?
- How is the information from the case studies and the information from the sectoral models mutually supportive?

Figure 1 outlines modelling adaptation in BASE.

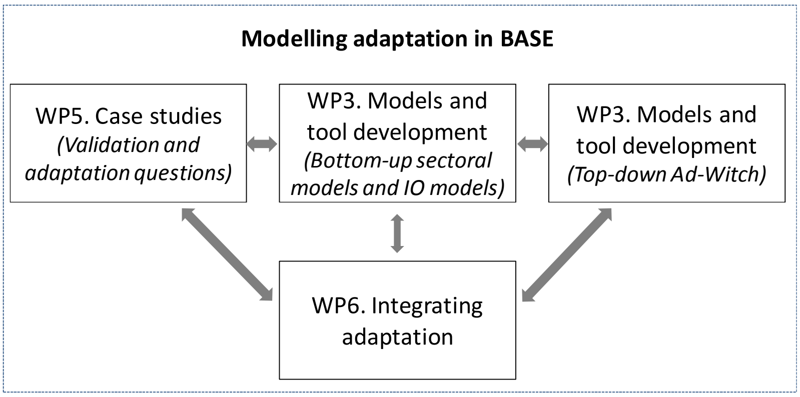


Figure 1 Sectoral models developed in BASE and their scales and relationship to the Case Studies and the Global models

Within BASE three different types of models are used (Figure 2):

- Economy wide models: describing the consequences of climate change adaptation and mitigation on GDP and other macroeconomic indicators. These types of models describe the interactions within the economy in some detail but are very coarse in spatial resolution. In BASE we use the Ad-Witch model to describe EU-wide economic implications of different climate strategies. On a lower scale we use the IO-model of Univ. Leeds to study cross-sectoral impacts on the regional economy (Urban scale). As input from other models these economy wide models require estimates of damages from climate change and avoided damage and investment costs of climate adaptation. These models are described in D3.1.

- Sector models provide the direct (avoided) damages and effects of climate adaptation. Sector models usually have a higher spatial resolution. In BASE we have sector models available for flood and drought damage, health impacts, impacts on environmental flows and ecosystem services. As input these models require spatial explicit information on climate effects, its consequences and adaptation measures. This Deliverable D3.2 describes the sectoral models for quantitative estimation of adaptation.
- At the case study level, decision support tools like PRIMATE, which supports users in assessment of cost and benefits or multi criteria analysis under uncertainty in a multi-stakeholder setting. These tools are described in D4.1.

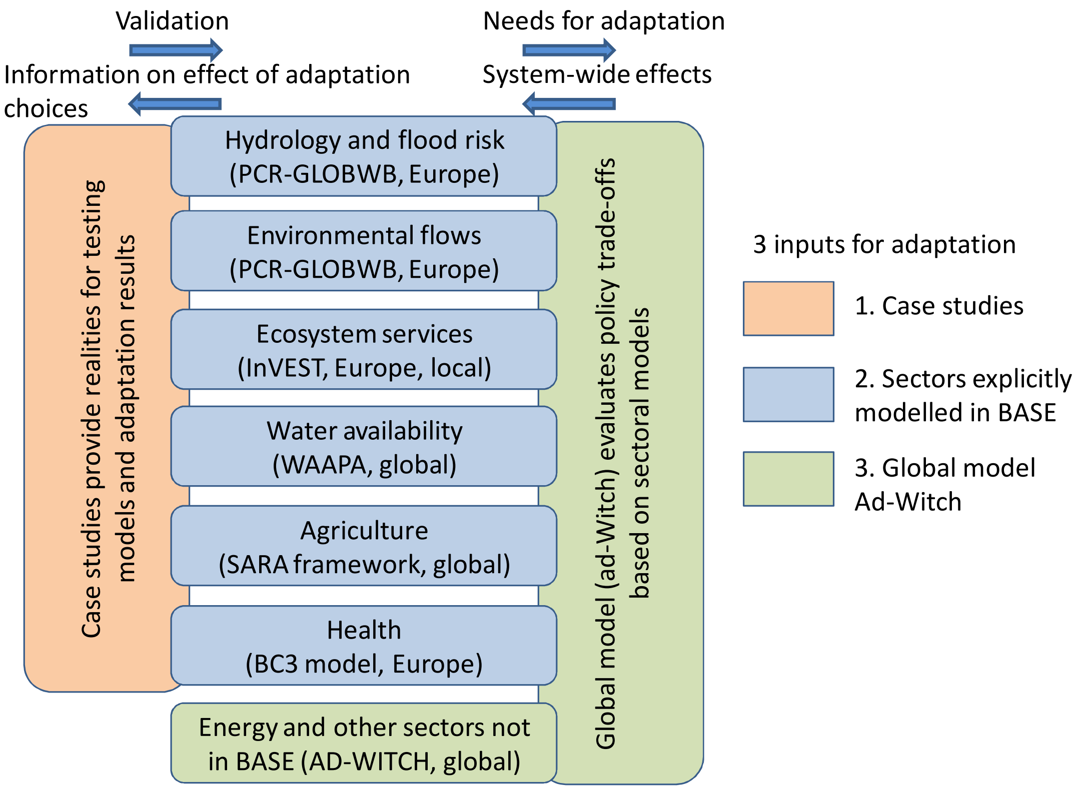


Figure 2 Sectoral models developed in BASE and their scales and relationship to the Case Studies and the Global models

1.2 BASE context

One of the final aims of the BASE project is to improve the current knowledge on climate change adaptation processes. BASE approaches adaptation knowledge by providing quantitative information on costs and benefits of adaptation and providing higher integration, access and use of this information.

D3.2 aims to develop appropriate methodologies and models and contributes to three specific Goals of BASE with a strong methodological content. These are:

Goal 2: Improve current, develop new and integrate methods and tools to assess climate impacts, vulnerability, risks and adaptation policies to and enrich past and current EU research project outputs.

Goal 4: Assess the effectiveness and full costs and benefits of adaptation strategies to be undertaken at local, regional, and national scales using innovative approaches (mainly by integrating bottom-up knowledge/assessment and top-down dynamics/processes) with particular attention on sectors of high social and economic importance.

Goal 5: Bridge the gap between specific assessments of adaptation measures and top-down implementation of comprehensive and integrated strategies.

The contribution to Goal 2 is the development of different modelling tools and approaches to the study of adaptation. The models will then be used in the assessment of the costs and benefits of adaptation (Goal 4). D3.2 also provides an integration of the data from the Case Studies (Goal 5).

Deliverable D3.2 reports on the development of tools for quantitative analysis of adaptation priorities in key social economic contexts. This deliverable D3.2 is linked to Task 3.3. The objective of Task 3.3 is to improve the models underpinning the sectoral assessments of adaptation potentials, costs and benefits. Key sectors have been selected due to their importance for adaptation prioritising and model development.

2 Hydrology and flood risks

Laurens Bouwer, Hesel Winsemius, Andreas Burzel (Deltares)

2.1 Introduction

There is increasing attention in the scientific and policy communities for large scale global assessments of natural disaster risks. For example, the United Nations International Strategy for Disaster Risk Reduction (UNISDR) now coordinates the production of the two-yearly Global Assessment Report (GAR) on Disaster Risk Reduction (UNISDR, 2009, 2011), which provides a global overview of natural hazard risk and risk reduction efforts, and analyses of the underlying trends and causes. Furthermore, risk due to extreme events and disasters are at the core of the report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) of the Intergovernmental Panel on Climate Change (IPCC) (Field et al., 2011). Large-scale risk assessments are required by a number of organisations. International Financing Institutes need to assess which investments in natural disaster risk reduction are most promising to invest in; supra-national institutions need to monitor progress in risk reduction activities, for example those related to the implementation of the Hyogo Framework for Action (UNISDR, 2005); (re-)insurers need to assess insurance conditions, coverage and premium setting; and large companies need to assess risks to their regional activities. In particular at the European level, large-scale risk assessments and flood hazard mapping are required to implement the European Floods Directive.

The GAR2009 and GAR2011 reports show current estimates of global risk in terms of fatalities and economic exposure for several natural disasters, as well as trends in disaster risk over the past few decades. Extending these global risk assessments to include future changes in both natural disaster frequency and intensity (for example due to climate change) and socioeconomic conditions. Such assessments would allow societies to develop and consider different options for disaster risk reduction. The results of global risk assessments may in particular be used to compare risks from region to region in order to decide which region deserves most commitment to the development of risk reduction measures or mitigation procedures in a changing future.

Flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide and floods are, together with windstorms, the most frequent natural disasters (Munich Re, 2010; UNISDR, 2009). It therefore has a prominent place in the GAR2011 report, where flood hazard is based on a methodology published by Herold and Mouton (2011). Here the methodology is further developed and updated as described below.

The goal of this work is to develop a flood risk model for Europe that is able to project changes in flood risk due to climate change and socio-economic developments. It has been argued that both may lead to increases in flood impacts and damages (see Field et al., 2012; Bouwer et al., 2010; Bouwer et al., 2013).

2.2 Overview of modelling approach in BASE

In EU-BASE we will build upon the global flood risk estimation method, presented by Winsemius et al. (2013) and Ward et al. (2013) to fit the needs of European scale flood risk assessment. In this section, we provide a brief overview of the model cascade and its functionalities, taken from Ward et al. (2013) with regard to the flood hazard. The impact module will be further tailored and developed, to fit the data availability and requirements of the case studies in BASE. The overview is schematised in Figure 3. The framework estimates hazard at a resolution of about 1 km^2 using global forcing datasets; here the CMCC dataset will be used. It also uses a global hydrological model, a global flood-routing, and more importantly, a inundation downscalling routine.

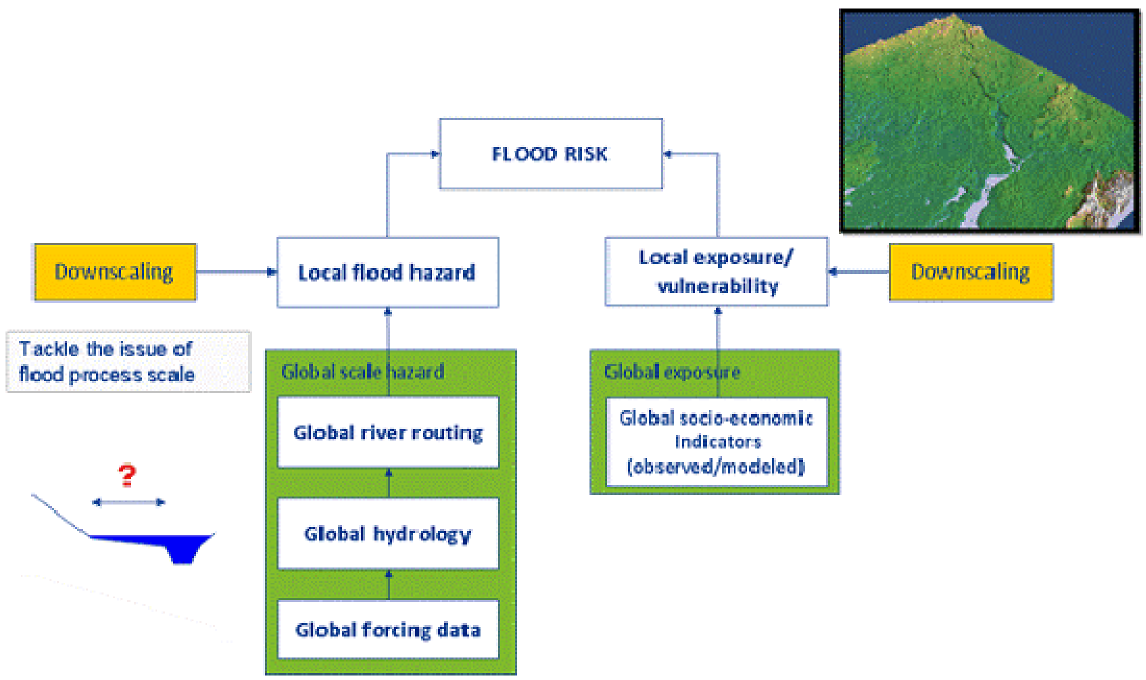


Figure 3 Overview of the GLOFRIS model cascade

Below, the different steps in the analysis of flood risks and adaptation will be discussed. These are:

- Hydrological and hydraulic modelling
- Impact modelling
- Implementing and assessing adaptation options

2.3 Hydrological and hydraulic modelling

For the BASE project, we will simulate daily discharges and flood volumes (0.5◦× 0.5◦) using the global hydrological model PCR-GLOBWB (Van Beek and Bierkens, 2009; Van Beek et al., 2011), and its extension for dynamic routing, DynRout (PCR-GLOBWB-DynRout). Discharge arises from flood-wave propagation; in each cell the associated flood volume is stored in the channel or on the floodplain in case of overbank flooding. The suitability of these models is discussed in Winsemius et al. (2013). In brief, the model runs on a daily time-step, which is sufficiently short for runoff generation and flood propagation. Two other important features are that the runoff scheme resolves infiltration excess as a non-linear function of soil moisture; and the routing differentiates river flow from overbank flow dynamically. PCR-GLOBWB is forced by meteorological fields (precipitation, temperature, potential evaporation).

Across Europe, the LISFLOOD model (Van Der Knijff et al., 2010) has been used to assess flood risks. LISFLOOD is used in an operational system called European Flood Awareness System (Alfieri et al., 2012; Roo et al., 2011). The LISFLOOD_FP system (Neal et al., 2011, 2012) is a flood routing and inundation scheme, which functions as an extension of the water balance model of LISFLOOD. Recently, this model has been applied at Pan-European scale to produce a 100-year return period flood hazard map, using the SRTM elevation model as underlying topography (Bates et al., 2013).

At the global scale, Winsemius et al. (2013) developed a framework to assess river flood risks globally called Global Flood Risk estimation with IMAGE Scenarios (GLOFRIS). The framework takes into account multiple return periods in order to include frequent and less severe floods, as well as rare and more severe floods. It combines flood hazard maps at 30" resolution with impacts in terms of affected people, agricultural land, asset damage and can estimate future flood risk using bias-corrected GCM outputs. The framework has been applied at the full global scale for the first time by Ward et al. (2013). These efforts prove that large-scale flood mapping using a cascade of hydrological and hydraulic models is feasible.

Extreme value statistics

Inundation maps will be developed for different return-periods estimated using the Gumbel distribution. From the daily flood volume time-series (derived from PCR-GLOBWB daily simulations), an annual time-series of maximum flood volumes is extracted over the run-time period. For each cell, a Gumbel distribution is fitted through the time-series, based on non-zero data (extracting Gumbel parameters for the best-fit and the 5 and 95% confidence limits). For cells in which zero flood volume is simulated in one or more years, also the exceedance probability of zero flood volume is calculated. These Gumbel parameters can then be used to calculate flood volumes per grid-cell for selected return-periods (e.g. 2, 5, 10, 25, 50, 100, 250, and 1000 years). Flood volumes are calculated conditional to the exceedance probability of zero flood volume.

Inundation modelling

The coarse resolution flood volumes will be converted into high resolution (30 arc minutes) inundation depth maps, which form the hazard maps. This is carried out using the GLOFRIS downscaling module described in Winsemius et al (2013). In brief, the module includes a high resolution digital elevation model (30” × 30”; or about 1 x 1 km) and a map of river cells at the same resolution. For each 0.5◦ × 0.5◦ grid-cell, the module iteratively imposes water levels, in steps of 10 cm, above the elevation of each river-cell in the high resolution. It then evaluates which upstream connected cells on the high resolution grid have an elevation lower than the imposed water level in the river channel. These cells receive a layer of flood water, equal to the water level minus the elevation of the cell being considered. This process is iterated (with steps of 10 cm) until the flood volume generated for the cell in the low resolution model (0.5◦ × 0.5◦) has been depleted. We assumed that flood volumes with 2-year return-period would not lead to overbank flooding (Dunne and Leopold (1978) estimate bankfull discharge to have an average return-period of about 1.5 years). Hence, this flood volume is first subtracted from the flood volumes for the different return-periods (5, 10, 25 year, etc), before the inundation downscaling is carried out. In practice, this means that any systematic overestimation of 2-year flood volume (whether that be related to the input climate data, hydrological–hydraulic modelling, or the use of extreme value statistics) is subtracted from the flood volumes for all return-periods.

Model data requirements

The GLOFRIS model cascade requires the following data:

<u>Meteorological forcing of current climate:</u> for baseline historical conditions, we use reanalysis datasets of the EU-WATCH project (Weedon et al., 2011). The WATCH forcing data (WFD) were derived from the ERA-40 reanalysis product (Uppala et al., 2005) via sequential interpolation to a horizontal resolution of 0.5◦ × 0.5◦, with elevation corrections and monthly-scale adjustments of daily values to reflect CRU (New et al., 2002) for temperature and cloud-cover and GPCC (precipitation) monthly observations (Fuchs et al., 2009). The EU-WATCH forcing data also corrected for varying atmospheric aerosol-loading and against observed precipitation from gauges. Specifically, we use the following time series from the WFD: air temperature, rainfall and snow (monthly bias-corrected by GPCC rainfall), and potential evaporation estimates estimated using the FAO- 56 Penman–Monteith method (Allen et al., 1998). All data are required as daily values. Although the WFD are available for 1901–2000, the pre-1958 dataset was developed by reordering the data for the later 1958–2000 period, prior to bias correction. Hence, we chose to use the later period, which represents actual years.

<u>Meteorological forcing for future climates:</u> In future periods, the model cascade runs on bias-corrected Global Circulation Model (GCM) data. As the uncertainty resulting from individual GCMs is large, we use an ensemble of GCM outputs. We use the bias-corrected GCM data from the ISIMIP project (Hempel et al., 2013); this previous bias correction is compatible with the sceanrios used in BASE. In this project, data from 5 different GCMs and all 4 RCP emission scenarios is available, and these data are bias corrected with reference to the WFD. The 5 GCMs are: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M. The fact that bias correction was done using WFD as reference data makes a valid comparison between runs in the historical period (also using WFD) possible. The difficulty with flooding processes compared to e.g. average, monthly or annualrunoff estimates is that they represent extreme values within the year and have a high inter-annual variability. The occurrence of floods and the variability therein is

therefore highly sensitive to the distribution of rainfall over time. Inter-monthly variability is important for an individual flood event (i.e. more rainfall concentrated within a short period of time can result in more severe flooding), while variability in rainfall from year to year has a large effect on the variability of all flood events (i.e. a similar amount of rainfall each year results in less variability in the severity of flood events, while large variability in annual rainfall will cause large differences in flood events from year to year). Bias-correction schemes for GCM data such as applied by Hempel et al., 2013 can only correct the empirical distribution function of rainfall of a certain month. However, such a scheme cannot fully account for biases in low-frequency climate variability such as inter-annual variability in rainfall, has been demonstrated by Johnson et al. (2001). As the severity and probability of flood extremes is strongly conditioned on inter-annual variability, the modelled probability distributions of flood events from GCM data are likely to still contain a considerable amount of bias, even though bias-correction has been applied. Such bias across larger time scales is of particular importance for reproduction of extreme values.

Therefore, we have investigated how large this bias is by simulating flood hazard estimates within the baseline period (1960-1999) from each of the five GCM baseline time series, bias-corrected by the ISIMIP project. We compare the flood hazard estimates, expressed by 100-year flood volumes with the hazard estimates obtained using the baseline run with WFD data. The hypothesis is that long-term persistence is not accounted for in the bias-correction scheme, resulting in differences between the hazard, estimated from the WFD run (based on observations), with respect to the GCM runs.

Figure 4 shows for all 5 GCMs the relative difference in the global 100-year return period flood volume simulated with GCM data, compared to the flood volume based onWFD throughout the baseline period (1960-1999). We also plotted other return periods, which show the same pattern and order of magnitude in relative differences (not shown here). The results show that in most regions, the runs with GCM data demonstrate a lower flood hazard (red colours) than the WFD run. This is also the case across Europe, important for BASE. We argue that the lower flood hazard is likely to be a result of the generally lower persistence in rainfall variability resulting from the GCM data compared to observations (WFD). We further stress that the different AOGCMs used here, show quite different patterns in the difference in risk with respect to WFD in some specific areas. In particular over parts of the Southern hemisphere (South America, Australia and South-East Asia), the sign of differences is variable among the GCMs considered in this study. Based on these differences, the model will be used to estimate model-model risk differences between baseline and future as a measure of flood risk change, so as to avoid the bias that occurs when comparing against a common baseline observation, such as WFD.

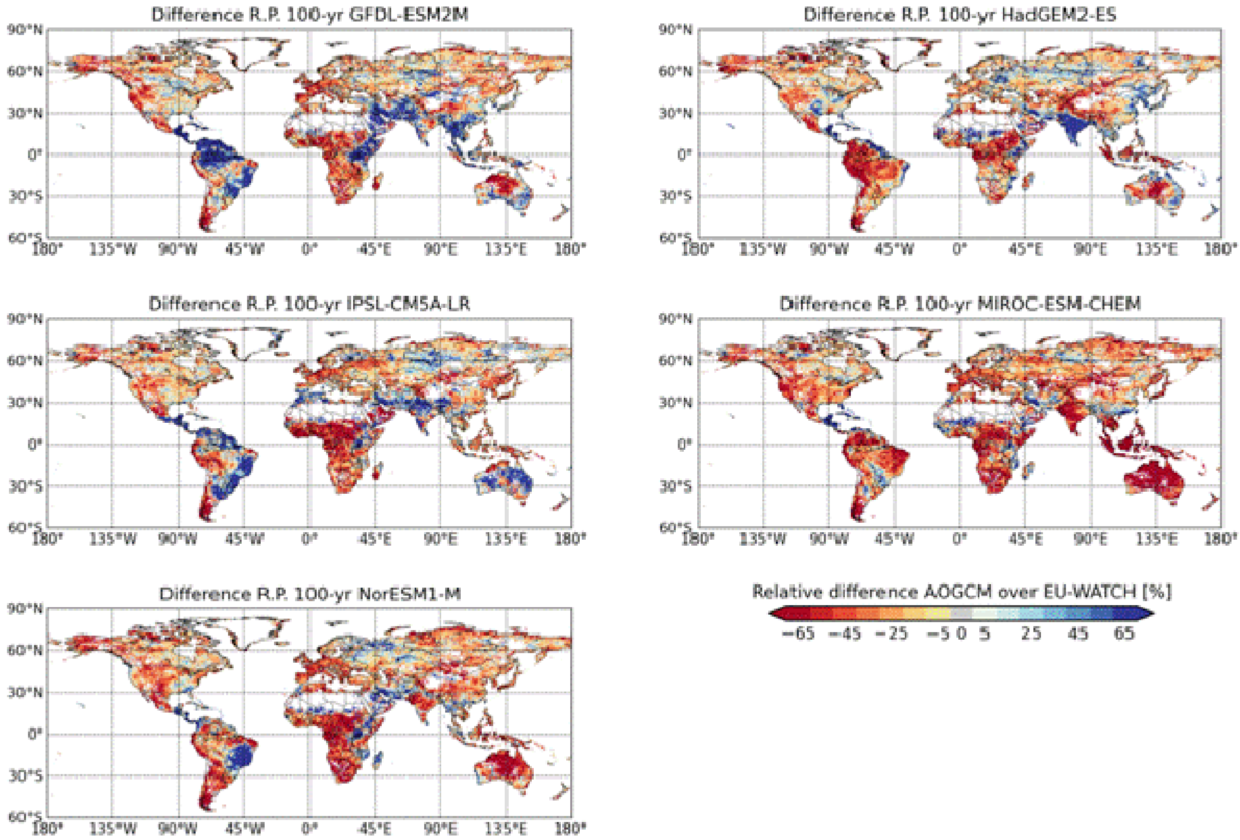
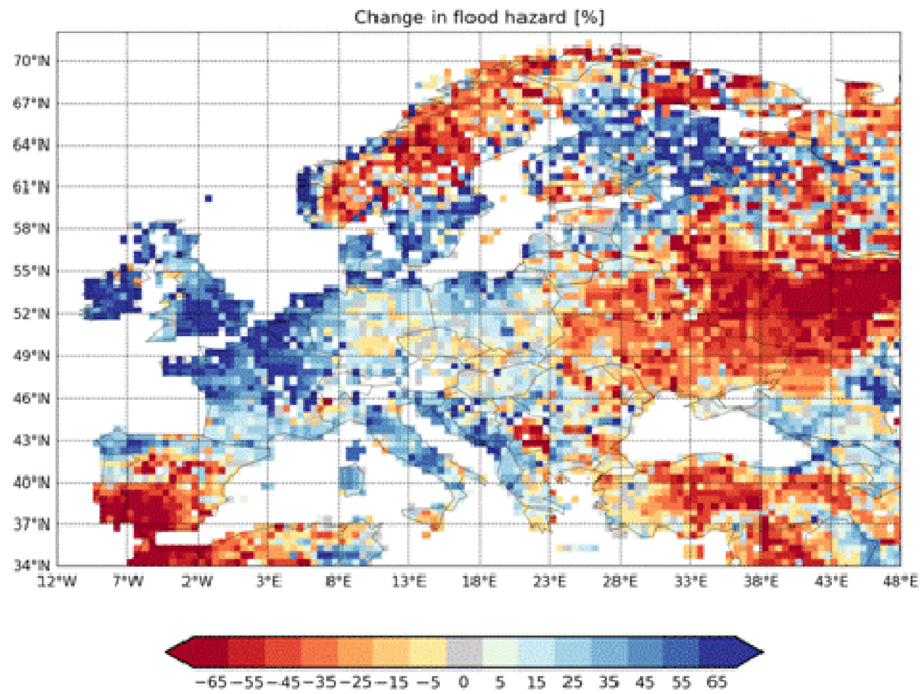


Figure 4 Relative differences between baseline flood hazard estimates, derived with AOGCMs, with respect to EU-WATCH

Model outputs

Flood hazard: Figure 5 shows a flood volume map from PCR-GLOBWB-DynRout, which gives the flooded percent changes in volume across Europe. In this map, the assumption is made that no flood protection is in place. This implies that even across the Netherlands, where a flood protection up to 1250-year return period is maintained, flooding can be observed.


Change in flood hazard [%]
70°N
67°N
64°N
61°N
58°N
55°N
52°N
49°N
46°N
43°N
40°N
37°N
34°N
12°W
7°W
2°W
3°E
8°E
13°E
18°E
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33°E
38°E
43°E
48°E
−65 −55 −45 −35 −25 −15 −5 0 5 15 25 35 45 55 65

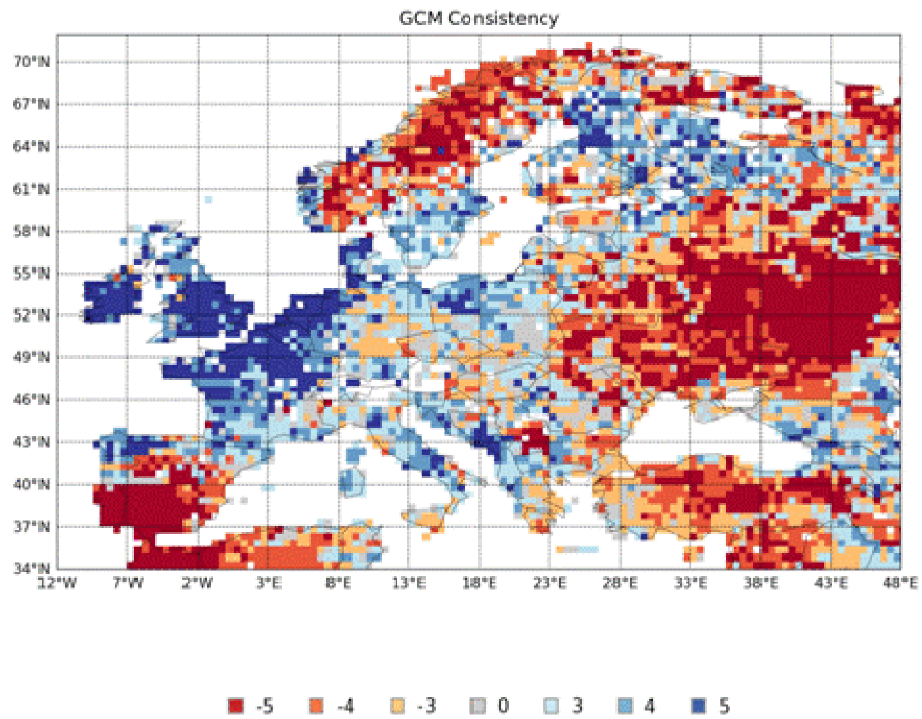
GCM Consistency
70°N
67°N
64°N
61°N
58°N
55°N
52°N
49°N
46°N
43°N
40°N
37°N
34°N
12°W
7°W
2°W
3°E
8°E
13°E
18°E
23°E
28°E
33°E
38°E
43°E
48°E
-5
-4
-3
0
3
4
5

Figure 5 Top: flood hazard change [%] across Europe according to GLOFRIS flood volume computations averaged for 5 GCMs, bottom: GCM consistency, where the number of GCMs that agree on the sign of change is indicated (minus is negative change; positive is positive change)

Flood hazard at 30" resolution: an impression of the results, obtained after downscaling to 30 arc minute (~1 km) resolution is given in Figure 6 (original downscaling scheme) and Figure 7 (downscaling using the updated inundation scheme) for the Ebor basin as an example. We have adapted the downscaling scheme such that smaller tributaries will be given a lower amount of flood volume than large tributaries within a flooded area. In the earlier described versions (Ward et al., 2013; Winsemius et al., 2013), all areas were treated equally, resulting in sometimes overestimation of inundation across small tributaries, and underestimation in large tributaries. This artefact can be seen in Figure 8 in particular in the most downstream parts of the Ebro, where areas around smaller tributaries have the same flood depth as areas around the Ebro itself.

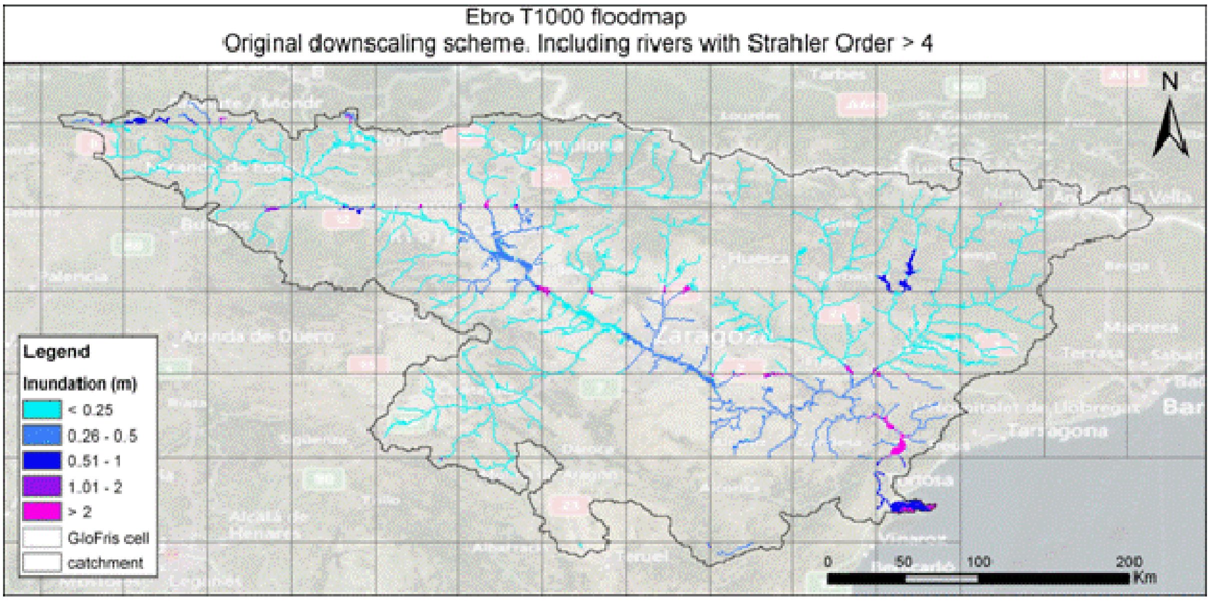

Figure 6 Downscaled flood map across the Ebro basin using the original downscaling scheme of Winsemius et al. (2013) and Ward et al. (2013). The map represents inundation with a 1000 year return period, assuming that no flood protection measures are in place. In the downscaling, it was assumed that rivers with a Strahler order larger than or equal to 4 were flood producing units

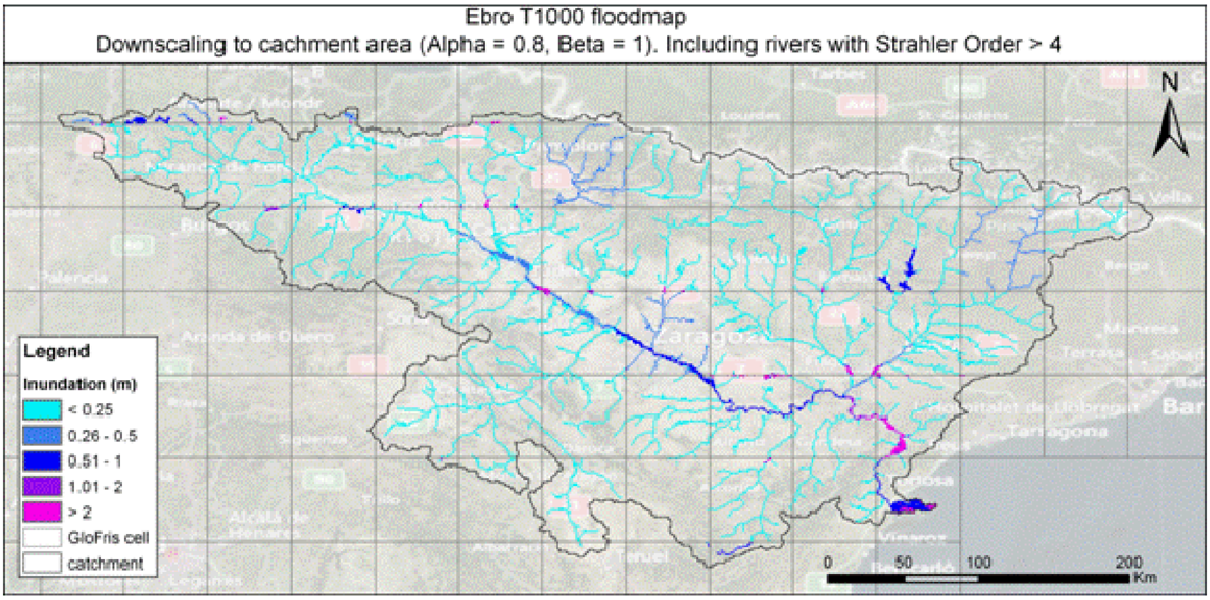

Figure 7 Downscaled flood map across the Ebro basin using the updated inundation scheme. To make results comparable, it was again assumed that rivers with a Strahler order larger than or equal to 4 were flood producing units

In BASE, further improvements will be to apply to Europe our downscaling scheme to 3" (about 90 meter) resolution. Additionally, experiments are performed to solve the dynamic equations fully at 90 meter resolution instead of at the 0.5 degree scale. A feasibility study is being performed at the time of writing and if successful, this approach may be applied in the BASE project as well.These activities would allow producing flood hazard maps across case studies for different return periods and combine them with damage models.

2.4 Impact modelling

Previous studies of European flood risk have combined information on flood hazards as described above, with information on exposed human activities, and their vulnerability. Usually, these activities are analysed using information on land-use types and their location, location of people, and information on their sensitivity to impacts and damages. For instance, Rojas et al. (in press) use the CORINE land-use database (EEA, 2012) to assess location and type of activities at a grid of 100 metres resolution. Note that the CORINE database provides a fixed pattern of dominant land-uses, although at timescales on which climate change becomes relevant for changes in the flood hazard (50-100 years) land-use changes such as the expansion of urban areas may lead to substantial changes in risk (e.g. Bouwer et al., 2010; Cammerer and Thieken 2013).In addition, Rojas et al. (in press) use gridded data on population density in 2011 at 100 metres resolution (Gallego and Peedell, 2001), which is based on the same CORINE land-cover data.

The use of land-use information for assessing exposed assets and population however, has some important limitations. Dominant land-use classes over areas that are relatively large (100 x 100 meter) provide no detailed information on the exact type and location of objects exposed to flood water levels. Also, contrary to other weather extremes such as high wind speeds or earth quakes, the flood hazard can vary considerably over very short distance, for instance the exact inundation depths, flood extents, flow velocities etc. In addition, urban land-use classes are critically important, as these are the locations where the majority of flood losses occur. Urban land-use may include residential areas, industrial areas, and areas used for commercial activities (services). However, land-use classes do not sufficiently distinguish between dispersed and more dense concentrations of these activities. This is important for flood damage estimation, but also for assessing the number or exposed people (see for instance also Maaskant et al., 2009).

In Ward et al. (2013), a number of global scale impact indicators have been described. Essentially, the impact is computed by combining flood hazard maps with exposed assets or people through a hazard-impact relationship (in particular stage-damage relationships). Within the BASE project we aim to improve and extend this impact models for application in Europe, as compared to the global scale, much more detailed information is available for Europe on exposed people and assets, and their vulnerability.

The impact model for flood risk assessment for BASE on a set-up, depicted in the figure below, with key elements being: a) vulnerability data (exposure of people and assets); b) hazard information (data on flood characteristics coming from the hydrological model, described above); and c) damage functions relating the flood characteristics to impacts (e.g. damages).

The following impact types will be assessed by the impact model:

- Area affected and economic activity (e.g. via GDP) affected: based on outline of the extent of flooded area for country, region or case study area;
- Number of people affected: based on intersection of population data for baseline and scenarios intersected with the flood extent maps.
- Monetary losses from damages to several land-use types/economic sectors: Using information on land-use and/or exposed assets and depth-damage functions, estimates of direct monetary losses will be made for several different land-use, object and sector types.

Figure 8 outlines the modelling structure that was developed for the BASE project.

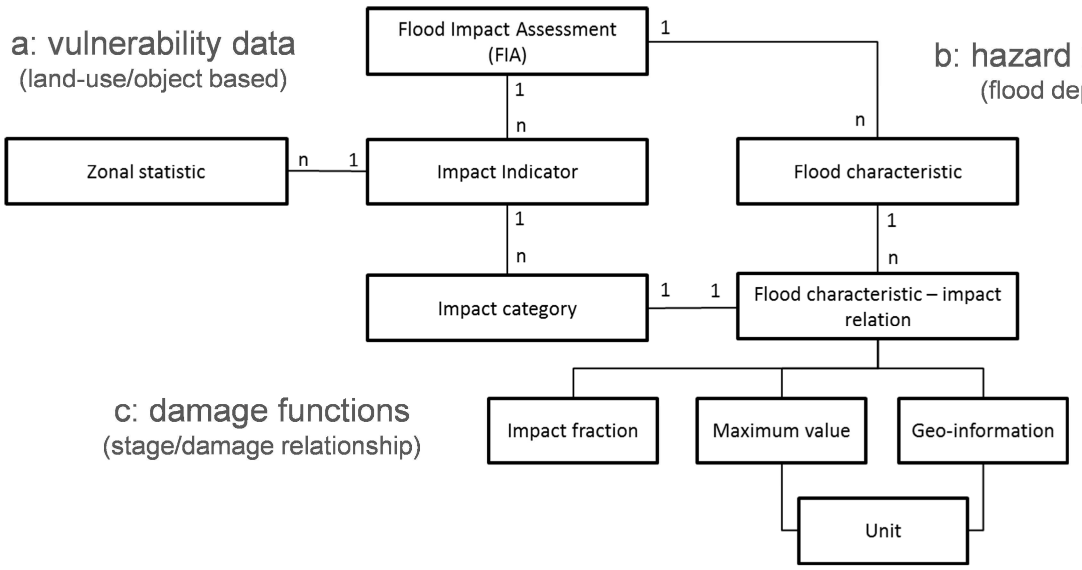

Figure 8 Impact model structure for the flood risk model in BASE

Exposure information will be based land-use types principally derived from the CORINE database with 100 metres horizontal resolution, covering 44 land-use classes. In order to improve the information specifically for the 11 urban and infrastructure related land-use classes, object information will be derived from object information databases (including Open Street Maps and other sources). Also, other sources of information will be used to determine the concentration of persons, for assessing the number of exposed and affected persons. For land-used based damage functions, we will use the JRC model (Huizinga, 2007) as a basis, with possible further modifications.

2.5 Implementing and assessing adaptation options

Design of adaptation options

Adaptation or risk reduction in flood risk management may consist of several types of actions. Traditionally, ex ante and ex post actions are distinguished, with the former aimed to reduce impacts anticipated before the event, and other actions aimed to mitigate impacts when they occur for instance by emergency response, evacuation, and transfer of losses through e.g. insurance (Bouwer et al., in press).

For the BASE project we will focus on ex ante measures at different scales. These adaptation measures consist of:

- Flood prevention through dike systems;
- Flood retention areas (flood wave reduction);

- Local measures such as adjusted building codes for flood damage reduction.

The effects of these measures will be assessed at the case study and European scale. Implementation of the first two adaptation strategies will be achieved through inclusion in the hydrological model cascade :

1. Temporary storage of water e.g. in allocated temporary inundation areas or reservoirs. This strategy will be implemented by assuming that any flood volume below the intended safety level will be temporarily stored and therefore will not convey any flood hazard to the surrounding flood plains. This approach can be relatively easily implemented by allowing subtraction of volume from the flood wave, being routed through the river network, prior to any downscaling.

2. Building of levees or dikes, thereby reducing the outflow of water from the river channels as the capacity of the main channel is increased. We will assume that the levees allow for protection of the surrounding flood plains up to a certain return period design standard. We will back calculate the levee height, resulting in the chosen design standard and implement this levee height in the routing scheme of PCR-GLOBWB. Hereafter, we will recalculate the flood risk. This approach can be followed across different parts of the river, and its effect should be evaluated over the total basin. This is because an increase in conveyance capacity in a certain part of the river due to increased levee height may result in an increase in flood risk in downstream areas, where higher levees are not considered.

Measures related to local damage reducing measures, will consist of the estimation of effects of building adjustments. These will be implemented through the adjustment of depth-damage functions, described above under the section on impact modelling.

Costing of adaptation options

Previous studies have also assessed the benefits and costs of flood prevention in Europe, for instance Rojas et al. (in press) for river basins, and Hinkel et al. (2010) for coastal floods. Rojas et al. (in press) estimate the costs for upgrading river dike systems in the EU to be around 8 billion Euros by the 2080s, under the A1B emission scenario. Their approach for assessing these costs relies on an assessment of average benefit-cost ratios, whereby investment costs are related to the avoided damages, and the level estimated from a fixed average b-c ratio of 4.

We propose to also assess actual costs related to the adaptation measures, based on unit costs available from other research. For instance, for dike systems we will rely on estimates produced for the Netherlands (Kind, in press). For local damage reducing measures in businesses and households, cost estimates are available for the required efforts. These include measures to reduce flood damage to heating systems, electricity systems, and floors, for which cost estimates are available (e.g. Thieken et al., 2006), as well as the potential response of citizens to implement such measures (Botzen, et al., 2006). For retention areas, costs are more difficult to assess, but examples of costs for creation of retention and management of the retention system will be used. These estimates, together with the possible costs for damage compensation will be used to scale up from single examples to the European scale and the number of measures required for this adaptation type.

3 Environmental flows

Karen Meijer, Cheryl van Kempen, Harm Duel (Deltares)

3.1 Policy context

Europe's water resources and aquatic ecosystems are impacted by multiple stressors, which affect ecological and chemical status, water quantity and ecosystem functions and services (Hendriks et al., 2013). The relevance of stressors differs regionally: in alpine and upland northern regions hydropower plants have fundamentally changed river and lake hydrology, morphology, sediment transport and connectivity; in lowland areas of Northern and Central Europe intensive agriculture and flood protection are important drivers of degradation, while Mediterranean catchments struggle with riparian degradation and water scarcity. Climate change poses additional threats increasing risk of floods, erosion and pollution in wet regions and of droughts in water scarce regions (EEA, 2012). In 2030, 50% of the river basins in Europe will show severe water stress (EEA, 2012). Therefore, water management authorities across Europe are seeking to balance water allocations while achieving Good Ecological Status as required by the European Water Framework Directive (WFD). However, the WFD recognises the importance of retaining major infrastructure, such as dams, that have a benefit to society (e.g. irrigation, flood protection, power generation) and where no other technically feasible and cost-effectives better environmental option exists. When these structures mean that achieving Good Ecological Status is not feasible, an alternative objective of Good Ecological Potential is applicable. In these circumstances best practices should be applied to optimise water management within the economic constraints of water use.

Many factors influence the condition or health of a river ecosystem including light, water temperature, nutrients, species interactions, discharge, channel morphology, physical barriers to connectivity (Moss, 2010). Discharge (i.e. river flow, measured as a volume per unit time) is a key habitat variable, which changes dynamically in space and over time (Bunn et al., 2002; Monk et al., 2006).. It is widely recognised that all elements of a river's flow regime have a role in influencing the biodiversity and functions of freshwater ecosystem, including floods, channel freshes and low or zero flows (Junk et al., 1989; Richter et al., 1996; Poff et al., 1997) with too much flow at the wrong time of year or season being as detrimental as too little flow. Extremes of flow and patterns of flow variability can directly influence local community structure of fish, invertebrates and vegetation (Poff & Allan 1995; Merrit & Poff, 2010; Cowx et al., 2012).

To protect ecosystem and maintain them in a desired condition, an ecological flow regime needs to be implemented. Following the definition in the Brisbane Declaration, ecological flows can be defined as describing the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. In the EU, this would mean the flow regime that corresponds with the 'Good Ecological Status'. This means that, in a way, ecological flows are implicitly included in the current EU Water Framework Directive. The recent 'Blueprint' (DG Environment, 2012), which addresses the challenges to safeguard Europe's water resources, identifies the issue of over-allocation of water resources as a key challenge and proposed the development of CIS guidance documents for the assessment and implementation of ecological flows in Europe.

Quoting the Blueprint : "there is a need in many EU river basins to put quantitative water management on a much more solid foundation: namely the identification of the ecological flow, i.e. the amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon. Fundamental to this is the recognition that water quality and quantity are intimately related within the concept of good ecological status".

Subsequently, the determination of *the* environmental flow requirements requires societal trade-offs between different water users (Millenium Ecosystem Assessment, 2005; Ziv et al., 2012). While for certain rivers a near natural condition is required, for other rivers, for example in urbanized areas, it may be acceptable that some degradation takes place. Therefore, without involvement of local stakeholders, it cannot be decided what the desired ecosystem condition is, nor which flow regime is required to maintain that ecosystem condition.

In absence of detailed flow-ecosystems response relationships and societal negotiation processes, the assessment of environmental flows should focus on gaining and understanding of flow regime alteration. A general assumption is that the more features of the flow regime disappear the more ecosystem degradation will occur. Whether or not this is acceptable, depends on the importance of the ecosystem (for biodiversity conservation or for ecosystem services for society), and the social and economic importance of the flow regulation that causes the flow regime change.

3.1.1 The concept of environmental flows

A key advancement in science of environmental flows was the formulation of the natural flow paradigm (Poff et al, 1997); which highlighted that all aspects of the river flow regime, including floods and droughts, are important for river species and communities (Lytle et al., 2004). Many rules of thumb have been established to define the degree of alteration from natural flows that can still maintain a healthy river ecosystem (Tennant, 1976). Methods to assess alteration from the natural flow regime were formalised (Richter et al, 1996) and have been applied across Europe (Laize et la., 2013). The natural flow regime concept is explicit in the regional Ecological Limits of Hydrologic Alteration (ELOHA) environmental flows framework (Poff et al., 2010).

Whilst the natural flow paradigm might be most applicable to managing natural or semi-natural river basins, it was recognised that the natural regime may be an unrealistic objective for intensively managed river systems, including heavily modified water bodies (HMWBs). It may be more effective to build an appropriate flow regime that delivers specific objectives, particularly where large dams have a major influence on the hydrology. This led to development of the Building Block Methodology in South Africa (Kling et al., 2000), that was recommended for assessment

GEP in the UK (Acreman et al., 2008) and proposed for application in Norway (Alfredsen et al., 2012).

As displayed in Figure 9 a flow regime below an impoundment can be constructed by defining the hydrograph elements that deliver specific ecosystem response, such as producing habitat for particular species or channel form. The approach can be targeted towards conservation of ecosystem functioning, rather than species, or services defined by society. A further development of this approach is included the DRIFT method (king et al., 2004), which optimises flow releases to achieve ecological targets whilst maximising water retained in a dams for power generation, public supply, irrigation or other purposes. DRIFT has been applied to a range of river types in Africa, South America and Asia.

A further conceptual step was the recognition that river habitat is in part defined by hydraulics, including water depth and velocity through the interaction of flow with channel morphology and aquatic plants, rather than flow per se (Maddock et al., 2013).

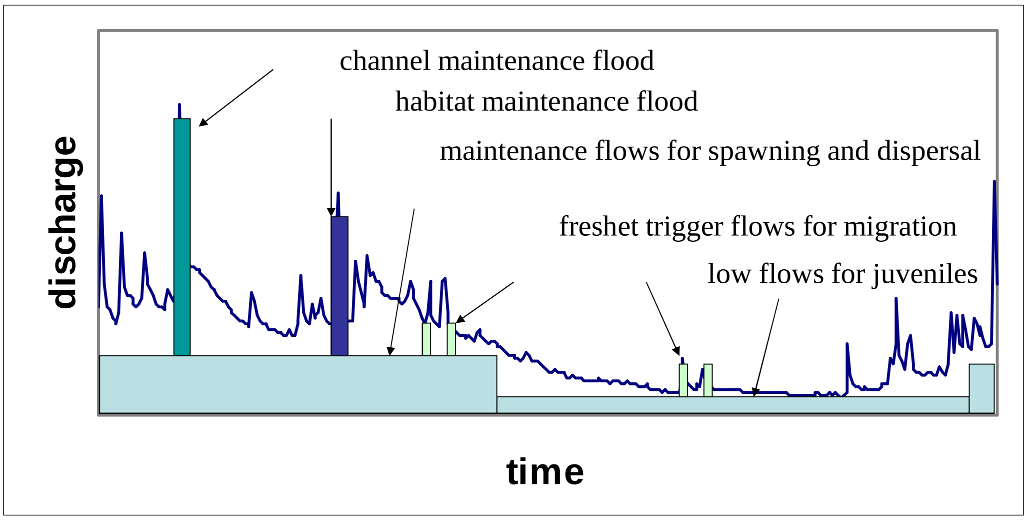

Figure 9 An environmental flow regime is constructed from hydrograph elements (blue and green blocks) within the natural flow regime (blue line) that deliver specific ecosystem components(after Acreman et al., 2004).Building blocks are different flow conditions to support different ecological processes and habitat availability

3.1.2 Environmental flow indicators in global assessments

In global assessments of environmental flows, the focus is on the deviation of discharge regimes from the natural discharge regime. Several flow indicators are presented in literature in order to describe the flow regime. Ideally, such a flow regime analysis is done using daily data for timeseries of more than 20 years. However, due to uncertainties resulting from the resolution and data availability at a global level, discharge series are often represented as a monthly average discharge.

Laizé et al. (2010) conducted a redundancy analysis of the Indicators of Hydrological Alteration (IHA method) by Mathews and Richter (2007), to propose a reduced set of indicators to describe flow regimes based on monthly discharge data. This method was then applied to monthly results from the WaterGAP model for all of Europe.

King and Brown (2010) developed an environmental flow assessment method for the Mekong in which the focus was on understanding changes in wet and dry season, including shifts in length, start and end of the seasons. This method has not yet been applied in global assessments, but it would be interesting to test the results.

Smakthin et al. (2004) developed a method in which the Environmental Low Flow Requirement (LFR) is assumed to equal to the monthly flow, which is exceeded 90% of the time on average throughout the year (Q90). Again monthly discharge results from WaterGAP were used. High Flow Requirement (HFR) was determined as a percentage of Mean Annual Runoff (MAR), through a comparison of the low flow requirement and the MAR.

3.2 Environmental flow analysis for BASE

3.2.1 BASE approach

For BASE, we have selected the IHA method developed by Laizé et al. to analyse the impacts of the future changes in flow regime. A method that provides insight in flow regime change is most suitable for BASE, not a method that sets environmental flow requirements and quantified deviations. This means that both the IHA method and the method by King and Brown are relevant. Europe’s river discharge regimes however are not suitable for King and Brown’s method, because often there is no clear wet and dry season. Therefore, Laizé’s method will be applied to analyse the changes in the hydrological regime of rivers due to climate change, land use change and catchment management, including the water retention measures. We will focus on the changes in ecological requirements with respect to magnitude and timing of hydrological patterns (Figure 10).

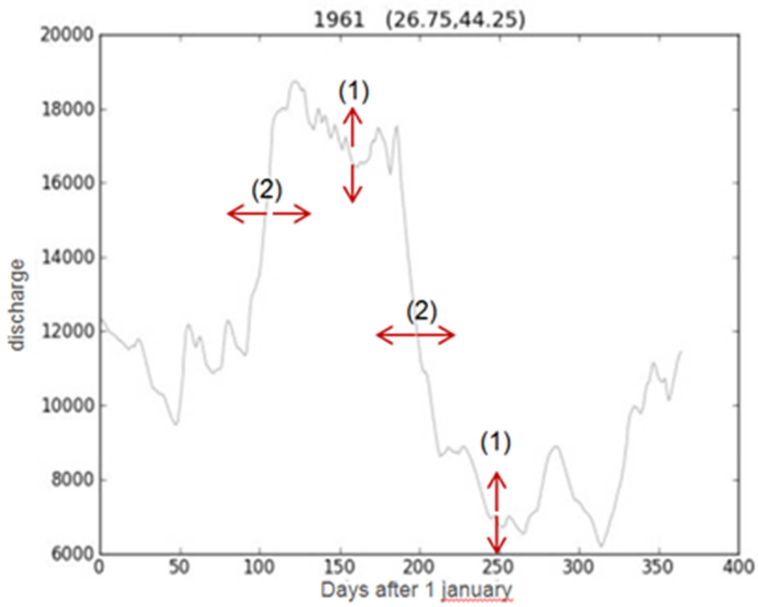

Figure 10 Capturing the changes in magnitude (1) and timing (2) of river flow characteristics

3.2.2 Method by Laizé et al.

The method by Laizé et al. is based on the Range of Variability Approach (RVA) and uses indicators of Hydrological Alteration. It is also described in the SCENES report D4.6 Volume C (Acreman et al., 2011). A redundancy analysis was done of 32 indicators which are normally assessed at daily basis, using monthly averaged discharges. This resulted in a set of 16 ecological relevant indicators with which hydrological alterations can be characterized. According to the IHA/RVA the flow regime can be characterized by the magnitude, duration, timing, frequency and rate of change of low and high flows and flood events. These can be impacted due to climate change. However, changes in landuse and catchment management, as well as flood protection measures, hydropower and channelization of rivers may alter flow regimes significantly. It is generally taken as a rule of thumb that any changes in the flow regime characteristics beyond 30% of natural baseline can be problematic for river ecosystems and reason for concern (Acreman et al. 2008).

In Laizé's method the flow regime is described by 6 regime characteristics which in turn are assessed through nine monthly time-step parameters (second column in Table 1). For each parameter statistical indicators can be calculated which describe the parameter's magnitude (50^{th} percentile) and variability (span between 25^{th} and 75^{th} percentiles). For the timing parameters (month in which low or high flow occur, described as the integer month number) however, percentiles would not be meaningful and therefore the mode is used.

The method uses percentiles because: (i) percentiles are less sensitive to outliers than mean and standard deviation; (ii) parameters are not necessarily normally distributed, hence, percentiles would better describe skewed distributions.

Table 1 Flow regime characteristics, the parameters with which they are described and the resulting set of 16 indicators with which they can be assessed according to Laizé et al. (2010)

Regime characteristic	Parameter monthly (one value per year)	Indicator (one value per record)
Flood Magnitude & Frequency	Number of times that monthly flow exceeds threshold (all-data naturalised Q5 from 1961-1990)	50th Percentile (magnitude) Span 25th-75th Percentiles (variability)
Flood Timing	Month (as number Jan=1, Dec=12) of maximum flow	Mode of month
Seasonal Flow	January flow (mm runoff)	50th Percentile (magnitude) Span 25th-75th Percentiles (variability)
	April flow (mm runoff)	Idem
	July flow (mm runoff)	Idem
	October flow (mm runoff)	Idem
Low Flow Magnitude & Frequency	Number of months that flow is less than threshold (thresholds = all-data naturalised Q95 from 1961-1990)	Idem
Minimum Flow Timing	Month (as number Jan=1, Dec=12) of minimum flow	Mode of month
Low Flow Duration	Number of times that two consecutive months are less than threshold (all-data naturalised Q95 from 1961-1990)	50th Percentile (magnitude) Span 25th-75th Percentiles (variability)

Laizé's method results in 16 indicators which are computed for the baseline data and for any scenarios under consideration. Departure from the baseline is assessed, with >30% change or more than 1 month difference in case of the timing parameters, considered as undesired. The number of indicators with an undesired outcome are finally summed up, resulting in a single indicator for flow impact (see Table 2).

Table 2 Classification of the aggregated results of Laizé's method and colour codes for maps

Number of parameters changes significantly	Impact on environmental flows	Color-code

0	No impact	Blue
1 – 5	Low impact	Green
6 – 10	Medium impact	Amber
11 – 16	High impact	Red

3.2.3 Adjusted Laizé method

For the magnitudes (p50) of high flow, low flow, and low flow duration some problems arose when comparing the future scenarios with baseline. These indicators had baseline values of zero or 1 while the scenario values could be higher. Because division over zero gave problems, while the departure from baseline observed was always more than 100%, the method is adapted in BASE: to assess these indicators by subtracting the scenario results from the baseline results and considering any deviation as undesired.

3.3 Modelling approach in BASE

Laizé's method was already applied in SCENES (Acreman et al. 2011) on results of the WaterGAP model. In BASE the method will be applied on new scenarios derived from the global hydrological model PCR-GLOBWB (Van Beek and Bierkens, 2009; Van Beek et al., 2011), which is also is used in the BASE assessment on Flood Risk. Although you can find detailed information on PCR-GLOBWB in the Flood Risk chapter, a short description of the model and data are included here.

PCR-GLOBWB is a large-scale hydrological model intended for global to regional studies . PCR-GLOBWB provides a grid-based representation of terrestrial hydrology with a typical spatial resolution of less than 50×50 km (currently 0.5° globally) on a daily basis and is essentially a leaky bucket type of model applied on a cell-by-cell basis. For each grid cell, PCR-GLOBWB uses process-based equations to compute moisture storage in two vertically stacked soil layers as well as the water exchange between the soil and the atmosphere and the underlying groundwater reservoir.Exchange to the atmosphere comprises precipitation, evapotranspiration and snow accumulation and melt, which are all modified by the presence of the canopy and snow cover. The exchange with the underlying groundwater reservoir comprises deep percolation and capillary rise and vertical fluxes. Sub-grid variability is taken into account as follows:

- fraction of cell covered with short and tall vegetation;
- fraction covered with freshwater, being either a river, lake or reservoir;
- and fraction glaciers;

- sub-grid elevation distribution determining the accumulation and melt rate of snow and ice as well as fraction of the river plain flooded (optional);
- soil type distribution and its effect on soil hydrological properties;
- distribution of water-holding capacity of the soil resulting in variable saturation excess overland flow as a result of variations in soil depth, effective porosity and elevation distribution.

Discharge was obtained from PCR-GLOBWB model and its extension for dynamic routing, DynRout (PCR-GLOBWB-DynRout). The model is forced by meteorological fields (precipitation, temperature, potential evaporation). The PCR-GLOBWB model was forced with the same data as in the flood risk analysis. For baseline historical conditions, reanalysed datasets of the EU-WATCH project (Weedon et al., 2011) are used, for which the forcing data (Watch Forcing Data) again are derived from ERA-40 reanalysis products (Uppala et al., 2005). Historical data consisted of daily discharge outputs for 1960 to 1999 (baseline) at 0.5 degree resolution.

For future periods, bias-corrected Global Circulation Model (GCM) data from the ISIMIP project (Hempel et al., 2013) was used. From the Flood Risk calculations data from 5 different GCMs and all 4 RCP emission scenarios are available, and these data are bias corrected with reference to the Watch Forcing Data. For this first application of Laizé's method we only use one of these GCM's, namely GFDL-ESM2M. For this future scenario daily data for the period 2006 – 2009 was available. The method was applied to two time periods, namely for 2006-2099 (94years) and the period 2060 – 2099 (40years). The latter interval was chosen because it represents a period spanning 40 years, like the baseline, while being 100 years in the future. The former interval was chosen as it represents the net changes to be expected in the following 100 years.

As PCR-GLOBWB is a global model, for the BASE project a submodel has been created covering the latitudes ranging from 32 to 72 degrees North and longitudes from -13 to 43 degrees East.

3.4 Testing the modelling approach

3.4.1 Analysis of flow regimes: *spatial variability*

Figure 11 shows the variability in discharge regimes observed at different locations in the Danube river basin. Similar variability can be expected for the ensemble of European river basins.

To test the applicability of the method to analyse the impact of future climate on the environmental flows, a first analysis of the baseline and GFDL-ESM2M climate scenario is carried out. For the Danube catchment a number of locations were selected (Figure 11 and Table 3 for location of the modelling sites) to analyse the calculated flow regimes in more detail. Locations 2, 3, 4 and 15 are situated in Ramsar sites.

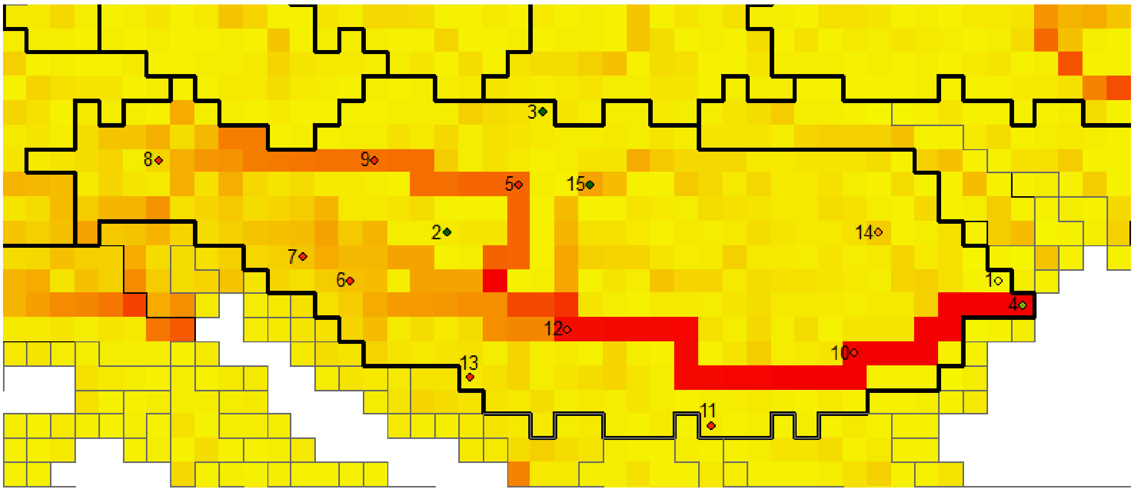

Figure 11 Map of selected locations in the Danube River Basin for analysis of flow regimes. Red cells have higher discharge rates (i.e. contain the main river).

Table 3 Selected locations in the Danube River Basin for analysis of flow regimes

location name	coordinate X	coordinate Y	country	name of location
1	29.25	45.75	Ukraine	
2	17.75	46.75	Hungary	Lake Balaton
3	19.75	49.25	Slovakia	Orava river
4	29.75	45.25	Romania	Danube delta
5	19.25	47.75	Hungary	Budapest
6	15.75	45.75	Croatia	Zagreb
7	14.75	46.25	Slovenia	Ljubljana
8	11.75	48.25	Germany	Munich
9	16.25	48.25	Austria	Vienna
10	26.25	44.25	Romania	Bucharest
11	23.25	42.75	Bulgaria	Sofiya
12	20.25	44.75	Serbia	Belgrade
13	18.25	43.75	Bosnia	Sarajevo
14	26.75	46.75	Romania	
15	20.75	47.75	Hungary	Hortobágy

3.4.2 Analysis of flow regimes: temporal variability

Figures12 and 13 are depicting the variability of the annual discharge regime for the lower Danube river near Bucarest (location 10 on the map). This simulation was done for testing the model that will be applied in BASE with the CMCC scenarios. Note that certain trends are recognizable. For example, there are often high flow events around day 100 – 150 (in April-May) and low flows often occur around day 200 – 250 (July – August). However, high and low flow events may also occur in very different seasons. These differences make it difficult to characterize the discharge regime of this location with a method as applied by King and Brown et al. (2010) which is focussed on recognizing wet and dry seasons, or recurring seasons of high and low flows.

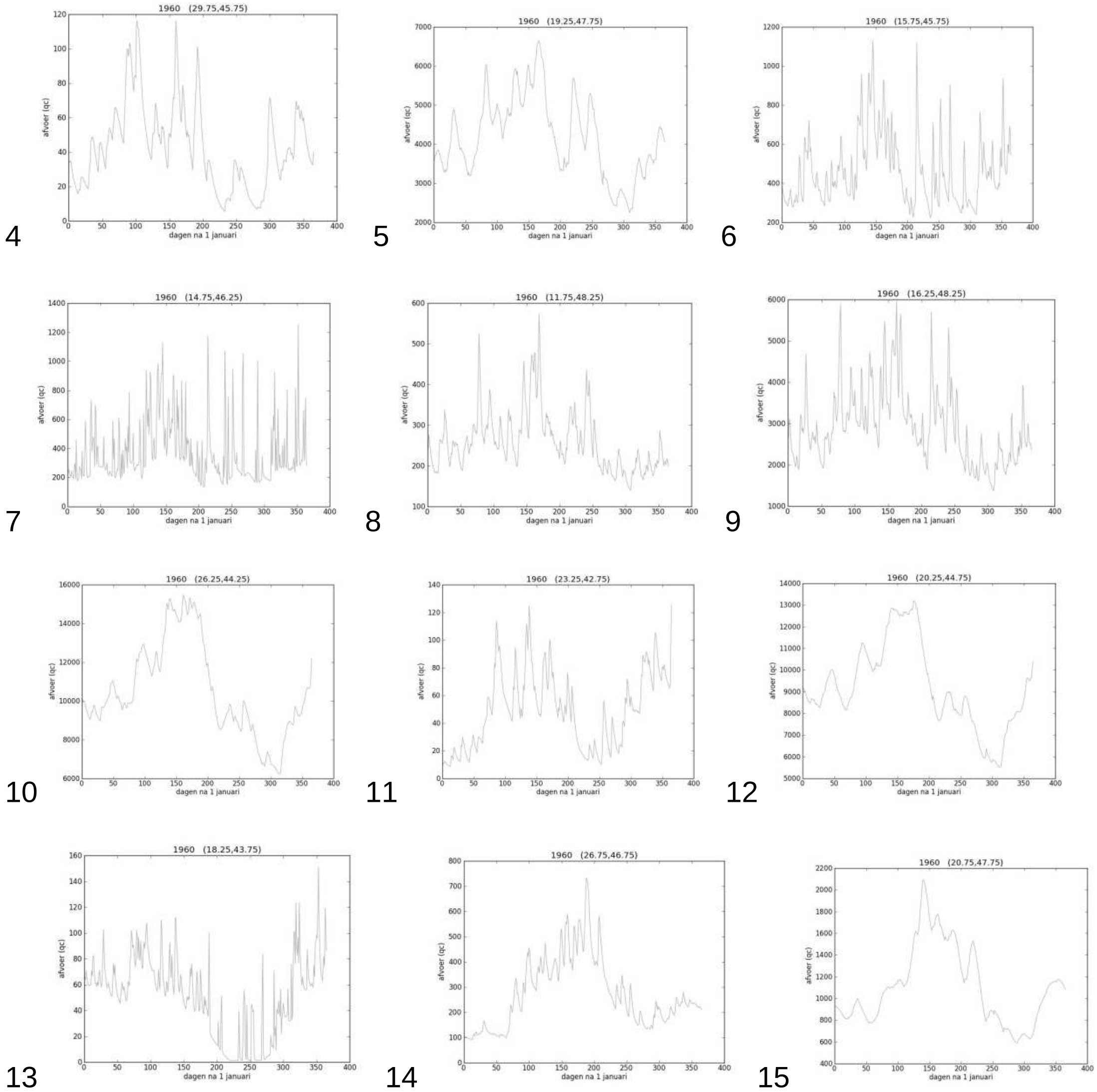

Figure 12 Annual discharge regimes for different locations in the Danube River basin show that very different discharge regimes may be observed within the same river basin.

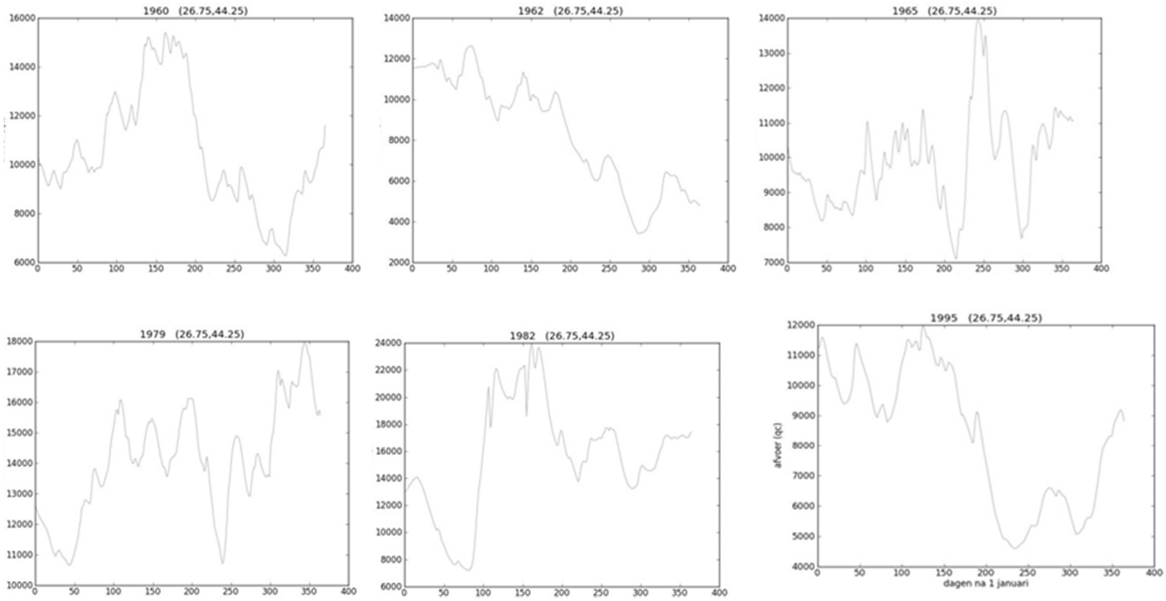

Figure 13 Different patterns of annual discharge of river Danube near Bucharest: years 1960, 1962, 1965, 1979, 1982 and 1995. Discharge in m3/s on day x after the first of January.

3.4.3 Future changes in flow regime and adaptation

The predicted changes in flow regime for the lower Danube due to climate change (based on simulations with the CMCC scenarios) will be a component of WP6.

3.5 Evaluating Environmental flows

3.5.1 Illustrating the application of the method

Applying Laizé's method to forecasted flow regime of the lower Danube river (location 10) for time period 2006 – 2099 shows that future environmental flows at this location will be low-impacted due to climate change. Future changes that will impact environmental flows are related to a change in the discharge's variability late in the year and a change in the variability of the low flow events (see Table 4). Note that division over zero leads to no result in the "change"-column, while in reality division over zero leads to an infinitely great result and therefore the % change from baseline is infinitely great. In our calculation for the whole of Europe division with zero lead to problems when calculating the %change of the magnitudes of the flood, low flow and low flow durations. To overcome this, Laizé's method was slightly adjusted, assigning points to any deviation from baseline for these three indicators.

Table 4 Impact of climate change on environmental flow requirements for the lower Danube river based on a set of 16 ecological relevant hydrological parameters (based on Laizé's method adapted by BASE)

	Parameter	Indicator	Baseline	Future	Difference	Change	Pnts
1	flood magnitude	p50	0	0	0	#DIV/0!	0
2	flood frequency	p75-p25	1	1	0	0%	0
3	flood timing	mode	4	4	0	0	0
4	January	p50	346,367	346,802	435	0%	0
5	January	p75-p25	109,231	117,763	8532	8%	0
6	April	p50	395,394	379,838	-15556	-4%	0
7	April	p75-p25	111,032	116,947	5915	5%	0
8	July	p50	332,300	367,960	35660	11%	0
9	July	p75-p25	153,907	153,155	-752	0%	0
10	October	p50	253,527	243,620	-9907	-4%	0
11	October	p75-p25	154,064	101,019	-53045	-34%	1
12	low flow magnitude	p50	0	0	0		0
13	low flow frequency	p75-p25	0	1	1		1
14	minimum flow timing	mode	9	9	0	0	0
15	Duration	conseq p50	0	0	0		0
16	low flow duration	conseq p75	0	0	0		0
					Result	(low impact)	2

3.5.2 Future changes in environmental flows in Europe due to climate change

Future changes in environmental flows due to climate changes are simulated based on data obtained from the PCR-GLOBWB-dynrout modelling cascade forced with GFDL-ESM2M scenario data, and for two time-periods, namely for the period 2006-2009 (94 years) and the period 2060 – 2099 (40 years). As an example of previous application of the method, the simulation results show the future changes in climate will significantly have an impact on the ecological flows in many rivers basins in Mediterranean region as well as in Northern and Eastern Europe (Figure 14). Over a long time interval (94 years) the average conditions with respect to ecological flows are relatively limited compared to the final decades of this century: indicating the changes in flow regime by climate change will be significantly differ from current flow regime. About 35% of the river basins will be medium or high impacted.

The predicted changes in environmental flows for Europe due to climate change (based on simulations with the CMCC scenarios) will be a component of WP6.

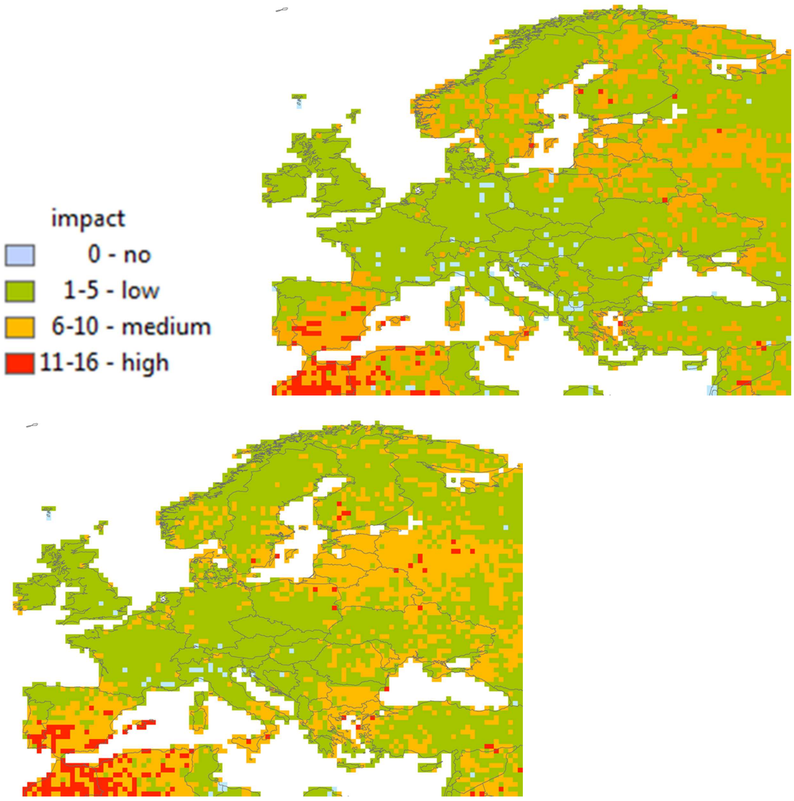

Figure 14 Assessment of changes in ecological flows using Lasize's method. Changes in hydrology due to climate change are calculated by using PCR-GLOBWB-dynrout. Baseline is current flow regime and is compared with an average flow regime over the period 2006-2099 (upper figure) and over the period 2060-2099 (lower figure)

3.5.3 Comparison of the Lasize method with other methodologies

When comparing the results of this project to the results of the SCENES project (Figure 15), the level of impacts seems to be lower. There are, however, two important differences.

1) The futures of Europe's freshwater in SCENES were not only based on climate scenarios, but socio-economic scenarios, including the water demands of different economic sectors, were taken into account as well. Nevertheless, regions where environmental flows are heavily impacted are comparable in both projects.

2) Within BASE Laize's method is adapted, and when using the original method the results are more comparable (Figure 16).

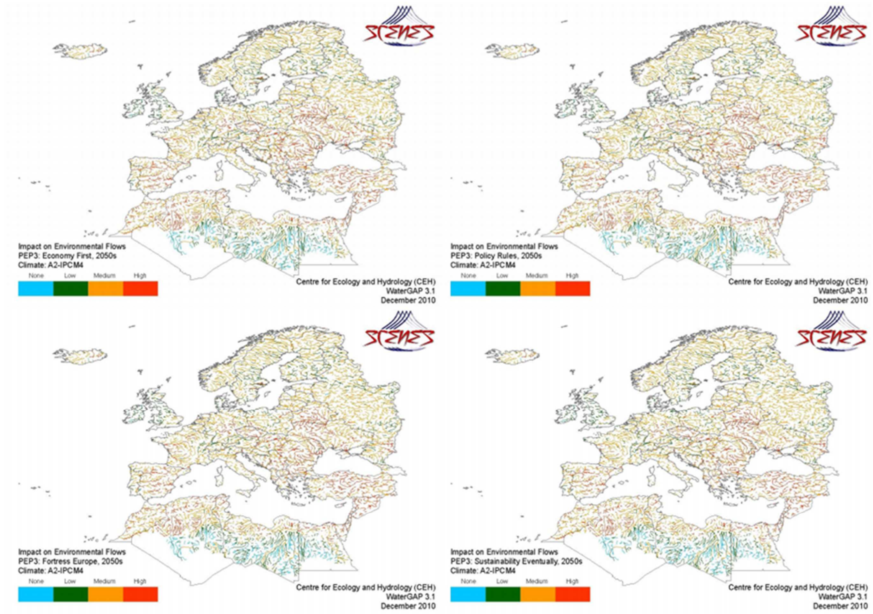

Figure 15 Changes in environmental flows in different water scenarios from the SCENES project in 2050s compared to baseline (current situation). (Acreman et al., 2011)

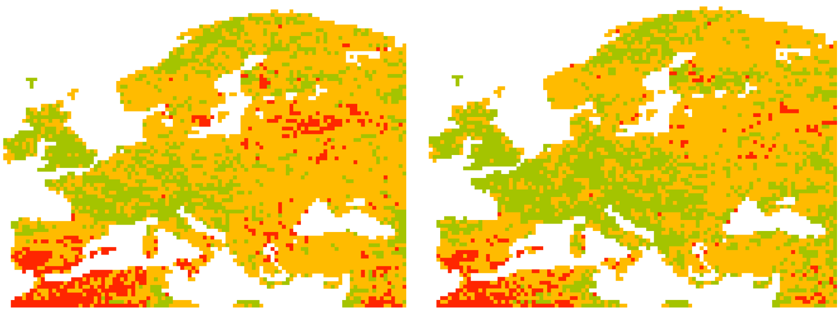

Figure 16 Laizé's original method applied to Europe for 40 years (left) and 94 years (right)

3.6 Climate adaptation and environmental flows: analysis framework

The modelling approach will be used in BASE for evaluating adaptation of environmental flows to climate change. The results will be presented in WP6. Climate adaptation in the water management sector includes (natural) water retention measures to reduce flood risks at on hand and to increase the availability of water during dry periods. Natural water retention measures when applied on catchment scale will promote restoring hydrological processes and flow regime of rivers and therefore supporting the environmental flow requirements. When developing climate adaptation pathways water retention measures for the water management sector will be taken into account and the impact on ecological flows and their costs and benefits will be assessed. Therefore a series of water retention measures will be included in the PCR-GLOBWB model. Information on the efficacy of the different water retention measures will be collected from scientific literature and available reports, as well as information on costs and benefits.

Analysis framework for assessing climate adaptation measures with respect to water retention measures include the following building blocks (Figure 17):

(1) Climate data from global circulation models: forcing data for the hydrological modelling

(2) Water use scenarios: addressing the water demands of different sectors based on the socio-economic scenarios of the SCENES project.

(3) Climate adaptation pathways with respect to water retention measures: selection of water retention measures and collecting input data for the hydrological modelling

(4) Simulating the changes in the flow regimes, focusing on the hydrological parameters that are relevant for assessing environmental flows

(5) Comparing the flow characteristics (ecological relevant hydrological parameters) with the environmental flow requirements.

(6) Providing information for the assessment of costs and benefits.

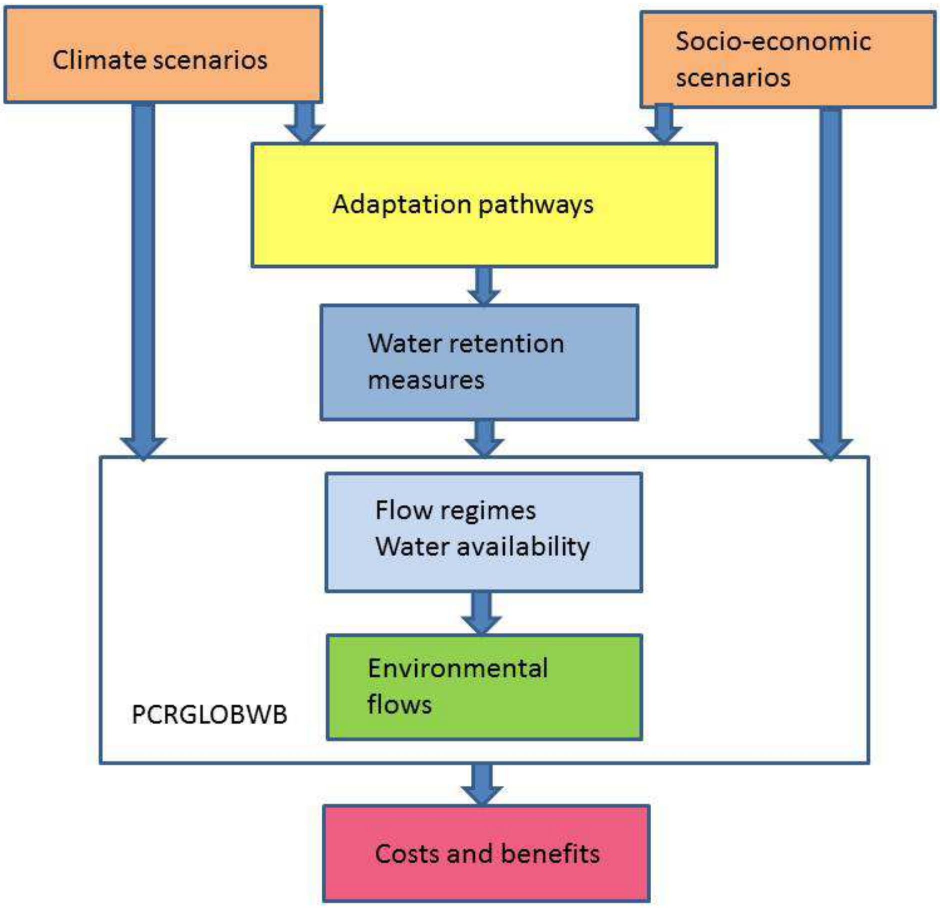

Figure 17 Analysis framework for the impact of climate adaptation on meeting the environmental flow requirements

4 Water availability and policy

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4.1 Introduction

In the water sector, institutions, users, technology and economy cooperate to achieve equilibrium between water supply and demand in water resource systems. This equilibrium could be achieved if conditions persisted during a sufficiently long span of time. However, even if climatic conditions were stationary, the socioeconomic dynamics of the population act as an external forcing that result in a non- equilibrium system. Water policy is designed to correct deviations and to recover equilibrium as a response to socioeconomic forcing. However it is questionable that the return to current equilibrium is the desirable option, and an optimal equilibrium could be defined. The socioeconomic dynamics usually translate into a change (usually an increase) of population water needs for different purposes, which are supplied by means of the construction of hydraulic infrastructure or the definition of new management or operating rules. The possibility of climatic change is only a new external forcing that should be considered in this continuously adaptive process.

How much does water management need to adapt in view of climate change?

The aim of this modelling effort is to provide some insight to the policy priorities for the adaptation of water resources to climate change. Two questions are of critical importance for the assessment of adaptation needs: How much does water management needs to adapt in view of climate change? How able are societies to adapt to these changes? We address these questions by evaluating the impacts of climate change on water resources and their management, the adaptive capacity and the policy responses.

The assessment is based on indicators aiming to facilitate information transfer from water resource science to policy.

European countries are diverse from various points of view including their socio-economic development, climate, water availability, infrastructure levels, or social and ecological pressures natural resources. However, the region as a whole is undergoing rapid social and environmental changes which may harbour negative implications for current and future sustainability. This is particularly true for the European water sector where pressures and impacts on water scarcity are projected to multiply under climate change, especially in southern countries. Water scarcity often results in conflicts among users which are compounded by complex institutional and legal structures that threaten the development of policies geared towards sustainable management (Iglesias et al., 2007; Iglesias et al., 2011).

A number of studies have shown that under climate change annual river flow is expected to decrease in Southern Europe and increase in Northern Europe; changes are also expected in the seasonality of river flows with considerable differences over the European region (Arnell 2004; Milly et al. 2005; Alcamo et al. 2007). Nevertheless many of these projections do not take into account the effects of policy. One alternative measure that has been used to include some policy aspects is the water exploitation index (WEI), which is calculated annually as the ratio of total freshwater abstraction to the total renewable resource (Raskin et al. 1997). But even though the WEI can provide additional information regarding runoff, such an analysis still struggles to fully reflect the level of available water resources.

In many basins of Southern European countries throughout the region, water demand already exceeds water availability and often impose a strain on ecosystems (Iglesias et al., 2007; Yang and Zehnder, 2002; Hoff, 2011) this indicates the need for a policy-sensitive approach.

The difficulty in forecasting highly variable rainfall multiplies the challenges faced by water resource managers and increases the likelihood of water conflicts. The Mediterranean is considered to be a region that will experience large changes in climate mean and variability; that is a climate change hot-spot (Giorgi, 2006).

The region's overall socio-economic model places available water resources under considerable stress. In many cases, agriculture is responsible for water imbalances because it accounts for more than 50% of water use of many Southern European water basins (FAOSTAT, 2010). Thus, other economic uses of water – urban, energy and tourism – are imposing further challenges for meeting ecosystem services (Hoff, 2011) and increasing conflicts among the affected parties. Some of the potential solutions to these problems – such as changes in infrastructure or limitations of irrigation – are not accepted by all social sectors.

Water resource managers face the dilemma of ensuring future sustainability of water resources while maintaining strategic agricultural, social and environmental targets. Climate change imposes an additional challenge, and understanding its implications and policy requirements is a complex process. Table 5 summarises some water resource indicators in Southern European countries highlighting the scarce nature of the resource and the potential conflicting problems with shared waters.

Table 5 Water resource indicators: Total freshwater resources, available resources, use, and water availability in selected Southern European countries (Source: Iglesias et al., 2007)

Country	Total area (x 103 km2)	Population (million)	Rainfall (mm/yr)	Internal usable water resources (km3/yr) (a)	Usable water resources (km3/yr) (b)	Internal groundwater (km3/yr) (c)	Total water use (km3/yr)	Total water use (% Renewable)	Potential total usable water resources per capita (m3/capita per year)
France	552	60	867	178.50	203.70	100.00	35.63	17	3,439
Greece	132	11	652	58.00	74.25	10.30	7.99	11	6,998
Italy	301	57	832	182.50	191.30	43.00	43.04	22	3,325
Spain	506	41	636	111.20	111.50	29.90	35.90	32	2,794

(a) Water resources within a country. The values refer to both regulated and unregulated water. Real available water resources in all cases are a fraction of these values.

(b) Water resources that could be used because they are regulated. These values include transboundary water. See also Wolfe, 1999.
(c) A proportion of these values is included in the total renewable water resources.
Source of data: FAO, 2005 (data of 2004).

Scenarios of water resources availability are developed from climate projections but need to take water management, infrastructure and demands into account.

Our current understanding of European climate leads to projected overall temperature increase from 2 to 4 ºC and precipitation changes of +30 to -50% by 2080s (IPPC 2013). The changes are not equally distributed across the regions or the seasons. The changes are likely to be more pronounced in Southern Countries, with temperature increase that reaches +5°C by the 2080s in some scenarios and an alarming increase of extreme temperature (hot and very hot days); drought periods may increase throughout the Mediterranean (Giorgi, Lionello, 2008; Christensen et al., 2007). As a result, evaportranspiration rates will increase, soil structure changes will result in increased rates of soil erosion. Climate change may also produce some positive changes in water resources in some areas, give an adequate adaptive management. The changes may results in risks and opportunities for the water system and the environmental and social systems that depend on water. The opportunities arise from changes in the water cycle that may benefit some agricultural activities, of from the improvement of water allocation and management. A summary is provided in Table 6.

These projections may result in reductions of average annual runoff up to 50% challenging the whole socioeconomic model which is based largely on water demanding activities: recreation, tourism, and food production.

The solution to those problems will imply social changes, a progressive increase of water demand management and a consensus reallocation of water availability to essential users. The agreement on essential uses remains a controversial issue across the region. In this process, policies regulating water usage, water accessibility and hydraulic infrastructure, will play a critical role in making water available to users by overcoming the spatial and temporal irregularities of natural regimes.

In Europe, climate change impacts on water will have a large impact on human water security and biodiversity (Vorosmarty et al. 2010). There are several hundred studies on the potential impacts of climate change on water resources in the Europe which apply many different approaches (European Environment Agency, 2009). These studies have different focus – from ecosystems to water pricing to recreational water, a wide range of time-frames, different scenarios and spatial scales that vary from the local to the global analysis. Although the results are diverse and sometimes contradictory, a common element is that one of the primary impacts of climate change will be a reduction of water availability in a large part of the European region (European Environment Agency, 2007, 2009).

Table 6 Climate change induced risks and opportunities and degree of expected impacts on different sectors. Source Iglesias, 2013

Description	Ecosystems	Urban areas	Agriculture	Health	Economic activities (excluding agriculture)
RISKS					
Expansion of area with water deficit	High	Low	High	High	Medium
Increase in water demand (irrigation)	High	Low	High	High	Low
Increased drought and water scarcity	High	Medium	High	High	Medium
Increased floods	Medium	High	Medium	High	Medium
Water quality deterioration	High	Medium	Medium	High	Low
Increased soil erosion, salinity and desertification	High	Low	High	Medium	Low
Loss of snow and glaciers (natural reservoirs)	High	Low	High	Medium	Low
Sea level rise	High	High	Medium	High	Low
OPPORTUNITIES					
Increased water availability	High	Medium	High	Low	Medium
Increased potential for hydroelectric power	n.a.	High	Medium	Low	High
Increased potential to produce food and bio-fuels	n.a.	n.a.	High	n.a.	High

Sources: Alcamo et al. 2007; Arnell 2004 ; Barnett et al. 2005; Blanco-Canqui 2010; Copetti et al. 2010; EEA 2009; Iglesias et al. 2009; IPCC 2007; Milly et al. 2005; Parry et al 2004; Plan Bleu 2010; Rosenzweig et al 2004; Vorosmarty et al. 2010; Wreford et al. 2010 ; Wolf et al., 2011

Scenarios of water availability: An example in the Mediterranean region

Patterns and trends of climate studies show that the effects of climate change will ultimately affect water resources availability and thus have an impact on water management (EEA, 2011, 2012). The consensus is that the effect will accentuate the extremes with more pronounced drought and flood periods. Certain regions dependent on water (e.g. major farming areas, or large population centres) will experience more water scarcity, thus stressing the need for adaptation strategies. Hydrological stress is expected to increase in central and southern Europe (EEA, 2012). For the 2070s, the percentage of surface area under conditions of severe water stress is expected to increase from the current 19% to 35%. Populations living under water stress conditions in regions from 17 countries of Western Europe are projected to increase by between 16 to 44 million. It is also predicted that the volume of certain rivers may diminish up to 80% during summer seasons; reservoirs may lose resources due to decrease of rainfall and droughts frequency will be increased. A reduction of average natural water resources will produce increasingly more frequent and more intense episodes of water shortage. It is also foreseen that climate change will produce alterations in the variability of water resources, intensifying the frequency and magnitude of extreme events, like floods and droughts, which will produce important impacts on the population. Climate change is expected to result in an increased water demand; higher temperatures are expected to lead to increased water demand for irrigation and urban supply, hydroelectric potential of Europe may decrease 6% in average and between 20 and 50% in the Mediterranean region. However, industry may not increase consumption of water because of technology efficiency.

Water quality is also expected to deteriorate. There are many possible routes of interaction, such as reducing the flow available for pollution dilution, the temperature increase, with consequent changes in the activity of biological processes, chemical modification of the flow of water through the soil, with the alteration of the transport of nutrients and pollutants, and so on. Although there are many processes involved, the results so far point to a likely deterioration of water quality, especially in areas where the natural river regime has been significantly altered.

Natural ecosystems will be altered in a diversity of ways. The challenge of environmental management consists on anticipating the negative effects of climate change by means of the analysis possible scenarios and on adopting management strategies that are positive in the current situation and do not worsen the situation in case of adverse climate change.

Scenarios of water resources availability are developed from climate projections but need to take into account water management, infrastructure and demands. In water scarce regions, the impacts of climate change on natural resources will affect water uses through water resource systems, which perform functions of regulation, transportation and distribution of water resources. In these regions, water resources systems are highly developed and they have achieved a profound transformation of the natural characteristics of water resources to accommodate the needs of demands. Hydraulic infrastructure plays a critical role to make water available to users by overcoming the spatial and temporal irregularities of the natural regimes.

In the Mediterranean, climate change impacts on water will have a large impact on human water security and biodiversity (Vorosmarty et al., 2010). There are several hundred studies on the potential impacts of climate change on water resources in the Mediterranean which apply many different approaches. According to Gleick and Palaniappan (2010), more and more watersheds appear to have passed the point of peak water, a concept related to the sustainability of water management. These studies have different focus – from ecosystems to water pricing to recreational water–, a wide range of time-frames, different scenarios and spatial scales that vary from the local to the global analysis. Although the results are diverse and sometimes contradictory, a common element is that one of the primary impacts of climate change will be a reduction of water availability in the Mediterranean.

In the North of Europe climate scenarios project increases in air temperature and precipitation during the 21st century and these will results in changes in hydrology. Seasonal changes in discharges in Finland are the clearest anticipated impacts of climate change. Floods caused by spring snowmelt are expected to decrease or remain unchanged, whereas autumn and winter floods caused by precipitation increase especially in large lakes and their outflow rivers (Veijalainen, 2012).

Nordic catchments can be very responsive to even limited variation in precipitation and temperature in terms of river flow and chemistry (Bouraoui et al., 2004). Predicted changes in precipitation and temperature increases the nutrient load from catchments to water bodies in future climate (Rankinen et al., 2009).

Meier et al. (2012) state that due to the increased temperature and increased net precipitation in the Baltic catchment area the decomposition of organic material in the sediments will be accelerated and the nutrient loads from land will increase. Both processes accelerate eutrophication in the Baltic Sea. Eriksson Hägg et al. (2010) have estimated a 3-72 % increase in total nitrogen flux from catchments surrounding the Baltic Sea by 2070.

Climate adaptation in the north of Europe requires changes in current water resources management measures. Changing the management practices and permits of many of the regulated lakes in Finland will become necessary during the 21st century in response to climate change induced shifts in hydrological regime (Veijalainen, 2012). According to Meier et al. (2012), nutrient load reductions performed under current legislation will not be sufficient to improve the water quality at the end of the century. Efficient allocation of water protection measures requires detailed analysis of different sources of loading (Rankinen et al., 2009).

Nevertheless many of these projections do not take into account the effects of policy. The solution to climate problems will imply social changes, a progressive increase of water demand management and a consensus reallocation of water availability to prioritised users. The agreement on essential uses remains a controversial issue across the region. In this process, policies regulating water usage, water accessibility and hydraulic infrastructure, will play a critical role in making water available to users by overcoming the spatial and temporal irregularities of natural regimes.

To summarize, areas exposed to drought and water scarcity are very sensitive to climate change, because the current high degree of water resources use, the imperative need to allocate more water for environmental uses and the narrow margin which is available to improve water availability. Climate change in these regions is perceived as an intensification of existing pressures, which will imply strong reductions in water availability and further increases in water demand. This will lead to the intensification of water management conflicts, due to the competition for water among different social agents and the degradation of water quality through the alteration of the hydrological cycle. In some regions, current water uses cannot be maintained in the future. If climate predictions are right, reductions of up to 50% of average annual runoff will lead to a deep crisis of the ecosystem, society and the whole socioeconomic model, based largely on highly productive agriculture and tourism industries. The solution to those problems will imply profound social changes, progressive reduction of water demand and reallocation of water availability to those uses that are deemed socially as more appropriate.

BASE will develop a database of management alternatives in the Case Studies and therefore contribute to the limitations of the current literature.

Scenarios of flood intensity and frequency

According to the IPCC report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012), there is limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at a regional scale because the available instrumental records of floods at gauge stations are limited in space and time, and because of confounding effects of changes in land use and engineering. Furthermore, there is low agreement in this evidence, and thus overall low confidence at the global scale regarding even the sign of these changes. There is low confidence (due to limited evidence) that anthropogenic climate change has affected the magnitude or frequency of floods, though it has detectably influenced several components of the hydrological cycle such as precipitation and snowmelt (medium confidence to high confidence), which may impact flood trends. Projected precipitation and temperature changes imply possible changes in floods, although overall there is low confidence in projections of changes in fluvial floods. Confidence is low due to limited evidence and because the causes of regional changes are complex, although there are exceptions to this statement. There is medium confidence (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in rain-generated local flooding, in some catchments or regions. Earlier spring peak flows in snowmelt- and glacier-fed rivers are very likely, but there is low confidence in their projected magnitude.

This evaluation of floods will be integrated with to the Hydrology and Flood Risk presented in Section 2 of this Deliverable D3.2.

4.2 People and policy may modify water availability

Water supply and demand scenarios

All water-abstracting sectors require a reliable supply in order to provide sufficient water during periods of prolonged lack of rainfall (EEA, 2012). Over time, people have developed a number of ways to guarantee their water supply. As a result, the storage of surface water in reservoirs is commonplace and transfers of water between river basins also occur as is the artificial recharge of groundwater by river water. Recently, the production of freshwater via desalination or recycling is also playing an increasingly important role.

However, as we have seen, climate change jeopardizes the equilibrium of water resources systems and the impacts will vary as a result of local regulation capacity. Although there are many studies on the impacts of climate change in the natural hydrological regime, climate change impacts on regulated systems have not received as much attention. An analysis of climate change in regulated systems in the Mediterranean water basins would highlight the effects of adaptive regulation as management alternative.

Reservoir regulation has been one of the most important water resources management in arid and semiarid regions and has generated significant impacts. A reservoir is a dynamic storage of water, which can be controlled, and is used to balance the irregularity of water resources. Existing reservoirs are being subjected to intense multi-objective demands on limited resources. Reservoir water uses include water supply, flood control, hydropower, navigation, fish and wild life conservation, and recreation. Water quality may also be considered a reservoir purpose when water is provided to assimilate waste effluents. It is not surprising then that defining optimal reservoir operation for reservoirs with multiple water uses is a challenge.

Reductions of water inflow and increased variability may result in significant decreases in the water availability. This clearly demands for adaptation measures with large impacts to society. In most SE basins the reductions in water availability will result in impositions of demand restrictions since regulatory capacity is already at a maximum.

This is particularly true in the case of irrigation water demand scenarios since it is reasonable to assume that, without changes in policy, land use or technology, projected irrigation demand in the basin will be higher than present irrigation demand even if farmers apply efficient management practices and adjust cropping systems to the new climate. Moreover, when policy and technology remain constant, it has been shown that agricultural water demand will increase in all scenarios in the region (Iglesias et al., 2007, Iglesias 2009). The main drivers of this irrigation demand increase are the decrease in effective rainfall and increase in potential evapotranspiration (due to higher temperature and changes of other meteorological variables).

Defining water availability

We will present in Section 5.4 a modelling approach to compute water availability and reliability as result of implementing climate or policy scenarios. The models will be used to compute water availability and demand-reliability curves, which provide a simple way to evaluate water availability under different policy and climate change scenarios.

4.3 A review of approaches to evaluate water resources adaption

This section summarises a range of modelling tools to evaluate water resources adaptation.

Modelling

Climate change can alter regional water requirements through two pathways: sector-level changes in biophysical water demand (i.e., agriculture, urban, ecosystems responses) and adaptation policy responses (i.e., EU Water Framework Directive). These changes are best documented by modelling approaches.

Models provide means to represent regional variations of the effect of a warming climate on soil-moisture, evaporative losses and changes in precipitation, irrigation, water availability and urban or tourist use. Döll (2002) offers for the first time a global analysis of irrigation requirements under climate change. Her results highlight that two-thirds of the global area equipped for irrigation in 1995 will possibly suffer from increased water requirements, and on up to half of the total area (depending on the measure of variability), the negative impact of climate change is more significant than that of climate variability. Strzepek et al. (1999) use a suite of models to evaluate changes in water supply and demand for agriculture in the USA. Following the same methodology, Rosenzweig et al. (2004) define scenarios of water resources for agriculture in a changing climate in five major agricultural regions: USA, Europe, China, Brasil and Argentina that account for almost two thirds of the total global food trade. Iglesias et al. (2012) evaluate the need for additional irrigation as an adaptation strategy considering scenarios of urban water demand are driven by changes in population and lifestyles. Population is expected to increase slightly, projections of increased GDP result in lifestyle changes that demand more urban water (from collective living to single home living). Unless GDP growth is decoupled from urban and industrial water use it is likely that the demands from these sectors will continue to grow. The calculation of changes in irrigation requirements aim to reach demand satisfaction according to assumptions on technological capacity of the country, limited by the country environmental flow requirements. Logar and Bergh (2013) provide an overview on methods for the assessment of the costs of droughts. Reviews of flood damage evaluation methods are provided by Meyer and Messner (2005), Messner et al. (2007), Merz et al. (2010), Green et al. (2011).

Evaluation of water resources reallocation

Regarding climate change predictions, water resources re-allocation seems to be a key adaptation measure to tackle water scarcity problems (Grantham et al., 2010, Varela-Ortega et al., 1998). However, there are some potential solutions to water allocation problems such as changes in infrastructure, land-use or limitations of irrigation that may not be well accepted by the whole society (Iglesias et al., 2011b) and decision-making processes often can lead to conflicts among different stakeholders. Thus it is essential to incorporate the interests of the different stakeholders affected by the consequences of these processes, including policy makers, farmers and the public (Conde et al., 2005, Semenza et al., 2011). The Water Framework Directive (EUWFD), which represents a benchmark in the design of water policies in Europe, greatly promotes stakeholders and public participation in decision- and policy-making processes. Relly and Sabharwal (2009) claim that there is a growing demand for the processes used to allocate resources to be transparent, based on scientific evidence, and deliver outcomes that are in the public’s interest. This reinforces the need to study public preferences for climate change adaptation measures in order to incorporate public opinion into policy- and decision-making processes. Thus a better understanding of how stakeholders' perceive climate change, adaptation policies, and the factors or predictors influencing their support for adaptation policies can be a helpful tool in the development of these decisions and policies.

The European Floods Directive (FD) (European Parliament and the Council, 2007) also takes climate change adaptation into account. Member states have to undertake a preliminary flood risk assessment within their river basins, and have to compile flood hazard and risk maps at an appropriate scale in order to serve as a basis for flood risk management plans. The directive requires that the likely impact of climate change on the occurrence of floods shall be taken into account … in the periodic reviews of flood risk assessments and risk management plans (European Parliament and the Council, 2007). At least for the development (and review) of flood risk management plans participation is promoted: Member States shall encourage active involvement of interested parties in the production, review and updating of the flood risk management plans (European Parliament and the Council, 2007).

Participatory approaches

Public concern of the state of the environment has grown rapidly and this has also increased interest in participatory decision making (Mustajoki et al., 2004). Consequently, public approval has become an important decision objective, and the public participation a common element in environmental decision making processes. However, the large number of stakeholders also induces a large number of conflicting views, and transparent and structured processes are needed to reach participants' shared understanding of the problem and collective build a proposal that reaches consent.

Cost-benefit evaluation of concrete measures

Cost benefit analysis is used for the evaluation of concrete measures where costs associated with action and inaction are well documented. McEvoy and Wilder (2012) evaluate the potential impacts of proposed climate change adaptation interventions in the Arizona–Sonora border region, focusing on desalination —the conversion of seawater or brackish groundwater to fresh water—as an adaptation response that can help meet growing water demands and buffer against the negative impacts of climate change on regional water supplies. However, the uneven distribution of costs and benefits of this expensive, energy-intensive technology is likely to exacerbate existing social inequalities in the border zone.

Gersonius et al. (2013) evaluated the role of flexible options to face flood risk. Flexibility will restrict the effect of erroneous decisions and help avoid maladaptation. Real In Options (RIO) analysis can facilitate the development of an optimal managed/adaptive strategy to climate change. The authors show the economic benefits of adopting a managed/adaptive strategy and building in flexibility, using RIO analysis applied for the first time to urban drainage infrastructure.

De Roo et al. (2012) have recently reported a multi-criteria optimisation of scenarios for the protection of water resources in Europe. Multi-criteria as well as cost-benefit evaluation for regional adaptation options of water scarcity management have been conducted by Meyer et al. (2011) for the Elbe River basin (see also Grossmann et al., 2011).

Cost-benefit analyses for flood risk management options have already a quite long tradition in policy, in particular in the UK (MAFF, 1999, Pearce and Smale, 2005). The current challenge is to consider the dynamics of flood risk (due to climate and socio-economic change) in such evaluations (Elmer et al., 2012, Meyer et al., 2012). This cost-benefit analysis will be implemented in some BASE Case Studies and reported in WP6.

Learning from expert judgement

In many cases the attributes of adaptation strategies are not clear from the studies. In such cases, expert judgement is often used to make proposals (Mukheibir and Ziervogel, 2007, Mukheibir, 2008). De Bruin et al. (2009) describe an inventory of climate adaptation options and ranking of alternatives in The Netherlands, including options for water for agriculture. The study evaluates the options based on stakeholder analysis and expert judgement, and presents some estimates of incremental costs and benefits. The qualitative assessment focuses on ranking and prioritisation of adaptation options.

Evaluating the role of institutions

Berman et al. (2012) evaluate the role of institutions in the transformation of coping capacity to sustainable adaptive capacity. The study identified four key challenges to understand the transformation of coping to adaptive capacity include (1) the concealed nature of adaptive capacity; (2) the temporal trade-offs between coping and adaptive capacity; (3) the limited focus to date on rural communities, and; (4) the lack of empirical evidence. Agrawal (2008) provides a clear review of adaptation to climate change, highlighting the role of local institutions. Huntjens et al. (2012) propose a theoretical improved institutional design, and Groves et al. (2008) identify concrete actions for water management institutions.

Understanding public choices

Understanding public choices on environmental issues has evolved from the rational choice logic that explains choices based on self-interest (Sears and Kinder, 1985) to the analysis of beliefs of individual groups (Davis and Shipp, 2009, García de Jalón et al., 2013). Regardless of the sociological theory behind the process, sociologists tend to accept that those actions —not opinions— are explained by interests and resources rather than values and beliefs. Why do individuals adopt certain action? Addressing the social and psychological causes behind the individual choice, is beyond the aims of this study, but we provide an understanding of the main drivers that shape motivations and barriers.

Environmental commitment and climate change concern are not driven by the same social characteristics, as we would have expected. This reflects the theory that choice is driven by both cultural and rational approaches. The individuals that have relatively well formed views about climate change are guided by values and beliefs that result from education and social responsibility. In contrast, individuals that may suffer personal costs derived from their decision reflect a rational actor model.

Public choice for adaptation in the European Union has been documented based on extensive surveys (Eurobarometer, 2009); in USA with more analytical approaches (Shwom et al., 2010). Perceptions and policy choices are often complex and reflect local values (Leiserowitz, 2006).

Studies concerning people's support for adaptation policies have been less numerous that those dealing with social perception of climate change. There is a number studies which assess people's support for adaptation policies by asking respondents directly how much they would be willing to pay for some adaptation measures to climate change (Fisher et al., 2012, Ku and Yoo, 2010, Solomon and Johnson, 2009, Zografakis et al., 2010). In this field there is also a growing literature highlighting the factors that influence stakeholders' willingness to adapt to climate change.

Planning new investments

Planning and developing irrigation is always a local choice (Mehta et al., 2012, Törnqvist and Jarsjö, 2012). Heumesser et al. (2012) define a method for investment in irrigation systems under precipitation uncertainty in Austria, assessing the optimal timing to invest into either irrigation system in the planning period 2010 to 2040. They then investigate how alternative policies, (a) irrigation water pricing, and (b) equipment subsidies for drip irrigation, affect the investment strategy.

Local needs and capacities

Local needs and capacitates are based in the potential for capacity to develop new infrastructure systems (Zimmerer, 2011, Siebert et al., 2007) or implementing improved technology for irrigation, desalinisation (Abufayed and El-Ghuel, 2001), water re-use technology (Trinh et al., 2013), alternatives of groundwater management (Causapé et al., 2006, Garrido and Iglesias, 2008), water harvesting (Moges et al., 2011, Oweis and Hachum, 2006), capacity to develop insurance or capacity to develop water markets (Garrick et al., 2009).

Although local needs set the scene for adaptation, cooperation is always a priority for adaptation that includes water resources management, as shown for example in the case of trans-boundary water management (Dieperink, 2000, Sadoff and Grey, 2002, Vugteveen et al., 2010).

Upscalling local initiatives is often impossible (Rodríguez et al., 2006), but knowledge transfer should play a major role in the development of adaptation strategies, especially the strategies that include local resiliency as a major component of the adaptation assessment needs. Kuhlicke et al. (2012) provide guidance for social capacity building for natural hazards, considering the social capacities of organisations as well as local communities.

Evaluating trade-offs

The need for developing win-win strategies to avoid the potential conflicts that may arise due to climate change impacts have been stressed endlessly (Carraro, 2007, Fankhauser et al., 1999). Given the costs and lack of incentives associated with promoting adaptive capacity, adaptation is unlikely to be facilitated through the introduction of new and separate policies, but rather by the revision of existing policies that currently undermine and the strengthening of policies that promote adaptation (Howden et al., 2007, Iglesias et al., 2011b). Finding common ground between competing claims is a serious challenge to policy development. Nevertheless, this challenge needs to be addressed to ensure the coherence and efficiency of policy measures under a changing climate (Juhola and Westerhoff, 2011).

Water availability and adaptation policy assessment

Three factors are at play in regulated water resource systems: stream flow variability, storage capacity and yield reliability. These are usually linked through storage-yield-performance characteristics, which describe how a system is able to supply its demands and with what reliability. There is a wide range of techniques which can be applied for this purpose, from relatively simple regression functions relating these variables to highly complex water resource systems models. Usually, these complex simulation or optimization models are used in River Basin Management Plans in areas prone to water scarcity. The result of the analysis is an estimation of the reliability of supply for each demand present in the system.

The Water Availability and Adaptation Policy Assessment model (WAAPA) (Iglesias et al., 2011a) may be used to compute the water availability and demand-reliability curve, which provides a simple way to evaluate water availability under different policy and climate change scenarios. WAAPA model architecture, system management options, system performance evaluation and demand performance analysis. The model has been applied to evaluate economic decisions of drought policy and water policy in the Mediterranean (Iglesias et al., 2013). The model links water supply, demand and management allowing the analysis of policy options. The model computes water availability and reliability as result of implementing climate or policy scenarios.

4.4 The WAAPA model

4.4.1 Summary

The proposed methodology to identify and evaluate climate change adaptation policies within the BASE project is presented in this section. The methodology is based on the development of a GIS-based model, called Water Availability and Adaptation Policy Assessment (WAAPA), which computes net water availability for consumptive use for a river basin taking into account the regulation capacity of its water supply system and a set of management standards defined through water policy. WAAPA model provides a simple way to account for the influence of socioeconomic factors (hydraulic infrastructure and water policy) on climate change impacts on water resources.

Aim of the model

Defining future water availability is a basic step for water policy formulation. We provide a platform for determining policy responses at the basin level. This evaluation helps define the sensitivity of a system to external shocks and to identify the most relevant aspects that can decrease the level of risk posed by climate change. With this modelling activity we will assess water availability resulting from different climate scenarios and multiple adaptation pathways. We will incorporate the local adaptation measures selected in the case-studies. If requested water availability maps can be made available to the case-study partners.

Description

Water availability modelling: UPM will calculate water availability under climate change on river basins using the European scale WAAPA model (460 subbasins). The Water Availability and Adaptation Policy Assessment model. WAAPA, (Garrote et al., 2011) links water supply, demand and management and is used to analyse policy options. The model computes water availability and reliability as a result of implementing climate or policy scenarios. WAAPA is used to compute water availability and demand-reliability curves, which provide a simple way to evaluate water availability under different policy and climate change scenarios. The model has been applied to evaluate economic decisions of drought policy and water policy in the Mediterranean. Here it will be extended to the EU27-wide area.

Adaptation pathways: Adaptation strategies and measures will be collected from those case-studies focusing on water resources. The adaptation measures will be aggregated and integrated in the European model to assess potential benefits (water for environmental flow requirements) under different climate scenarios.

End-product: The results will be European water availability maps for different climate scenarios and adaptation paths. These will be aggregated to several overall values of water availability changes: for agriculture, for domestic use and environmental flow requirements. The output will be water availability maps which can be aggregated to one value at the river basin scale and to one value at the EU-27 countries scale as requested by Ad-Witch.

Data needs and linkages with other models/cases study within BASE

For adaptation measures from the case-studies to be aggregated and integrated into the European scale model following information is needed:

Overview of local adaptation pathways + individual adaptation measures;

Estimated implementation- and environmental costs of adaptation measures;

Estimated economic climate extreme loss for current climate and future climate for different adaptation strategies;

Reference period, scenarios and time-horizon considered;

This is in line with the planned framework of Deliverable D6.2.

4.4.2 Models architecture and data

The Water Availability and Adaptation Policy Assessment model (Garrote et al., 2011, Figure 20) links water supply, demand and management and is used to analyse policy options.

The WAAPA model may be used to compute the water availability and demand-reliability curves, which provide a simple way to evaluate water availability under different policy and climate change scenarios. WAAPA simulates the joint operation of all reservoirs in a basin to satisfy a unique set of demands. Basic inputs to the WAAPA model are the river network topology, the reservoir characteristics (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates), the naturalized stream flow series entering different points of the river network, the environmental flow conditions downstream of reservoirs and monthly values of urban and agricultural demands for the entire basin. The model is based on the mass conservation equation, and main assumptions refer to how reservoirs are managed in the system: to supply demands for any given month, water is preferentially taken from the most downstream reservoir available, since spills from upstream reservoirs can be stored in downstream ones.

Model architecture is summarized in Figure 18. The WAAPA model is based on a basic reservoir operation model. The reservoir operation model takes as input the monthly inflows, the monthly required environmental flow, the monthly demand values sorted by priority with the corresponding return flow, the reservoir data (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates) and the reservoir initial condition (initial storage). The result of the reservoir operation model is a set of time series of monthly volumes supplied to each demand, monthly storage values and monthly values of spills, environmental flows and evaporation losses. From this output, demand reliability can be computed applying any conventional procedure. Additionally WAAPA can be operated as a joint reservoir operation model that combines all reservoirs in a basin to satisfy a unique set of demands. Reservoirs are ordered by priority (water is taken preferably from reservoirs with higher priority). In each time step, the model performs the following operations:

- Satisfaction of the environmental flow requirement in every reservoir with the available inflow. Environmental flows are passed to downstream reservoirs and added to their inflows.
- Computation of evaporation in every reservoir and reduction of available storage accordingly
- Increment of storage with the remaining inflow, if any. Computation of excess storage (storage above maximum capacity) in every reservoir.
- Satisfaction of demands ordered by priority, if possible. Use of excess storage first, then available storage starting from higher priority reservoirs.
- If excess storage remains in any reservoir, computation of uncontrolled spills.

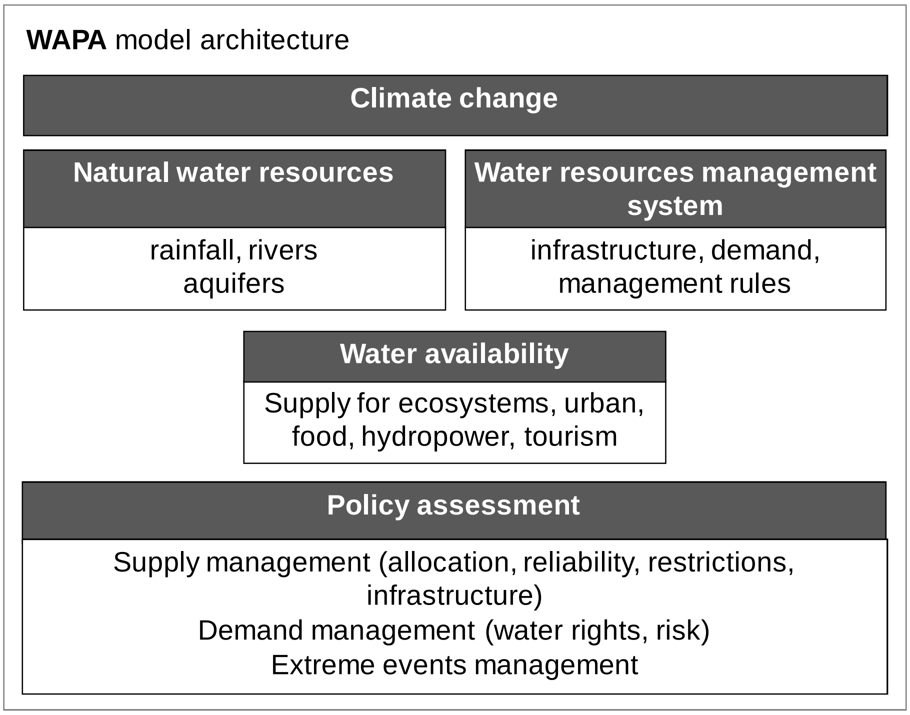


Figure 18 Architecture of the Water Availability and Adaptation Policy Assessment model (WAAPA)

Model data

WAAPA model data are geographically referenced. The following data are required to build a WAAPA model

Topology. The area under study is divided in a number of units of analysis, which should be homogeneous subbasins from the water management perspective. The size of the subbasins will depend on the required resolution and on data availability. The subbasins are related through the “drain-to” relationship, and the analysis is applied to all possible basins, from the small headwater subbasins to the largest basin draining to the sea. In the BASE project, subbasins in the Hydro1k or HydroSheds data sets may be used.

Naturalized streamflow. Naturalized streamflow will be obtained from the results of the hydrological model PCR-GLOBWB. Several model runs are available for the control scenario and different climate change RCP emission scenarios. Since runoff obtained from PCR-GLOBWB may present significant bias, average values will be corrected for bias using the UNH/GRDC composite runoff field, which combines observed river discharges with a water balance model.

Regulation. A basic input to the model is the storage volume available for regulation in every subbasin. Data may be obtained from the ICOLD World Register of Dams (ICOLD, 2003). Required information is reservoir location, storage capacity and flooded area. Evaporation losses from reservoirs were computed using the evaporation output from the regional climate models.

Environmental flows. Environmental flows may be computed through hydrologic methods. Monthly minimum required environmental flow will be defined as a given quantile in the distribution of naturalized monthly flows.

Urban demands. Urban demands are computed on the basis of population and per-capita water requirement. Subbasin population may be obtained from the Global Rural-Urban Mapping Project (GRUMP), available at the Center for International Earth Science Information Network. Per-capita water requirement may be obtained from a variety of sources. Average return flows from urban demands may be estimated as a function of per-capita water requirement.

Irrigation demands. Irrigation demands may be computed on the basis of potential irrigation area and per-hectare water requirement. Potential irrigation area can obtained from the Global Map of Irrigated Area dataset. Per-hectare water requirement can be obtained from studies by FAO or Plan Bleu. Average return flows from irrigation demands may be estimated as a function of per-hectare water requirement.

All data have to be aggregated recursively by subbasins, starting from the subbasins, which are the elementary computational units.

The single reservoir operation model

WAAPA model is based on a basic reservoir operation model. The reservoir operation model takes as input the monthly inflows, the monthly required environmental flow, the monthly demand values sorted by priority with the corresponding return flow, the reservoir data (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates) and the reservoir initial condition (initial storage).

In each time step, the model performs the following operations:

- Satisfy the environmental flow requirement with the inflow
- Compute evaporation and reduce available storage accordingly
- Increment storage with the remaining inflow, if any
- Satisfy demands ordered by priority, if possible
- If storage is larger than capacity, compute uncontrolled spills

The result of the reservoir operation model is a set of time series of monthly volumes supplied to each demand, monthly storage values and monthly values of spills, environmental flows and evaporation losses. From this output, demand reliability can be computed applying any conventional procedure.

The joint reservoir operation model

The joint reservoir operation model combines all reservoirs in a basin to satisfy a unique set of demands. It takes as input the monthly inflows in every reservoir, the monthly required environmental flow in every reservoir, the monthly demand values sorted by priority with the corresponding return flow, the reservoir data in every reservoir (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates) and the reservoir initial condition in every reservoir (initial storage). Reservoirs are ordered by priority (water is taken preferably from reservoirs with higher priority).

In each time step, the model performs the following operations:

- Satisfy the environmental flow requirement in every reservoir with the available inflow. Environmental flows are passed to downstream reservoirs and added to their inflows.
- Compute evaporation in every reservoir and reduce available storage accordingly
- Increment storage with the remaining inflow, if any. Compute excess storage (storage above maximum capacity) in every reservoir.
- Satisfy demands ordered by priority, if possible. Use excess storage first, then available storage starting from higher priority reservoirs.
- If excess storage remains in any reservoir, compute uncontrolled spills

The result of the joint reservoir operation model is a set of time series of monthly volumes supplied to each demand, monthly storage values and monthly values of spills, environmental flows and evaporation losses in every reservoir. From this output, demand reliability can be computed applying any conventional procedure.

System management options

The single reservoir operation model and the joint reservoir operation model are used by WAAPA to evaluate system performance in each basin under three management hypotheses (Figure 19):

Local management (LM): All reservoirs in the sub-basin are supposed to be jointly operated to supply local demands. System performance is evaluated for each sub-basin using the single reservoir operation model locally, assuming an equivalent reservoir with a capacity equal to the sum of capacities of all reservoirs in the sub-basin. Downstream basins can only use uncontrolled spills from upstream basins and return flows from upstream demands. It corresponds to a situation where there is well developed hydraulic infrastructure, but of local scope: the system is managed to supply only local demands and there are no system interconnections or large scale water distribution infrastructure.

Global management of distribution (GMD): All reservoirs in a large region composed of several systems are supposed to be jointly operated to supply all demands in the region. System performance is evaluated for each basin using the joint reservoir operation model globally. In each sub-basin within the region, the model considers an equivalent reservoir with a capacity equal to the sum of capacities of all reservoirs in the sub-basin. The model considers only one single demand which is the sum of all demands present in the region. It is assumed that any demand at a given point in the network can be supplied from any reservoir located upstream of it. It corresponds to a situation where there is little development of system interconnections, but there is a large development of water distribution networks which are managed globally to supply all demands present in the system.

Global management of supply and distribution (GMSD): System performance is evaluated for each basin using the single reservoir operation model globally (considering only one equivalent reservoir which takes all inputs and supplies all demands). All reservoirs in the system can be coordinated to maximize the effect of available storage. It corresponds to a situation where hydraulic infrastructure is highly developed, with many reservoir interconnections that allow inter-basin water transfers and large water distribution networks that reach all demands present in the system.

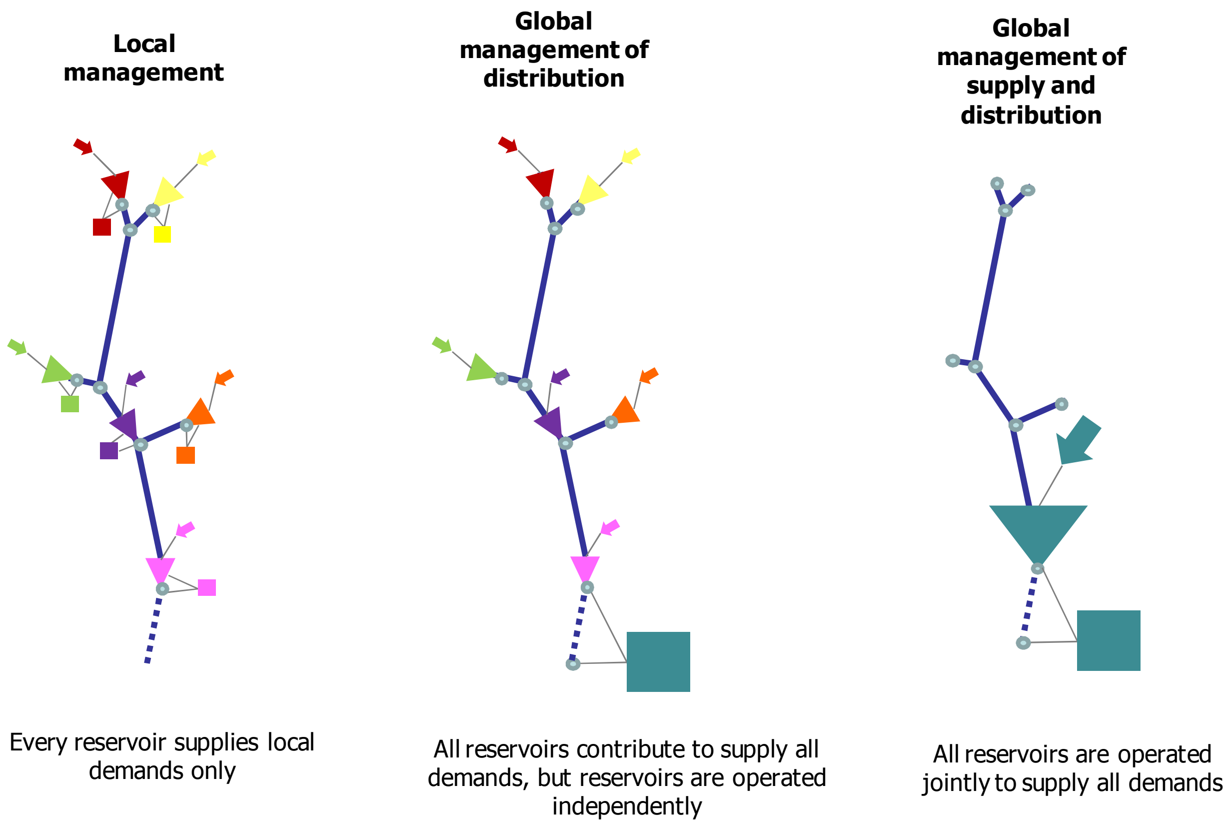


Figure 19 Management options in WAAPA

4.4.3 Water availability

Given a performance measure, WAAPA can obtain maximum water availability for a certain threshold of performance for demand components. Water availability is based on the concept of Maximum Potential Water Withdrawal (MPWW), defined as the maximum water demand that could be provided at a given point in the river network with the available water infrastructure. MPWW is associated to a given demand type, which implies a minimum required reliability and certain seasonal variation. WAAPA is well suited for the analysis using its sensitivity analysis feature

For demand *i* and performance measure *j*, the maximum representative demand value d^i_{kmax} with a given precision d_{prec} which satisfies a minimum required system performance p^j_{imin}, so that $f_i^j(d^i_{k\max}) \geq p^j_{i\min}$ and $f_i^j(d^i_{k\max} + d_{prec}) < p^j_{i\min}$.

Actual water availability A_k for demand component k would be the minimum value of d^i_{kmax}, which satisfies the requirement for all demand components:

$$A_k = \min_{i \in I}(d^i_{k\max}) .$$

In WAAPA, water availability may be evaluated under two hypotheses:

Water availability for urban demands: Water availability is estimated with only urban demand present in the system. System performance is evaluated as time reliability at monthly and decennial time steps with maximum deficits allowed of 10% of monthly demand and 8% of annual demand respectively. The required performance to estimate water availability is a 100% time reliability in both cases.

Water availability for irrigation demands: Water availability is estimated with a fixed urban demand and variable irrigation demand. System performance is evaluated as a function of irrigation demand. For urban demand, time reliability is applied at monthly and decennial time steps with maximum deficits allowed of 10% of monthly demand and 8% of annual demand respectively. For irrigation demands time reliability is applied at annual, biannual and decennial time steps with maximum deficits allowed of 50%, 75% and 100% of annual demand respectively. The required performance to estimate water availability is a 100% time reliability in all cases.

Demand-performance analysis

Curves of demand-performance analysis may be obtained by selecting a representative demand k and a performance measure j and obtaining the evolution of the performance measure j for any demand i as the representative demand k is changing.

WAAPA obtains system performance for all demand components as a function of one representative demand component for a given performance measure. System performance p_i^j for demand component *i* and performance measure *j* (for instance, reliability in volume for urban demand) is assumed to be a continuous function of the representative demand component d_k (for instance, irrigation demand): $p_i^j = f_i^{\,j}(d_k)$.

For instance Figure 20 presents an example of demand-performance analysis in a system with two demand components (α and β). In this example, demand component α represents urban demand, while demand component β represents irrigation demand. Urban supply has higher priority than irrigation. The analysis is performed as a function of a variable value of demand component β (irrigation) with a fixed value of demand component α (urban supply) and of reservoir capacity. Performance values for demand components α (p^α_β) and β (p^β_β) are represented as a function of demand value d_β. If required performances for urban supply and irrigation are, respectively, p^α_{req} and p^β_{req}, marginal productivity (MPWW, marginal productivity of water) values of demand component β would be $d^\alpha_{\beta max}$, according to the required performance for demand component α and d^β_βmax, according to the required performance for demand component β. The limiting factor would be demand component α, which has a lower d_{max} value. The figure on the right presents a similar analysis, although the factor that is allowed to change in this case is the reservoir storage, while demand values remain constant

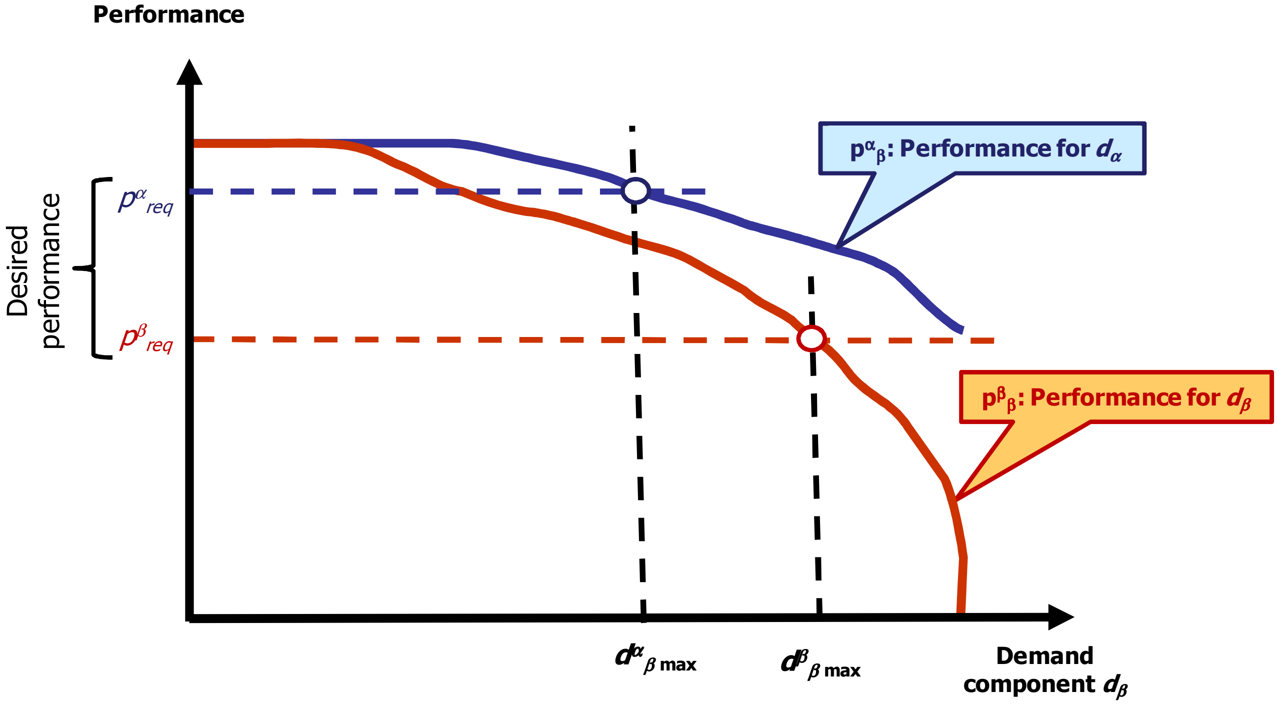


Figure 20 Example of demand performance analysis

Demand performance is evaluated under two hypotheses:

Performance analysis for urban demands: Performance analysis is carried out with only urban demand present in the system. Demand-performance curves are built by running the model with fixed environmental flows and variable urban demand, ranging from 0 to average streamflow. System performance is evaluated as time reliability at monthly and decennial time steps with maximum deficits allowed of 10% of monthly demand and 8% of annual demand respectively.

Performance analysis for irrigation demands: Performance analysis is carried out with a fixed urban demand and variable irrigation demand. Demand-performance curves are built by running the model with fixed environmental flows and urban demand and variable irrigation demand, ranging from 0 to mean streamflow minus urban demand. System performance is evaluated as a function of urban and irrigation demand. For urban demand, time reliability is applied at monthly and decennial time steps with maximum deficits allowed of 10% of monthly demand and 8% of annual demand respectively. For irrigation demand time reliability is applied at annual, biannual and decennial time steps with maximum deficits allowed of 50%, 75% and 100% of annual demand respectively.

Performance evaluation can also be analyzed by fixing the demand and changing other parameter in the system. For instance, an analysis of the effect of reservoir storage is presented in Figure 23.

Demand performances for demand components α (p^{α}_{S}) and β (p^{β}_{S}) are represented as a function of reservoir storage S. If a minimum performance is specified, the required reservoir storage would be S^{α}_{min} and S^{β}_{min}. The limiting factor would be demand component α, which has a higher S_{min} value.

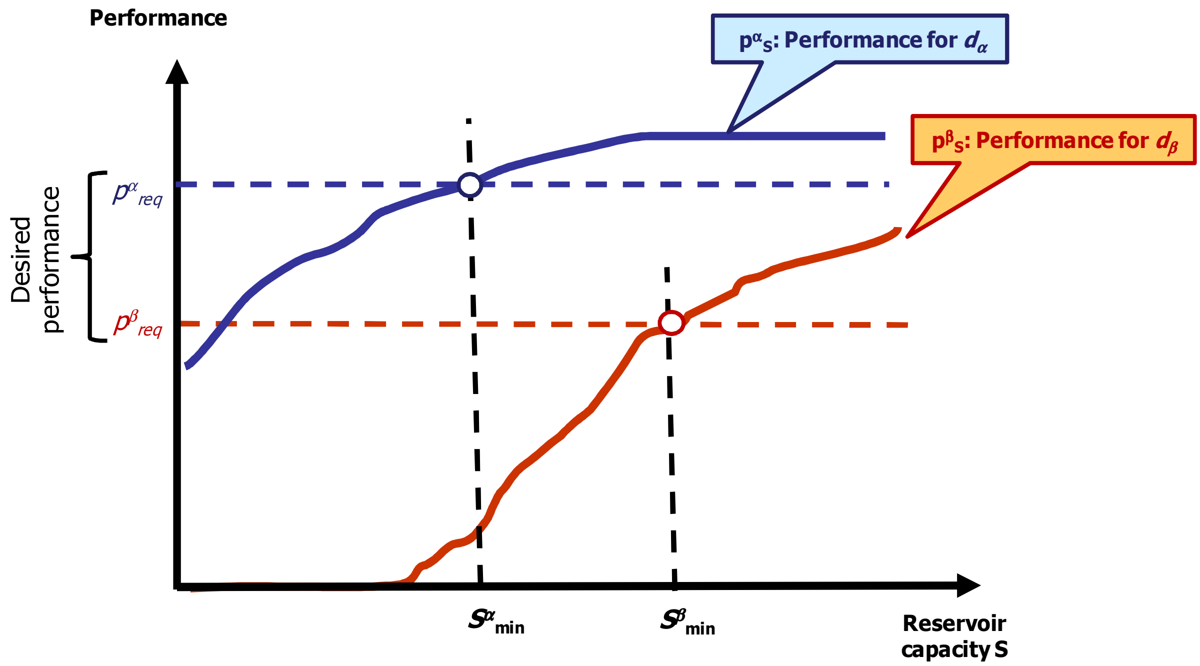


Figure 21 Example of sensitivity analysis to reservoir storage

Estimation of the adaptation effort

The demand performance analysis may be applied to estimate the exposure of the basins to climate change. The methodology of analysis is presented in Figure 22, also under the hypothesis that the system supplies an urban water supply demand (α) and an irrigation demand (β). An additional assumption is that urban demand is fixed, because it is not expected to change significantly in the future. In Figure 22, the analysis presented in Figure 22 is applied in two different scenarios: the control period (blue) and the climate change period (red). The comparison between the MPWW for irrigation in the control and in the climate change scenario provides a proxy variable to estimate exposure to climate change. If the objective of water policy is to maintain adequate reliability for both urban and irrigation demand, we can estimate the adaptation effort from the difference between water availability for irrigation in the control and in the climate change scenario. In water scarcity regions, like the Mediterranean, water resources are developed to satisfy existing demands. If we make the assumption that in the control period irrigation demand is similar to MPWW for irrigation, irrigation demand would have to be reduced in the future to adapt it to water availability. The larger the difference between current and future water availabilities for irrigation, the greater the effort required to compensate for climate change though adaptation.

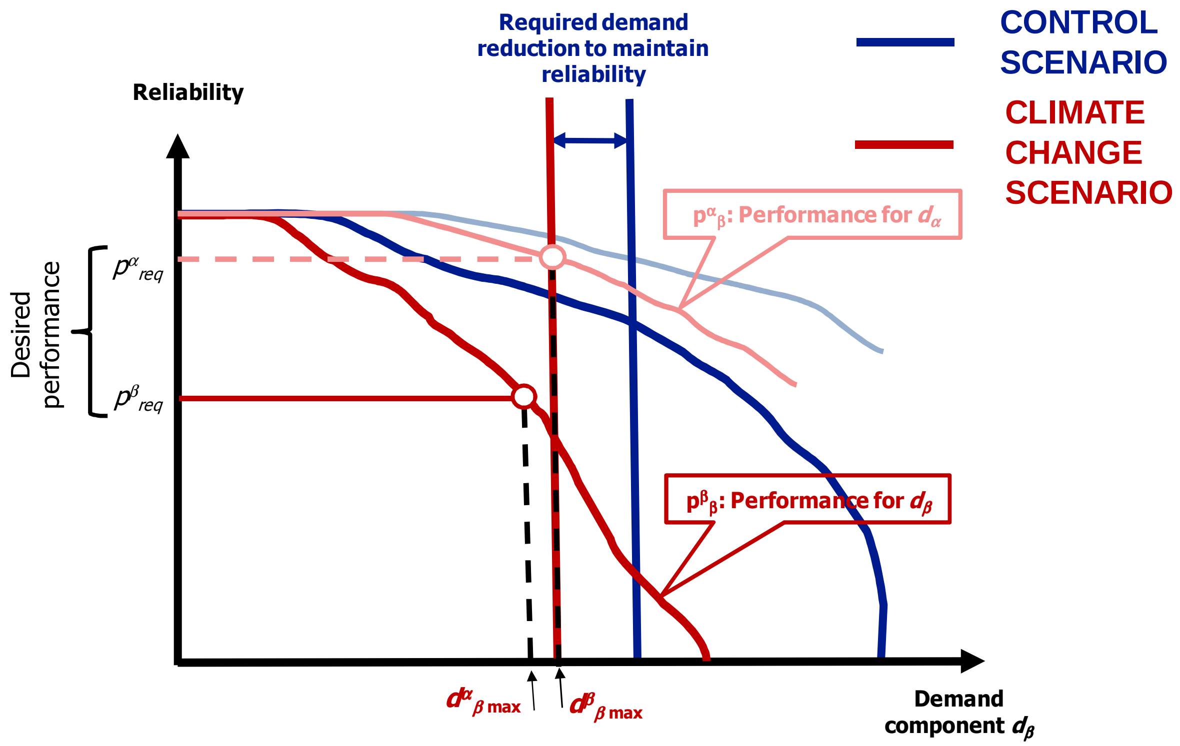


Figure 22 Estimation of the adaptation effort

4.4.4 Index-based analysis

Demand performance analysis is an adequate tool to analyze one or a few water resources systems. If a comparative analysis of a very large number of systems is required, system performance has to be summarized in a few representative values. In this work, several indices have been developed to compare water resource system performance under climate change scenarios. Indices allow for a quick evaluation of the effect of global water policy measures on different systems.

The basis for index definition is the adimensional demand performance (DP) curve used below, which is obtained dividing demand values for a fixed quantity (for instance, mean annual streamflow Y) and reliability values for their theoretical maximum (100 if they are expressed as percentages). Figure 23 presents an example of a system with two consumptive demands (urban and irrigation). Total urban demand is D_u and total irrigation demand is D_i. If desired performance values are defined for each demand category, k, an acceptable reliability level, r_k, is fixed, depending on the nature of the demand and the requirements of water usage. For instance, in the irrigation class the acceptable reliability threshold could be set to 85%, while in the urban supply class it could be set to 100%.

The following quantities are also relevant

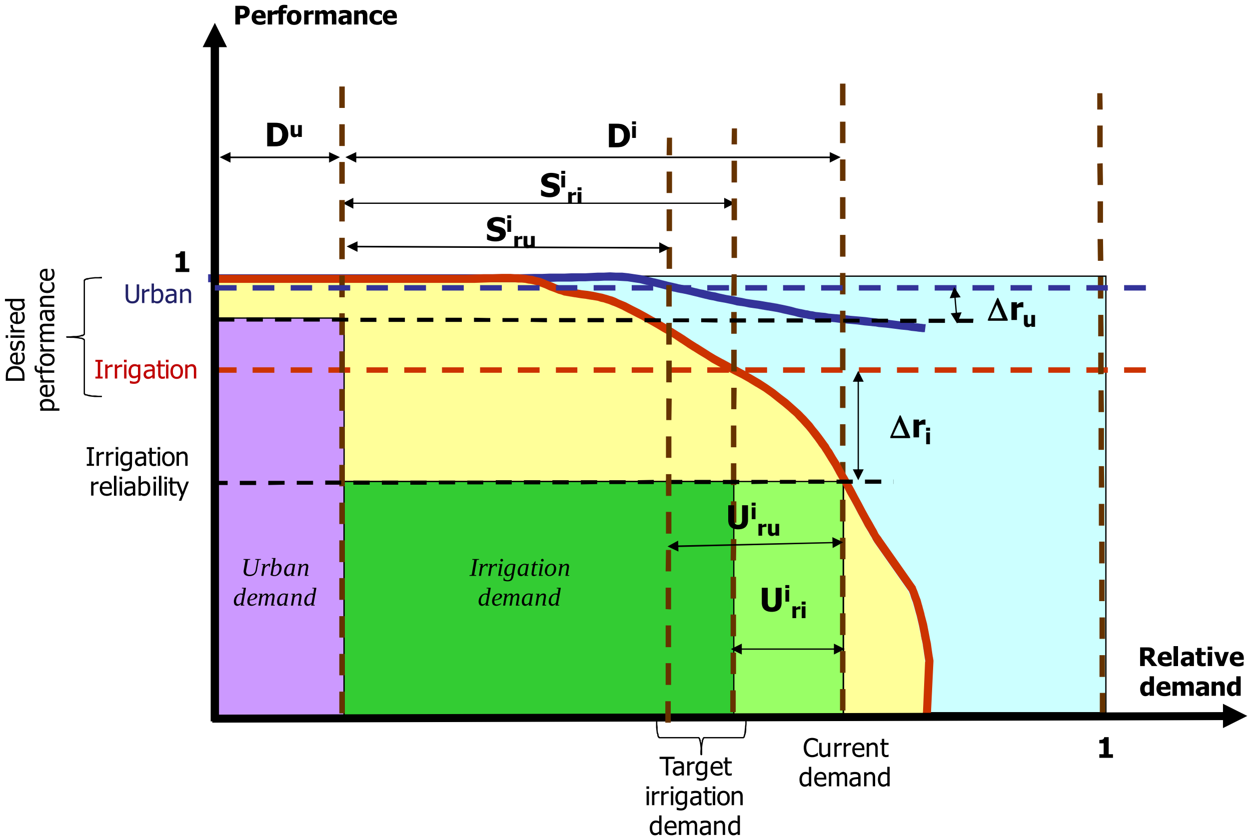


Figure 23 Indicators for water performance and reliability

Policy actions should, in part, be oriented to improve reliability. A target for reliability improvement, Δr_k , is defined in every class, as the reliability increment that should be achieved through policy actions.

According to these definitions, the following indices could be computed from the demand performance DP curve:

Demand reliability index: I_R

This index quantifies the reliability of the system to satisfy demands. It is computed as the ratio between demand in each class k supplied with acceptable reliability l ($S_{r_l}^{k}$) and total demand k (D^k):

$$I_R^{k,l} = \frac{S_{r_l}^k}{D^k} \quad (6)$$

The average index value for demand class k is computed as the weighted sum of indices for all demands affected by demand k:

$$I_R^k = \sum_{i=1}^{i=K} \alpha_i I_R^{k,i} \quad (7)$$

where α_i is a weight assigned to each demand class affected, according to its relevance in water management

Global index value for the system would be computed as the weighted sum of indices for all demand classes subject to management

$$I_R = \sum_{k=1}^{k=K} \sum_{i=1}^{i=K} \alpha_i \beta_k I_R^{k,i} \quad (8)$$

where β_k is the weight assigned to demand class k, according to its suitability for water management

Sustainability index: I_U

This index evaluates the fraction of natural resources available for further development in the system. It can only be computed for the entire system, as the ratio between water not allocated to demands and natural yield:

$$I_U = 1 - \sum_{i=1}^{i=K} D^i \quad (9)$$

where Y is average yield of water resources in the system under natural conditions, in hm^3/yr.

Regulation index I_S

This index evaluates natural or artificial regulation in the system. For a given demand class k and an affected demand class l, this index is the area below the demand performance curve:

$$I_S^{k,l} = \int_0^1 r_l dD^k \quad (6)$$

The average index value for demand class k is computed as the weighted sum of indices for all demands affected by demand k:

$$I_S^k = \sum_{i=1}^{i=K} \alpha_i I_S^{k,i} \qquad (7)$$

where α_i is a weight assigned to each demand class affected, according to its relevance in water management

Global index value for the system is computed as the weighted sum of indices for all demand classes subject to management

$$I_S = \sum_{k=1}^{k=K} \sum_{i=1}^{i=K} \alpha_i \beta_k I_S^{k,i} \qquad (7)$$

where β_k is the weight assigned to demand class k, according to its suitability for water management.

Demand management index: I_D

This index quantifies the scope of demand management measures. It is computed as the ratio between the reduction in demand in class k required to achieve acceptable reliability for class l and total demand in class k:

$$I_D^{k,l} = \frac{U_{r_l}^k}{D^k} \qquad (6)$$

The average index value for demand class k is computed as the weighted sum of indices for all demands affected by demand k:

$$I_D^k = \sum_{i=1}^{i=K} \alpha_i I_D^{k,i} \qquad (7)$$

where α_i is a weight assigned to each demand class affected, according to its relevance in water management

Global index value for the system would be computed as the weighted sum of indices for all demand classes subject to management

$$I_D = \sum_{k=1}^{k=K} \sum_{i=1}^{i=K} \alpha_i \beta_k I_D^{k,i} \qquad (7)$$

where β_k is the weight assigned to demand class k, according to its suitability for water management

The model will be implemented in BASE for the Tagus Case Study and presented in WP5 and for Europe and presented in WP6.

4.4.5 Policy assessment

Water policy decisions are introduced in WAAPA through the modification of different coefficients or parameters which modify system performance.

Water allocation for environmental and consumptive uses. Policy makers establish the criteria to authorize water abstractions from rivers based on the environmental conditions that should be respected for natural ecosystems. In the past, little attention was paid to environmental status of water bodies, and abstractions were usually approved even if there was no minimum environmental flow specified. Recently, the Water Framework Directive has placed emphasis on environmental status, and therefore strict control is placed on environmental flows before water abstractions are authorized. This policy decision is implemented in WAAPA through the selected quantile of the monthly marginal distribution to specify minimum environmental flow requirements. This component will be linked to the Environmental Flows modelling described in Section 3 of this Deliverable D3.2.

Reuse of urban water. The system contemplates a coefficient for internal water reuse within cities. If total population is P_u, per-capita water requirement is d_u and there is a return coefficient of k_r and a reuse coefficient of k_u, reused water equals $P_u d_u k_r k_u$, so that the urban demand D_u required from the system is: $D_u = P_u d_u (1 - k_r k_u)$. Therefore, if maximum water availability for urban demands computed by WAAPA is D_{max}, the maximum population which could be supplied is

$$P_{\max} = \frac{D_{\max}}{d_u (1 - k_r k_u)}$$

Reduction of per-capita or per-hectare water use. Demand management measures which tend to reduce per-capita or per-hectare water use are included through the reduction of per-capita water requirements in the model, d_u and d_i.

Water rights exchange programs. Measures to promote the exchange of water rights to overcome temporary deficits can be very effective to increase system performance. These measures are introduced in WAAPA as changes in the required performance for urban demands. If these measures are in operation, urban demand reliability could be lowered because additional resources will be available if the main source of supply fails.

Proactive drought management. Measures to improve drought management will reduce drought impacts on agricultural demand and will increase their drought resilience. These measures are introduced in WAAPA as changes in the required performance for irrigation demands. If these measures are in operation, agricultural demand reliability could be lowered because farmers will be able to cope with droughts better.

Reduction of water allocation. Reduction of water allocation for a given use can be analyzed through its effect on demand reliability.

Increase water supply. WAAPA allows to estimate the effect of supply increase measures by analyzing the effect of an increase of the regulation volume available for water conservation or a densification of the water distribution networks.

Policy tradeoffs

The main reference for the climate change adaptation policy is the reduction in irrigation demand that would be required in the climate change scenario in order to restore the same level of performance that is observed in the control scenario. This value is equal to the difference in MPWW in the control and climate change scenarios. However demand reduction is not the only policy alternative to reach the objective of adequate supply reliability. Other measures that increase water supply or improve water use efficiency in other sectors can be applied in combination with irrigation demand management. The trade-offs between some of these policy measures and irrigation demand management are analysed in this study. The procedure is illustrated in Figure 26. If demand management is applied in combination with another policy, the resulting reliability values for every demand present in the system can be plotted against both adaptation efforts. The line that corresponds to the minimum required reliability for every demand type enables us to identify the required efforts when both measures are applied in combination. As shown in Figure 24, there is always a trade-off between both measures. If an estimate of the cost of each measure is available, the optimum course of action can be easily identified

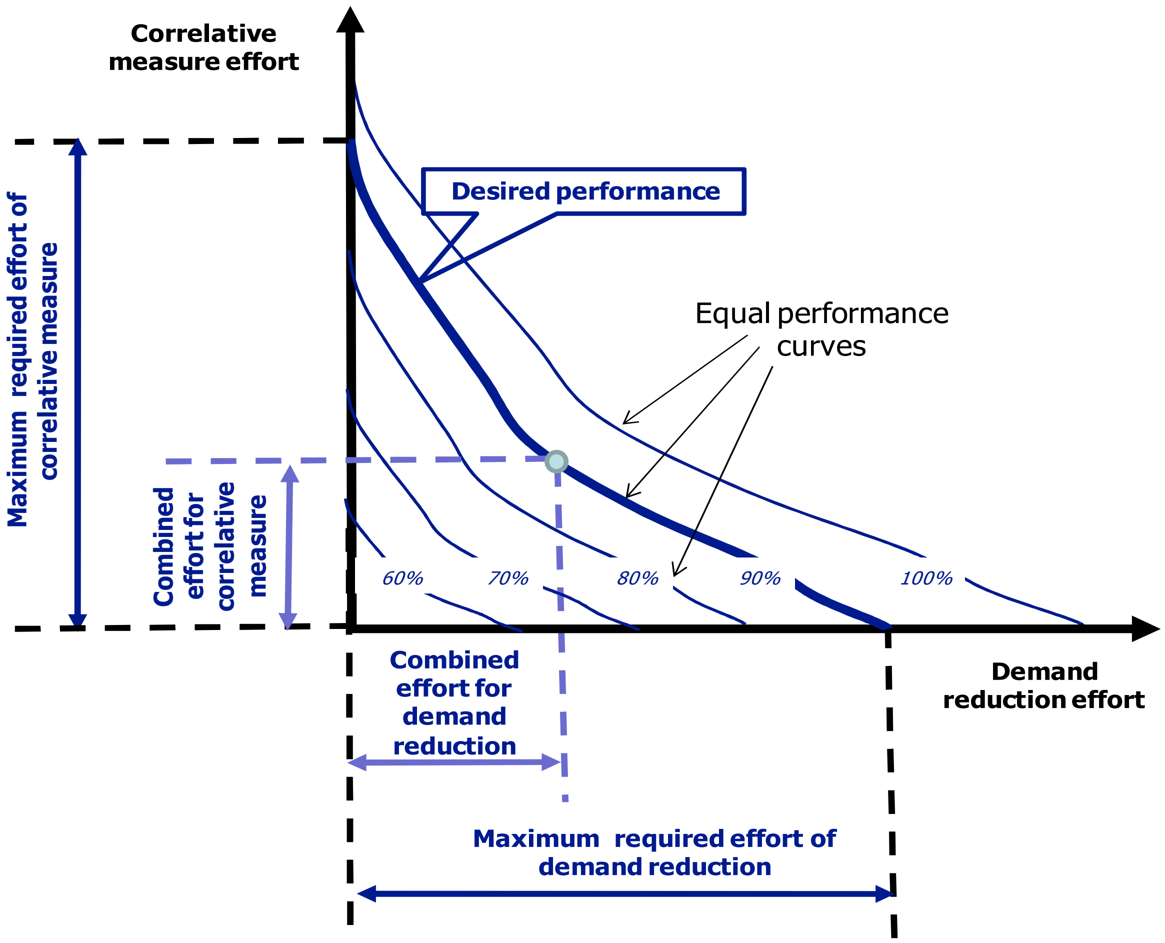


Figure 24 Example of policy tradeoffs

Example of estimation of water availability

WAAPA model can be used to evaluate water availability for a set of specific demands under different conditions. As an example of model results, we present an analysis of water availability for irrigation demands, once urban demands are adequately satisfied. Runoff is estimated from the results of the CMCC models provided in D3.1. Monthly time series of runoff in every sub-basin are generated from the results produced by RCMs for the runoff variable. Urban demands are estimated on the basis of population and per-capita water requirement. Sub-basin population was obtained from the Global Rural-Urban Mapping Project (GRUMP), available at the Center for International Earth Science Information Network. An average value of 300 l/p.day was used as per capita water requirement.

WAAPA computes water availability for irrigation demand with a loop that considers a fixed amount of urban demand and a variable amount of irrigation demand. For every value of irrigation demand, the model assigns available water in every month to urban demand first, and then to irrigation demand, computing demand reliability for both types of demands. Water availability for irrigation corresponds to the maximum irrigation demand that satisfies both urban reliability and irrigation reliability. Results are shown in Figure 25, which corresponds to the Regional Climate Model developed by the Danish Met Office (DMI). The per-unit reduction in runoff in climate change scenario with respect to the control scenario is compared to reduction in water availability. In many European basins, the proportional reduction of water availability is larger than the reduction in mean annual runoff.

In WP 6 the model will be used to estimate water availability across the entire European territory.

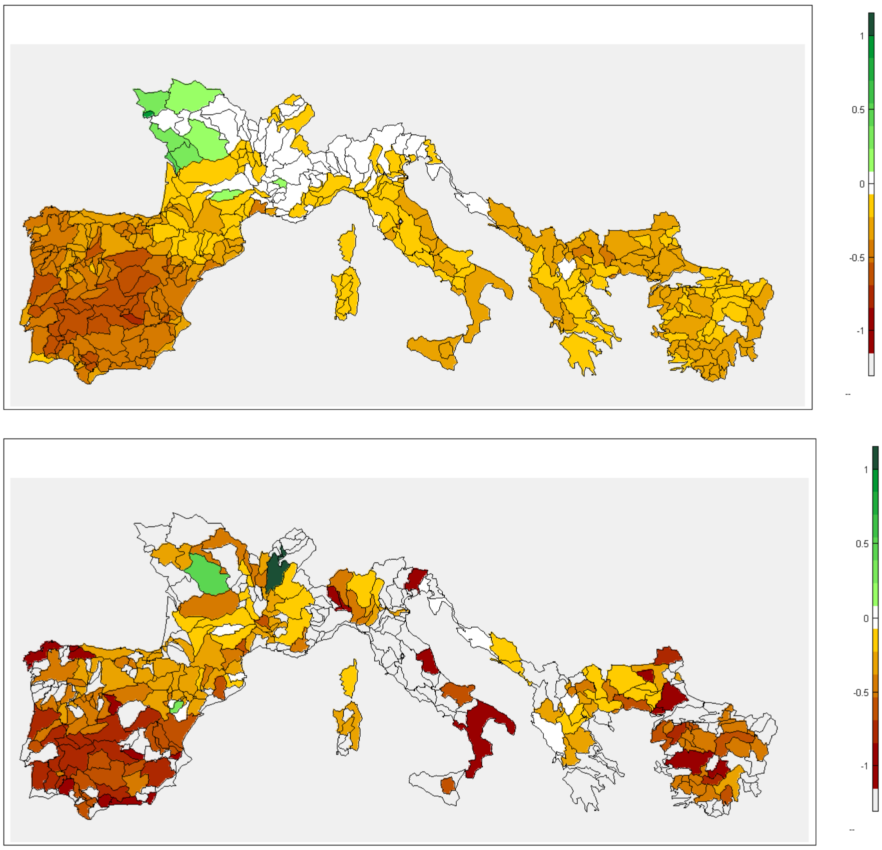


Figure 25 Per unit reduction of runoff (above) and water availability for irrigation (below) in climate change scenario (2070-2100) with respect to control run (1960-1990) for DMI model in Mediterranean European basins

4.4.6 Estimation of trade-off between water allocation and supply reliability

The regulatory effect is evaluated through water availability, i.e. the maximum demand that could be potentially attended in a certain point of the fluvial network for a pre-determined reliability criteria. In order to facilitate the comparison, this variable is normalized using the average annual flow in a particular point of the system. Then it is possible to evaluate the effect of climate change scenarios.

Reliability is computed for every demand by comparing the actual supply values during the simulation with theoretical demand values. Figure 26 shows a theoretical supply reliability curve under current climate and climate change scenarios. In the current situation a defined volume of water is supplied to a sector with acceptable reliability. Some assumptions can be taken. For example, reliability of urban supply is always 100% in European cities while reliability of agricultural supply may be as low as 50% in some areas. Under climate change scenarios, the water allocation may remain the same (Management 1), but in this case reliability has to decrease significantly. This choice is not acceptable for urban supply. An alternative option (Management 2) is a reduction of the water allocation that is compatible with an acceptable reliability. For urban supply, a reduction of reliability is not an option. But for agricultural supply, a reduction of reliability may be acceptable if farmers have risk transfer mechanisms.

The choice between reduction of water allocation and reduction of reliability depend on the risk aversion that stakeholders (water managers and users) are willing to take. For example, reducing the water allocated for irrigation (Management 2 in Figure 26) seems to be the optimal decision, independently of the risk aversion coefficient considered. On the other hand, when stakeholders accept a certain amount of risk, reducing water reliability (Management 1) is the optimal decision. Reducing water allocation has a lower associated risk level, and would therefore be preferred by managers that are more risk averse. Reducing water reliability has a higher associated risk level and would therefore be preferred by those less risk averse. The results show that there is no optimal policy response and that this is highly dependent on the scenario considered and the willingness to accept risk of the stakeholders.

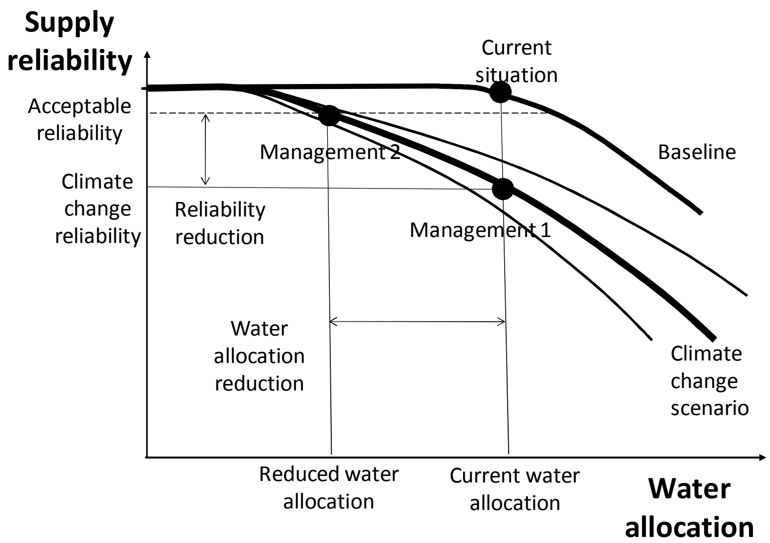


Figure 26 Summary of the trade-off between water allocation and supply reliability under current climate and climate change scenarios.

4.4.7 Evaluation of water management policies

Management policies may be evaluated in WAAPA by modifying the different coefficients or parameters which affect system performance and create policy scenarios. Two broad management policy categories may be considered: supply management and demand management (Table 7).

Table 7 Types of polices and implementation in the WAAPA model

Type of policy	Actions	Implementation in WAAPA (example)
Supply management policies	Water allocation for environmental and consumptive uses	Selected quantile of the monthly marginal distribution to specify minimum environmental flow requirements
	Reuse of urban water	A coefficient for internal water reuse within cities that takes into account the population per-capita water requirement is and the return coefficient and a reuse coefficient
	Reduction of water allocation	Reduction of water allocation for a given use can be analyzed through its effect on demand reliability
	Increase water supply	Increase of the regulation volume available for water conservation or a densification of the water distribution networks
	Increase supply efficiency	Selected quantile of the monthly availability
Demand management policies	Reduction of per-capita or per-hectare water use	Reduction of per-capita water requirements in the model
	Water rights exchange programs	Changes in the required performance for urban demands
	Increase resource efficiency	Changes in the required performance for irrigation demands

Prioritising adaptation needs

Policy is deeply involved in the water sector. Usually, policy development is based on an historical analysis of water demand and supply. It is therefore a challenge to develop policies that respond to an uncertain future.

We recognise that the data needs for developing a decision-making tool are complex and may be hard to satisfy. Building on the results of the WAAPA model we characterise water scarcity to define policy thresholds.

Policy options and thresholds

Here we summarise a diagnostic tool to identify and evaluate climate change adaptation policies in areas of water scarcity based on the indices of water scarcity developed by Martin-Carrasco et al (2006). The methodological framework comprises a set of three indices, described below, that must be used jointly to quantify the severity of potential water scarcity problems in a system, its causes, and possible solutions. The indices are numerical index values that are classified in qualitative categories:

Water scarcity index (SI) evaluates the system's capacity to supply its demands.

Demand reliability index (RI) quantifies the system reliability to satisfy demands.

Potential for more infrastructure index (II) evaluates the natural resources available for development in the system.

Figure 27 shows a characterization of the intensity of water scarcity through a combination of the demand reliability index and the demand satisfaction index that are included in the Y and X axis of Figure 27. This characterization is used to define thresholds of water scarcity based on their intensity – this is the first step in formulating water policy.

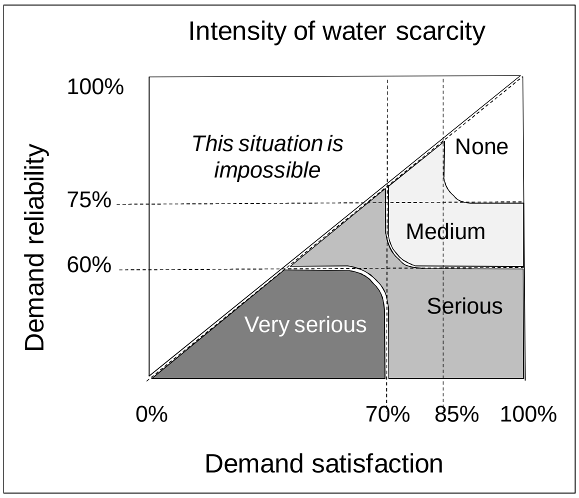


Figure 27 Intensity of water scarcity problems and thresholds of demand reliability and satisfactions

Next a combined analysis of the indices is used to diagnose water management problems and the reliability and vulnerability of systems under climate change scenarios this also helps identify public policies to recover equilibrium between water supply and demand. In general, systems with high water scarcity require actions that increase available resources while systems with low demand reliability generally require structural actions to consolidate water supply to demands or non-structural actions to mitigate drought impacts. When these problems coincide with low values of potential infrastructure development, actions should focus on the demand side, trying to improve water conservation by reducing losses, increasing water efficiency, encouraging water recycling, and making different demands compatible. Table 8 shows how the characterisation of water scarcity problems can be combined with broad categories of policy solutions. Each category of policy solution proposes the utilisation of different tools that target different user groups in order to tackle the problem of water scarcity flexibly.

Table 8 System characterisation as a function of index values

		No water scarcity		Low water scarcity		High water scarcity	
		Problem	Solution	Problem	Solution	Problem	Solution
Reliable demand	Potential more infrastructure	n.a	n.a	1	B	1	B, C
	No new infrastructure	n.a	n.a	1	A, B	1, 3	A, B, C
Some unreliable demand	Potential more infrastructure	2	D	1, 2	B	1, 2	B, C
	No new infrastructure	2	A, D	1, 2	A, B	1, 2, 3	A, B, C
High unreliable demand	Potential more infrastructure	2	B, D	1, 2	B, C	1, 2	B, C
	No new infrastructure	2, 3	A, B, D	1, 2, 3	A, B, C	1, 2, 3	A, B, C

Problems	Solutions
1: Vulnerable: water scarcity may produce important damages **2:** Unreliable: low intensity droughts may lead to water scarcity **3:** Excess of demand with respect to natural resources	**A:** Demand management **B:** Supply management: regulation **C:** Supply management: water transfers or additional resources (i.e., water re-use) **D:** Efficiency management: Communication and education

Adaptation policy recommendations

The effect of water policy decisions may be evaluated by considering the resulting water availability for nature and non-nature use. Figure 28 outlines how policy interventions may modify water for nature and for non-nature uses. Water allocation for environmental and consumptive uses is an essential policy (type B in Figure 28). Policy makers establish the criteria to authorize water abstractions from rivers based on the environmental conditions that should be respected for natural ecosystems. In the past, little attention was paid to environmental status of water bodies, and abstractions were usually approved even if there was no minimum environmental flow specified. Recently, the Water Framework Directive has placed emphasis on environmental status, and therefore strict control is placed on environmental flows before water abstractions are authorized.

The reuse of urban water may be included in a group of policies (type A, C and D in Figure 28) that will need to become increasingly important since future scenarios project higher population and per-capita water requirement. Other demand side policies could make use of appropriate water pricing mechanisms, investments in technology to improve efficiency, upgraded distribution networks and making sure that agricultural subsidies are linked to efficient use (European Environment Agency, 2009). Efficiency policies may play a major role for improving management (type D in Figure 28). For example reduction of per-capita or per-hectare water use that always results in an increase of water availability and reliability.

A number of polices may be implemented to overcome temporary water deficits. Water rights exchange programs (type A in Figure 28) may be implemented to overcome temporary deficits and to increase system performance. Proactive drought management measures to increase drought resilience may include improved performance for irrigation demands (type A and D in Figure 30). Policies that foster communication and education are also since it has been shown that joint participative knowledge is an important factor in facilitating efficient water management (Huntjens et al. 2010).

Finally, polices may seek to increase water supply (type B and C in Figure 28) by effectively increase of the regulation volume available for water conservation or a densification of the water distribution networks. Among other measures this may include water recycling and desalination (European Environment Agency, 2009).

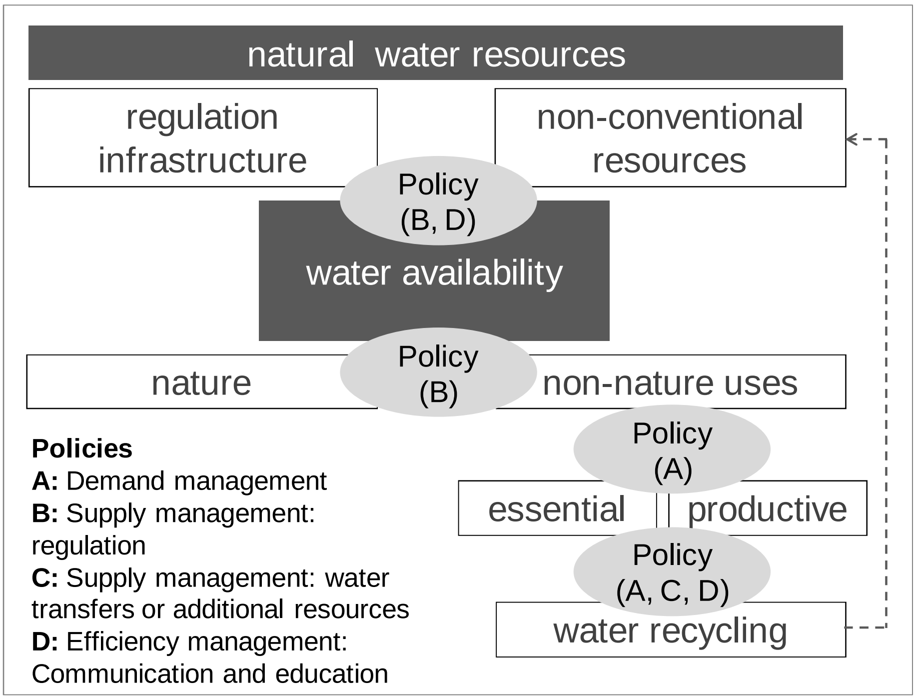


Figure 28 Role of policy interventions on the water sector

As example, the analysis was carried out in the Mediterranean region of Europe. In WP6 the model will be implemented in Europe. The quantitative assessment of the effect of policy options may be carried out with the help of WAAPA model. Alternative policy options may be implemented in several ways. For instance, the effect of four policy alternatives for water availability analysis performed on European Mediterranean basins is presented on Figure 29.

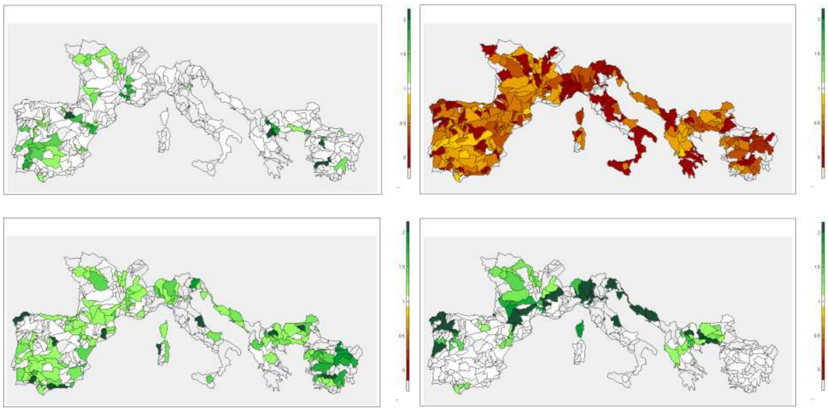


Figure 29 Effect of policy options on water availability for irrigation: per unit change in water availability for irrigation in climate change scenario (2070-2100) with respect to control run (1960-1990) for DMI model in Mediterranean European basins under four policy options: a) Improved water resources management (top left) b) Water allocation for environmental uses (top right) c) Improved water efficiency in urban use (bottom left) and d) use of hydropower reservoirs for water conservation (bottom right)

Example of application in the Ebro basin

The Ebro basin is representative of a medium size water unit in the Mediterranean; the system is composed of 34 rivers, 27 major reservoirs totalling 7,13 km3 of reservoir storage, an urban demand of 0,96 km3/yr and current irrigation demand of 6,35 km3/yr. Climate change scenarios were generated for every streamflow point in the Ebro basin by transforming the mean and coefficient of variation of the original series as suggested by the corresponding climate projection. Environmental flows were fixed at 10% of mean annual flow in every location.

Garrote et al (2010) estimated change in water availability under climate change (Table 9). The study first estimated changes in runoff and runoff variation under a range of climate change scenarios, then applied the WAAPA model to evaluate optimal management that represents the optimal policy options with the corresponding trade-off between supply and reliability as determined by the WAAPA analysis. According to the results of the climate change simulations, runoff and water levels will change significantly during different seasons (Figure 30). The results are in line with the results from previous studies in the Mediterranean regions (Iglesias et al. 2007, IPCC 2007, European Environment Agency 2008, Giorgi & Lionello 2008); climate change results in a moderate increase of flood risk throughout the year and a large increase in spring and summer drought. This implies the need to establish alternative options for water management for all sectors and highlight the importance of hydrological forecast to enhance the potential for improved regulation planning.

Table 9 Simulation of water availability in the Ebro water unit under different management alternatives in the current climate

Type of management	Variable	Value
Current management	Annual streamflow Mean [hm3/yr]	16,921.78
	Annual streamflow Coefficient Var. [--]	0.27
	Storage volume [hm3]	7,276.00
	Water availability [hm3/yr]	2,928.31
Simulated effect of management alternatives that imply no further expansion of infrastructure (effects of optimal reservoir management)	Water availability in the Local management alternative [hm3/yr]	9,401.56
	Water availability in the Large distribution networks management alternative [hm3/yr]	11,173.11
	Water availability in the Global management alternative [hm3/yr]	11,464.45

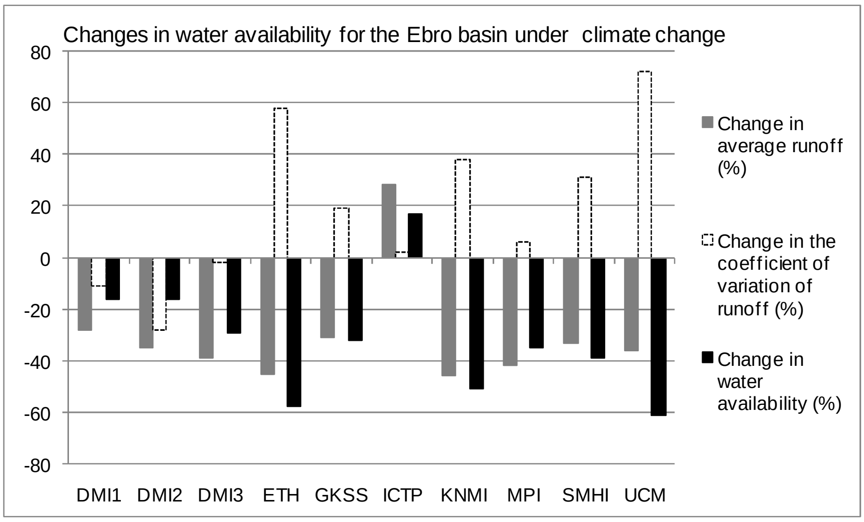


Figure 30 Changes (difference between scenario climate change scenarios and baseline in percent values) of the average value and coefficient of variation of runoff and of water availability in natural regime for the Ebro basin.

With the WAAPA results for water availability under current climate and under climate change it is then possible to estimate the trade-off between water allocation and supply reliability, therefore the results could be used to negotiate the amount of water allocated to a particular use (for example irrigation) and its reliability. The example is presented in Figure 31. As we will see in the next section, understanding how supply reliability and water allocation are affected by climate change is a crucial part of determining water scarcity and hence establishing policy priorities.

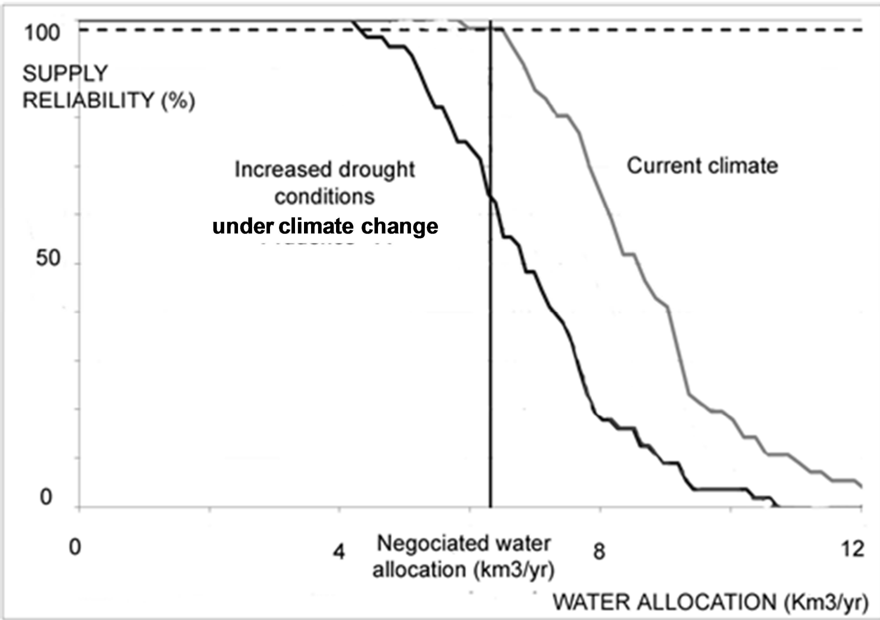


Figure 31 Application of the WAAPA model to estimate the trade-off between water allocation and supply reliability under current climate and climate change scenarios in the Ebro basin.

5 Ecosystem services: InVEST Modelling Tools

Eliška Lorencová, Zuzana Harmáčková, David Vačkář

5.1 Introduction

The ecosystems provide goods and services that make a considerable contribution to human welfare and provide an environment, in which ecological processes take place (Costanza et al., 1997; de Groot et al., 2002). Ecosystem services measures can be applied as indicators of the functioning and change in the land system, and therefore the analysis could be an important tool for management-relevant communication concerning recent, past or potential future states of human-environmental systems (Rounsevell et al., 2012; Muller and Burkhard, 2012). Climate change will alter the provision of ecosystem services that we rely on today. In order to design suitable adaptation and mitigation responses, it is necessary to understand how ecosystems and ecosystem services respond to climate change (Lawler et al., 2011).

Integrated Valuation of Environmental Services and Tradeoffs (InVEST) are models that assist to quantify and map values of ecosystem services (Tallis et al., 2011a). InVEST is spatially explicit modelling tool that predict changes in ecosystem services, biodiversity conservation and commodity production levels. This approach of quantification and spatial determination of ecosystem services provision, can assist in conservation and make decisions in natural resources more effective, efficient and defensible (Nelson et al., 2009).

In BASE we use InVEST to evaluate adaptation needs to maintain ecosystem services in the Case Studies and across Europe and therefore define adaptation needs at different scales. The simulations will be done with the CMCC scenarios and will be presented in WP6. We aim to focus on two types of regulating ecosystem services, i.e. carbon storage and sequestration and water quality enhancement in terms of nitrogen retention, which have been chosen to represent both locally and globally demanded types of ecosystem services. Further details about the InVEST suite of models, data needs and modelling approaches are provided below.

5.2 InVEST description

InVEST represent a suite of models developed by the Natural Capital Project initiative at Stanford University (http://www.naturalcapitalproject.org/InVEST.html), to enable the assessment and evaluation of ecosystem services on various landscape scales. The suite of models is a freeware ArcGIS extension and has been utilized for ecosystem service evaluation in various research projects worldwide, especially in order to compare different alternatives of potential future landscape development (Kareiva et al. 2011, Goldstein et al. 2012, Isely et al. 2010, Nelson et al. 2009, Tallis et al. 2009).

InVEST presents a group of spatially explicit modelling tools, based on current land-use maps and future landscape scenarios, ecological and socio-economic parameters. During the scenario building, participation of local stakeholders is preferred and including their opinions and preferences about future landscape features (e.g. ecosystem-based adaptive measures) is recommended. In addition, the results of the modelling tools are presented as spatially explicit maps of future ecosystem service levels and can serve as the basis for following discussions with the stakeholders (Figure 32). InVEST intends to incorporate biophysical and economic information about ecosystem services, focuses on ecosystem services themselves rather than on underlying biophysical processes alone, is spatially explicit and scenario driven and reveals relationship among multiple ecosystem services (Tallis and Polasky, 2011).

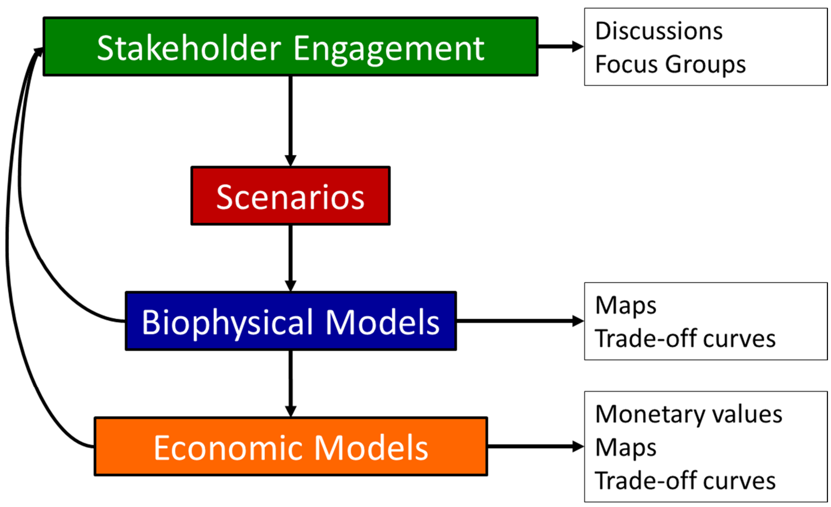


Figure 32 Set up of the InVEST model (According to: Natural Capital Project, 2007)

5.3 Data needs

InVEST includes several modelling tools, focused on various types of ecosystem services. InVEST tools modelling regulating ecosystem services seem especially suitable for the case studies within the BASE project. Therefore, three modelling tools will be utilized: the Carbon Storage and Sequestration model, the Water Purification: Nutrient Retention model and the Sediment Retention model.

The basic data inputs, common for all the above mentioned tools, are current land use maps and future scenarios. The expected sources of LULC maps are CORINE Land Cover data sets; however, InVEST tools can be run even with LULC maps with finer resolution. Future LULC scenarios can be developed using ArcGIS, based on the collaboration with local stakeholders.

Subsequent data needs depend on the individual tools utilized (see following Tables). In general, various ecological and socio-economic parameters of the study location, mainly in the form of raster maps and table databases, are required. Tables 10, 11 and 12 present the data needs from European and local studies and databases.

Table 10 Data needs for the Carbon Storage and Sequestration model

Data type	Unit of measurement	Data format	Data sources (example of the Green Roof case study)
Current LULC maps	–	ESRI GRID	CORINE Land Cover 2006, 2013
Future LULC maps	–	ESRI GRID	Future scenarios
Carbon pools: Aboveground biomass, belowground biomass, soil carbon, dead organic matter	[Mg ha-1]	*.dbf	Literature review
The value of sequestered ton of carbon	[€ Mg-1]	–	Tol, 2009

Table 11 Data needs for the Water Purification: Nutrient Retention model

Data type	Unit of measurement	Data format	Data sources (example of the Green Roof case study)
Current LULC maps	–	ESRI GRID	CORINE Land Cover 2006, 2013
Future LULC maps	–	ESRI GRID	Future scenarios
Digital elevation model	–	ESRI GRID	Czech Office for Surveying, Mapping and Cadastre
Soil depth	mm	ESRI GRID	European Soil Database, European Commission – Joint Research Centre
Average annual precipitation from the CMCC scanrios	mm	ESRI GRID	CMCC
Average annual potential evapotranspiration	mm	ESRI GRID	CMCC
Maximum root depth for vegetated LULC classes	mm	*.dbf	Literature review
Evapotranspiration coefficients for each LULC class (to modify potential evapotranspiration)	%	*.dbf	CZEG
Watersheds and sub-watersheds	–	Polygon shapefile	T. G. Masaryk Water Research Institute
Nutrient loading (export) coefficients for each LULC class	[g ha^{-1} yr^{-1}]	*.dbf	Literature review
Efficiency of nutrient removal by vegetation for each LULC class	%	*.dbf	Literature review
Annual cost of nutrient removal treatment	[€ kg^{-1}]	–	Vačkář et al., 2010

Table 12 Data needs for the Sediment Retention Model: Avoided dredging and water quality regulation model

Data type	Unit of measurement	Data format	Data sources (example of the Green Roof case study)
Current LULC maps	–	ESRI GRID	CORINE Land Cover 2013
Future LULC maps	–	ESRI GRID	Future scenarios
Digital elevation model	–	ESRI GRID	Czech Office for Surveying, Mapping and Cadastre
Rainfall erosivity index (R)	[MJ mm $(\text{ha h yr})^{-1}$]	ESRI GRID	Janeček et al., 2012
Soil erodibility (K)	[t ha h $(\text{ha MJ mm})^{-1}$]	ESRI GRID	CZEG
Watersheds and sub-watersheds	–	Polygon shapefile	T. G. Masaryk Water Research Institute
Cover and management factor for each LULC class (C)	–	*.dbf	Literature review
Management practice factor for each LULC class (P)	–	*.dbf	Literature review
Efficiency of sediment retention by vegetation for each LULC class	%	*.dbf	CZEG
Cost of sediment dredging	[€ m^{-3}]	*.dbf	CZEG
Cost of sediment for water quality	[€ m^{-3}]	*.dbf	CZEG

5.4 Description of selected InVEST models

5.4.1 Carbon storage and sequestration

The Carbon Storage and Sequestration model can be utilized to assess the ability of an ecosystem to sequester carbon and to quantify current and prospective future carbon stocks. When economic data on the social value of carbon is available, the economic value of carbon sequestration can be assessed.

Carbon sequestration of an ecosystem depends on the amount of carbon stored in four carbon pools: aboveground biomass, belowground biomass, soil carbon and dead organic matter. The model summarizes the amount of carbon stored in these four pools based on land use/land cover (LULC) maps and their classification. Aboveground biomass comprises all living parts of plants above the soil level, while belowground biomass consists of living roots. Soil carbon (the organic part of soil) represents the bulk of terrestrial carbon stocks and dead organic matter comprises the litter and dead wood.

The model is based on LULC maps in raster format in the ArcGIS geographic information system. Each raster cell is assigned a value characterizing its LULC type (e.g. coniferous forest, pasture, arable land). The modelling results can be presented in raster format or can be summarized for different municipalities, etc.

For each LULC type, at least one out of four carbon pool estimates is required to successfully fun the model. However, the less pools are included in the analysis, the less precise are the results and the model returns underestimated values. All the available carbon pools are aggregated and subsequently, the overall value of carbon storage in a given raster cell is assessed.

If not only the current LULC map, but also a future scenario is available, the change in carbon stocks (i.e. carbon sequestration or loss) between them can be evaluated, as well as its financial value. For that purpose, the model quantifies the change in carbon stocks for each raster cell. The results of the model are presented in Mg of carbon per raster cell or the financial value of sequestered carbon per raster cell.

The estimate of carbon sequestration financial value is based on damage costs associated with the release of an additional tonne of carbon (the social costs of carbon). The economic evaluation is possible only for carbon sequestration, not for carbon storage, as the social costs of carbon depend on carbon flows, not carbon pools. The financial value of sequestered carbon is given by:

$$vs_x = V \frac{s_x}{yr\_fut - yr\_cur} \sum_{t=0}^{yr\_fut - yr\_cur - 1} \frac{1}{\left(1 + \frac{r}{100}\right)^t \left(1 + \frac{c}{100}\right)^t}$$

where vs_xrepresents the value of sequestered carbon, V the social costs of carbon per tonne, s_x the biophysical value of carbon sequestration (as assessed by the previous parts of the model), yr_cur the year of current LULC, yr_fut the year of future land use, t the time period, r the market discount rate and c the annual rate of change in the price of carbon (Tallis et al. 2011a).

5.4.2 Water purification: nutrient retention

This model quantifies the amount of nutrients discharged from each raster cell of the study area. Subsequently, the retention of nutrients and their final export to water courses are evaluated. The calculations are performed on pixel scale; however, its results should be interpreted only for the whole watersheds, not individual raster cells.

The Water Purification model is again based on LULC raster maps and can be utilized to assess the amount of pollutants retained by the studied landscape in three steps. In the first step, the annual water yield from each watershed is calculated. In the second step, the amount of pollutant discharged from each watershed and its retained proportion is quantified. Finally, the amount of pollutant exported to water course is evaluated.

The modelling process can is described by following equations:

1) First, the annual water yield (Y_{jx})is assessed for each pixel of the landscape (x) with certain LULC type (j).

$$Y_{jx} = P_x - AET_{jx}$$

whereAET_{jx} is the annual actual evapotranspiration on pixel x with LULC j and P_x is the annual precipitation of pixel x.

2) For each pixel, nutrient discharge is quantified based on nutrient discharge coefficients distinctive for each LULC type, which are adjusted to local conditions:

$$ALV_x = HSS_x \cdot pol_x$$

whereALV_x is the adjusted loading value at pixel x, HSS_x the hydrologic sensitivity score at pixel x and pol_x the export coefficient.

The hydrologic sensitivity score is calculated as:

$$HSS_x = \frac{\lambda_x}{\bar{\lambda}_W}$$

whereλ_x is the runoff index at pixel x (calculated as follows) and $\bar{\lambda}_W$ is the mean runoff index in the watershed of interest.

$$\lambda_x = \log\left(\sum_U Y_u\right)$$

where$\sum_U Y_u$ represents the sum of the water qield of pixels along the flow path above pixel x.

3) Considering the amount of pollutant leaving each pixel, the model calculates the proportion of pollutant retained by each downstream pixel. The model routs down the runoff path determined by slope and allows each pixel downstream from polluting pixel to retain pollutant based on its land cover type and corresponding ability to retain the modelled pollutant. The results are aggregated for subwatersheds and watersheds.

4) Finally, the model quantifies how much of the pollutant reaches the stream.

Once the biophysical value of nutrient retention is assessed, the model can calculate its financial value, perceived as the financial value of avoided water treatment costs. This calculation is made as follows:

$$Uptake\_V_x = Cost(p) * Retained_x * \sum_{t=0}^{t-1} \frac{1}{(1+r)^t}$$

where $Uptake\_V_x$ is the value of retention for subwatershed x;$Cost(p)$ is the annual treatment cost for the polutant of interest (p), $Retained_x$ is the total pollutant retained by subwatershed x, T is the time span being considered for the net present value of water treatment t and r the market discount rate.

5.4.3 Sediment retention model

The InVEST sediment retention model uses the Universal Soil Loss Equation (Wischmeier and Smith, 1978) in order to calculate the average annual soil loss erosion in particular area. In the model, the rate of soil erosion is function of LULC, soil type, rainfall intensity and topography. Greater soil losses are predicted in agricultural areas and sites with steeper slopes. On the other hand, lower soil losses are in forested areas and paved areas (Nelson et al., 2009).

In the sediment retention module, hydraulic connectivity is used to account for the location of sediment generation, retention and transport in the landscape. Model outputs consist of sediment retention maps, and maps of cumulative amount of sediment exported downstream, model account for on-parcel and cross-parcel retention. In order to calculate total amount of sediment retention at parcel x, we need to calculate both, erosion avoided from parcel x, and amount of sediment reaching parcel x from upslope parcels that has been retained by x (Conte et al., 2011).

To calculate the amount of sediment originating from parcel x, $\mathrm{USLE_x}$ is defined:

$$\mathrm{USLE_x} = \mathrm{R_x} \cdot \mathrm{K_x} \cdot \mathrm{LS_x} \cdot \mathrm{C_x} \cdot \mathrm{P_x}$$

where$\mathrm{R_x}$ is the rainfall erosivity, which is ability of rainfall to move and erode soil, is function of average regional rainfall intensity and duration

$\mathrm{K_x}$ is the soil erodibility, representing soil´s susceptibility to erosion, is function of soil texture and characteristics

$\mathrm{LS_x}$is a slope-length index, $\mathrm{C_x}$ is the crop/vegetation and management factor and $\mathrm{P_x}$ is a management factor that accounts for specific erosion control practices (e.g. contour tilling or mounding)

$\mathrm{SEDR_x}$sediment retention of parcel x´s LULC of sediment originating on parcels higher upstream (Conte et al., 2011):

$$\mathrm{SEDR_x} = \mathrm{SE_x} \sum_{y=1}^{x-1} \mathrm{USLE_y} \prod_{z=y+1}^{x-1} (1 - \mathrm{SE_z})$$

where$\mathrm{SE_x}$ is parcel x sediment retention efficiency, $\mathrm{USLE_y}$ is the sediment generated on upstream parcel y and $\mathrm{SE_z}$ is the sediment retention efficiency of upstream parcel z.

$\mathrm{SEDRET_{xD}}$is the potential amount of sheetwash sediment captured by vegetation and best soil conservation management practices upstream of reservoir D. It can be estimated by the difference between the geomorphological characteristics of parcel x that might promote soil loss and the retention properties of parcel LULC and upstream transport $\mathrm{SEDR_x}$(Conte et al., 2011):

$$SEDRET_{xD} = R_x \cdot K_x \cdot LS_x \cdot (1 - C_x \cdot P_x) + SEDR_x$$

The first term on right hand side of equitation is the amount of sediment originating and retained by parcel x, while second term defines the amount of sediment originating on upslope parcels retained by parcel x.

5.5 Approaches to evaluate adaptation within BASE project

InVEST allows to model impacts of climate change on ecosystem services by analysing scenarios that combine land use and land cover data with climate projections. InVEST modelling tool can be applied to model the climate change impacts on ecosystem services. For instance, in the Willamette Basin of Oregon, climate change impacts on ecosystem services, particularly water availability and carbon sequestration together with biodiversity, has been assessed (Lawler et al., 2011).

5.5.1 Case study level

We illustrate possible InVEST application by the “Green Roof” case study:

“Green Roof” case study is focusing on ecosystem services and biodiversity in a Central-European mountainous forested range Šumava (Black Forest, Bohemian Forest). Within the case study, the so-called adaptation scenarios will be developed together with the local stakeholders by participatory approach, scenario workshop. The scenarios will be land use scenarios integrating climate and adaptation components. Based on the scenarios, selected regulating ecosystem services (carbon sequestration, nutrient and sediment retention) will be modelled in order to assess the impacts of particular adaptation scenario on ecosystem services.

The application of InVEST in the “Green Roof“ case study will provide useful outcomes, additionally contributing to local adaptive governance and decision-making.

In case of interest of any BASE partners to apply InVEST modelling, we can provide assistance with particular case study modelling.

5.5.2 Potential InVEST application on the European level

InVEST modelling approach could be also applicable on the European level. However, data availability could become the main challenge with respect to future land use European-wide land use scenarios that involves the adaptation component. Challenging data requirements cover future land use scenarios that reflect climate change and adaptation on the European level. This type of land use scenarios is not at the moment available for us. Therefore, possibility of European-wide modelling would need to be further explored.

6 Agriculture

Ana Iglesias, Luis Garrote, Mette Termansen, Marianne Zandersen, Alfredo Granados, Alvaro Sordo, Pedro Iglesias

6.1 Context

Food production faces some serious challenges in the coming decades: competition for water resources, rising costs due to environmental protection policies, competition for international markets, loss of comparative advantage in relation to international growers, changes in climate and related physical factors and uncertainties in the effectiveness of current European policies as adaptation strategies.Many of these threats are directly or indirectly influenced by climate change.

Agriculture is the main user of land, and water, and it still defines society in the rural areas of Europe. European agriculture accounts for one half of the global trade of food products and it is directly influenced by European and global policy. Climatic conditions directly affect agriculture and the water resources needed to maintain a stable production in many areas of Europe (Iglesias et al., 2007; 2009a; Olesen and Bindi, 2002) and the provision of essential ecosystem services (Metzger et al., 2006). It is likely that the stress imposed by climate change on agriculture and water intensifies the regional disparities in rural areas and the overall economy of European countries (Alcamo et al., 2007; EEA, 2008; Stern, 2007). Understanding the impact of climate change is complicated because changes in physical and social variables are often derived by using different assumptions and inconsistency of inputs across geographical and time scales. As a result, some of the most profound impacts of climate change may be more difficult to project than the future climate itself.

6.2 Previous studies

Based on the existing literature it is possible to list a number of risks and opportunities and adaptation options (see Table 13). Adaptation options might be divided into adaptation options at the farm (autonomous adaptation) and adaptation measures at policy-level (planned adaptation). Generally, policy instruments/measures are defined in different ways in the policy instrument literature; some studies (OECD, 1994, Vedung, 1998, Mickwitz, 2003) identify three general types of policy instruments, based on the varying degree of authoritative force included: Regulation (e.g. limit values, prohibitions etc.), economic instruments (e.g. taxes, quotas and grants) and information/advisory tools. All three types of instruments have a potential to affect the incentives of the farmers.

Table 13 Adaptation options for European agricultural/forestry production (adapted from Iglesias et al., 2012, Smit and Skinner, 2002, Olesen and Bindi, 2002)

Main risks (RS)/opportunities (OP)	(Farm-level) adaptation options (autonomous adaptation)	Adaptation options/measures/supports beyond farm scale (mostly at policy level) (planned adaptation)
Expansive spatial shifts in climatic suitability for crop choice and cultivation in the north (OP)	Altering portfolio of land allocation across different crops; changing land use; altering cultivation practices; diversifying crops; introducing new crops and varieties	Stimulation of innovation - technological and biotechnological advancement - including development of new, more productive crop varieties; monitor and control unintended aggregate consequences of farm scale change in production patterns. Create farmer incentives for more environmentally-friendly practises (e.g. for new cultivation methods, new silvicultural practises etc.) if the consequences are negative; provision of information and advice (e.g. through extension services)
Climate regime that potentially favours increase in crop yields and livestock productivity (OP)	Adjusting sowing and planting dates; adjusting time of farm operations; altering the use of external inputs (e.g. fertilizer application in the case of crop production); expanding livestock farming to new areas; increasing stocking rate	Innovation - technological and biotechnological advancement - including development of new, more productive animal breeds; monitor and control unintended aggregate consequences of farm scale change in production patterns. Create farmer incentives for environmentally friendly practises if the consequences are negative (e.g. if more pesticides are being used); provision of information and advice (e.g. through extension services)
Increased hazards associated with increased precipitation (e.g. waterlogging, floods) (RS)	Improving drainage systems; improving soil physical properties management; reducing grazing pressure or increasing intensive rotational grazing; changes in soil management practices (ex: Keyline design, subsoil plowing, direct seeding); changes in forestry management (change tree composition and crop selection), changes in silvicultural practises; enhancing flood plain management;	Zoning system; integrated catchment management; development of early warning system; other types of information/advice on the risks and opportunities; installation of hard defences; encourage farmers to become ‘custodian’ of floodplains (e.g. through reward system)

	restoring/creating wetlands;	
Intrusion and inundation of agricultural lands due to sea level rising (RS)	Improving drainage systems; substituting crops; changing location of production from vulnerable areas	Zoning system, development of early warning system; installation of hard defences; insurance system
Increased pest, disease, and weed problems (RS)	Livestock vaccination; introduction of pest resistant crop varieties; increased use of pesticides; Integrated pest management. Ecosystem restoration.	Incentives for reduced pesticide use, ecological farming, Integrated Pest Management, good crop selection, changed silvicultural practises, ecosystem restoration etc. (e.g. through pesticide taxes, grants, regulations, information); innovation - technological and biotechnological advancement - including development of pest resistant varieties;
Intensified drought and water scarcity problems due to decreased total precipitation (RS)	Reforestation and ecosystem restoration; intensive rotational grazing; Keyline design; implementing water conservation measures; improving irrigation efficiency; improving water allocation and distribution; changing location of production; introduction of drought tolerant or less water intensive crops and varieties	Create farmer incentives for desired behaviour (e.g. water-saving practises/technologies) through regulation, economic instruments and/or information). Innovation - technological and biotechnological advancement - including development of climate resilient varieties;
Crop yield decrease (RS)	Altering portfolio of land allocation across different crops; altering cultivation practices; diversifying crops; altering the use of external inputs (e.g. fertilizer application in the case of crop production); changing land use; changing farming system; introducing new crops and varieties; farm financial management especially through purchase of crop insurance and investment in crop shares and futures	Create incentives for appropriate crop selection, alternative cultivation methods, changes in silvicultural practises, forestry guidelines, soil management practises, through regulation, economic instruments and/or information. Innovation - technological and biotechnological advancement - including development of more productive crop varieties
Deterioration of livestock conditions (RS)	Intensive rotational grazing, Keyline design, ecosystem regeneration. Introducing	Ecosystem regeneration policies; information on how to cope with changes. Innovation - technological and

	more heat tolerant species/breeds; adjusting time for different operations and breeding; altering pasture composition; complementing grazing with supplemental feeding; increasing shelter and heat protection	biotechnological advancement - especially development of climate resilient varieties; provision of information and advice (e.g. through extension services)
Certain crops become unsuitable under the new climate regime (RS)	Substituting with different varieties or cultivars	Innovation - technological and biotechnological advancement - especially development of climate resilient varieties; provision of information and advice (e.g. through extension services)
Contraction of areas suitable for agriculture in the south (RS)	Changing land use; diversifying household income source; ecosystem regeneration	Programs to promote and facilitate livelihood diversification (e.g. through grants); provision of information and advice (e.g. through extension services). Create incentives for e.g. ecosystem restoration, appropriate crop selection, alternative cultivation methods, and changes in silvicultural practices. Changes in forestry guidelines, changes in soil management practices
Water quality deterioration (RS)	Minimizing nutrient leaching; increasing fertilization efficiency; aerating ploughing equipment; new cultivation methods Minimizing use of pesticides. Ecosystem restoration.	Ecosystem restoration – e.g. allowing water to flow; create incentives for agroforests, policulture and permaculture methods; regulate drilling for water capture; Innovation - technological and biotechnological advancement - including development of highly efficient fertilizers; provision of information and advice (e.g. through extension services); regulating use of nutrients and pesticides
Soil quality degradation and desertification (RS)	Soil conservation and remediation actions	Zoning system; provision of information about potential and tested soil conservation measures; financial support to stimulate farm adoption of measures that demand high up-front investment
Increased frequency, magnitude, and duration of extreme events with greater risk of production loss (RS)	Changing location of production from vulnerable areas; taking on board a wide range of financial management measures including crop insurance, investment in crop shares	Development of early warning system; provision of information and advice (e.g. through extension services); solidarity fund; appropriate compensation and assistance programs; promoting effective and efficient insurance scheme

	and futures, and diversification of household income sources	

6.3 SARA (Supporting Agricultural Modelling in Regions for Adaptation to climate change)

Framework

Adapting agriculture to climate change raises four challenging questions about regional systems, land productivity, water requirements and adaptation choices, both planned and autonomous. We address these questions for agriculture in a changing climate in BASE within a modelling framework that is closely linked to local case study information and provides data to the macro-economic model.

SARA (Supporting Agricultural Modelling in Regions for Adaptation to climate change) is the modelling framework developed in BASE to support adaptation choices in the agricultural sector. The main components of SARA are outlined in Figure 33.

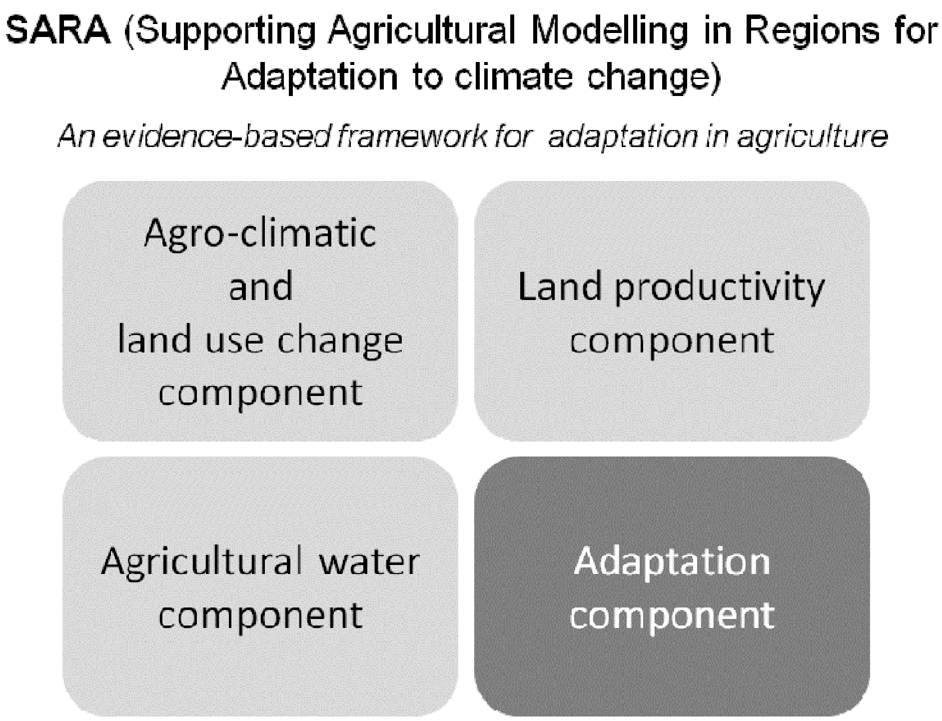


Figure 33 Components of the SARA (Supporting Agricultural Modelling in Regions for Adaptation to climate change) modelling framework

Aim of the model

Our approach considers that the main determinants of crop changes include: changes in agroclimatic regions and land use, crop productivity, water requirements, and adaptation management (autonomous and deliberate adjustments).

With the SARA modelling activity we assess the land productivity choices resulting from different climate scenarios and multiple adaptation pathways.

The framework allows for the development of adaptation scenarios in four dimensions: Local to National and private to public. Local adaptation measures selected in the case studies can be implemented.

The outputs include: maps of changes in agricultural productivity, water demand, nitrogen fertiliser application, adaptive capacity, that can be aggregated to one value in the different EU-27 countries as requested by Ad-Witch.

If requested, the agricultural productivity maps can be made available to the case-study partners.

Main Description

Crop productivity modelling: AU will focus on the agroclimatic analysis and land use modelling in selected areas in Europe.

Crop productivity modelling: UPM will focus on the analysis of climate change impacts on EU-27 using the global scale agricultural model Climate-Crop (global, 1300 sites) and a subsequent interpolating at the country scale.

Water requirements modelling: UPM will focus on the analysis of climate change impacts on EU-27 using marginal productivity estimates at the country and crop level developed for the BASE project. The irrigation component will be linked to the water availability modelling.

Adaptive capacity modelling: UPM will focus on the evaluation of adaptive capacity under current climate and climate change scenarios.

Adaptation pathways: AU and UPM will focus the evaluation of planned adaptation and adaptation policy with a dialogue with the case studies and the macro-economic modellers. Adaptation strategies and measures will be collected from those case-studies focussing on agriculture. The adaptation measures will be aggregated and integrated in the European model to assess potential benefits under different climate scenarios. A Cost Benefit analysis of different adaptation options could be assessed in different case studies. A policy analysis of tradeoffs between adaptation (1 or 2 adaptation policy scenarios) and mitigation could be developed at the EU-27 level.

End-product: The results will be European maps of agricultural productivity and water requirements for different climate scenarios and adaptation paths. The irrigation component will be linked to the water availability modelling (See section 6 of this Deliverable). The final set of maps will be adjusted as required by Ad-Witch (See Deliverable 3.1).

Data needs and linkages with other models/cases study within BASE

Adaptation measures from the case-studies will be aggregated and integrated in the European scale model therefore the following information is needed:

Overview of local adaptation pathways + individual adaptation measures;

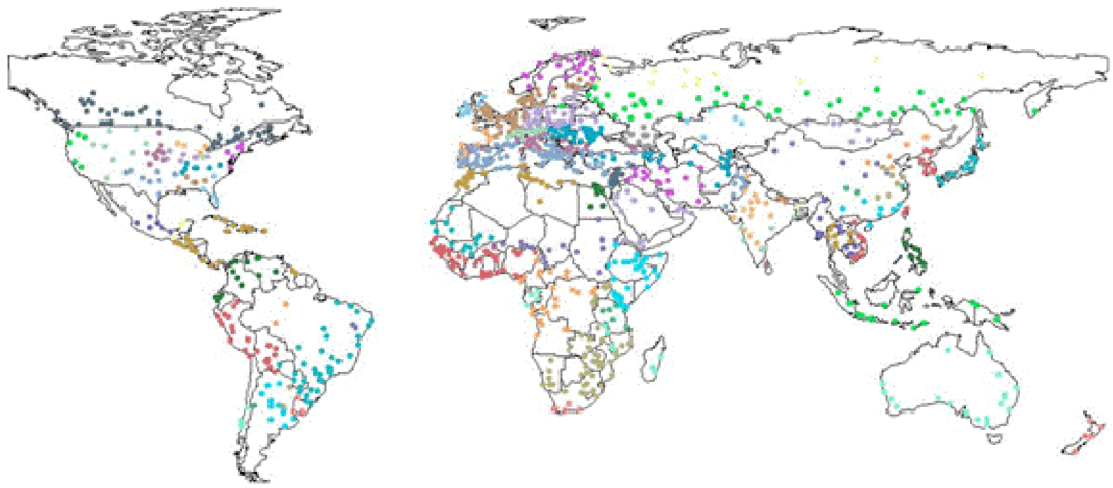
Estimated implementation costs of adaptation measures;

Estimated economic climate extreme loss for current climate and future climate for different adaptation strategies;

Reference period, scenarios and time-horizon considered are described in Deliverable D3.1 and Deliverable D6.1.

6.4 Agroclimatic component and datasets

Projections of changes in agricultural productivity reflect the sensitivity of the world major agricultural regions to global changes. 73 agroclimatic regions were developed based on temperature and precipitation data from 1141 meteorological stations and characteristics of the agricultural systems (Figure 34, Figure 35). This broad characterisation at the global level is consistent with the FAO Agro-Ecological Zones (FAO AEZs). In Europe the results are also consistent with the detailed spatial agro-economic analysis of farm information developed by Kempen et al. (2010). Datasets used were obtained from the Department of Geography at McGill University, who have developed maps and datasets describing contemporary and historical global land use practices. The data spans the time period 1700-2007 including pastural land, an advancement on the previous dataset from the same department.



Z	Zone	Sites	Z	Zone	Sites	Z	Zone	Sites	Z	Zone	Sites
1	Uruguay	4	20	USA Delta	4	39	SEA 3	13	58	W Africa 2	38
2	Chile	4	21	USA SE	4	40	Indonesia	14	59	Egypt	11
3	Argentina 1	11	22	USA App	6	41	Pakistan	9	60	N Africa 1	1
4	Argentina 2	1	23	USA CB	6	42	India 1	3	61	N Africa 2	24
5	Argentina 3	2	24	USA NE	6	43	India 2	14	62	Russia 1	46
6	Brazil 1	36	25	Canada	45	44	India 3	7	63	Russia 2	13
7	Brazil 2	2	26	N Zealand	5	45	Kazakh	5	64	Russia 3	26
8	Brazil 3	2	27	Australia	19	46	C Asia	15	65	Europe 1	21
9	S Amer 1	22	28	China 1	5	47	NES	14	66	Europe 2	69
10	S Amer 2	14	29	China 2	6	48	NEC	18	67	Europe 3	47
11	C Amer	23	30	China 3	7	49	NEM	17	68	Europe 4	9
12	Mexico 1	3	31	China 4	3	50	S Africa 1	49	69	Europe 5	68
13	Mexico 2	3	32	China 5	3	51	S Africa 2	11	70	Europe 6	14
14	Mexico 3	6	33	China 6	4	52	S Africa 3	5	71	Europe 7	19
15	USA PAC	5	34	FEAsia	18	53	Tanzania	7	72	Europe 8	43
16	USA SPL	8	35	Philippines	8	54	E Afr	31	73	Europe 9	85
17	USA MPL	10	36	Thailand	8	55	C Afr 1	24			
18	USA MT	9	37	SEA 1	7	56	C Afr 2	17			
19	USA Lake	4	38	SEA 2	12	57	W Afr 1	14			

Figure 34 1141 stations (all marks) and 73 agro-climatic zones (groups of marks with different colours) utilised for the calculation of changes in land productivity under climate change

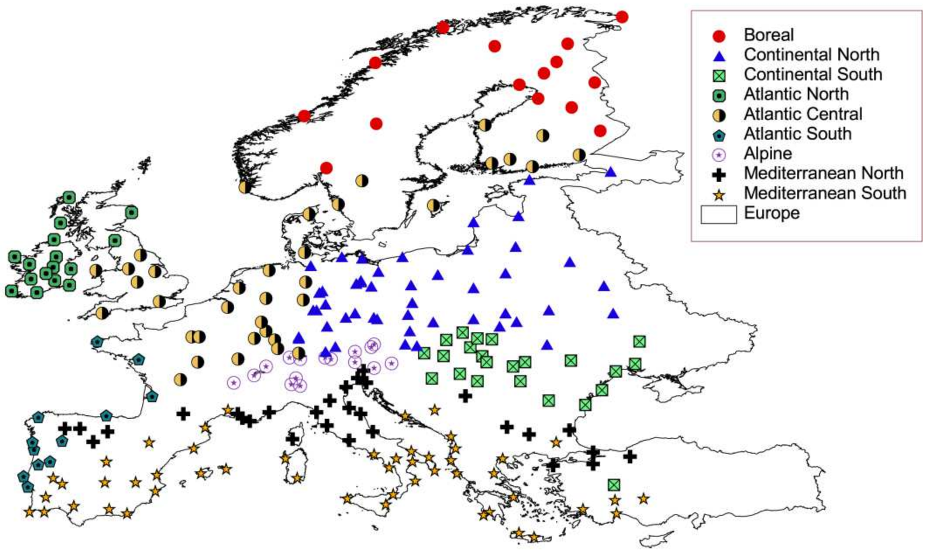


Figure 35 Agricultural simulation sites for the 9 agro-climatic regions under the climate change scenarios (period 2071-2100)

6.5 Land productivity component: The Climate-Crop model

Global scenarios of agricultural change (crop productivity, water demand, and fertiliser) for the years 2020s, 2050s and 2080s will be developed based on scenarios of changes in environmental and socio-economic variables based on simulations with the ClimateCrop model. The models incorporates the current understanding of the sensitivity of each agricultural region to global environmental.

The ClimateCrop model (Figure 37) addresses climate change impacts and adaptation in agriculture and water resources for agriculture. The model integrates land and water spatial analysis, agricultural models, and policy analysis.

Here we do not consider livestock production, except for the possible inference of crop productivity, since this is also influenced by changes in health and reproduction that is beyond the scope of this study.

The approach of computing land productivity changes is based on the development of land productivity functions for the agro-climatic areas (Iglesias et al., 2011). The model links biophysical and statistical models in a rigorous and testable methodology, based on current understanding of processes of crop growth and development, to quantify crop responses to changing climate conditions. Dynamic process-based crop growth models are specified and validated for sites in the major agro-climatic regions. The validated site crop models are useful for simulating the range of conditions under which crops are grown, and provide the means to estimate production functions when experimental field data are not available. Variables explaining a significant proportion of simulated yield variance are crop water (sum of precipitation and irrigation) and temperature over the growing season. Crop production functions are derived from the process based model results. The functional forms for each region represent the realistic water limited and potential conditions for the mix of crops, management alternatives, and potential farmers adaptation to climate assumed in each area.

This model:

- expands process-based crop model results over large areas and therefore overcomes the limitation of data requirements for process based crop models;
- includes conditions that are beyond the range of historical observations of crop yield data; and
- simulates the effect of management (for example irrigation water application) and therefore estimates agricultural responses to changes in regional climate.

The model incorporates a number of strengths: it is based on an interdisciplinary, consistent bottom-up evaluation can use a range of emission scenarios to provide insights into the effects of climate change policy. The physical component expands process-based crop model results over large areas and therefore overcomes the limitation of data requirements for the crop models; it includes conditions that are beyond the range of historical observations of crop yield data; and includes simulation of optimal management and thus estimate agricultural responses to changes in regional climate (Figure 36).

The ClimateCrop model bridges the detailed evaluation of process based models at the site level and empirical production functions at the wider scale. A similar methodology has been used in Parry et al. (2004), however major improvements of the ClimateCrop model include estimations of nitrogen and water demand elasticities for the major agro-climatic regions.

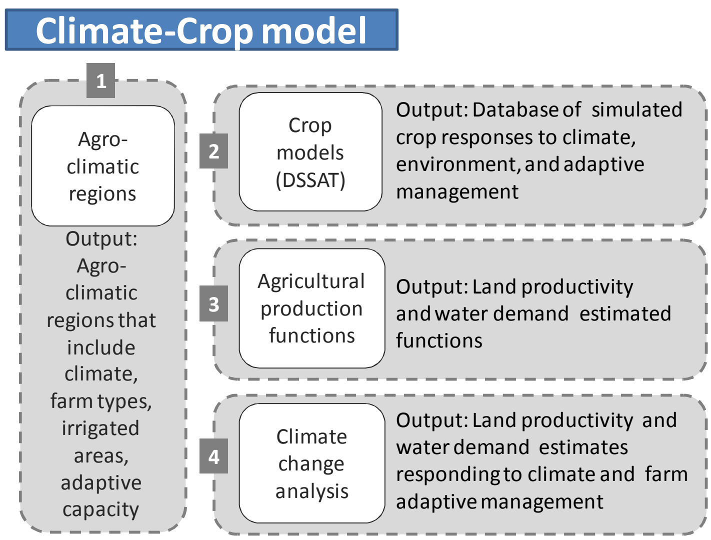


Figure 36 Climate-crop model to estimate agricultural productivity component of the SARA framework

A very detailed overview on existing models for evaluating agricultural production under climate change is given by Reilly and Willenbockel (2010).

Crop yield response to climate

Models are widely used to assess the impact of climate change on agriculture. Some of them are oriented towards regional analysis of the crop productivity (Parry et al. 2004) and others use methods that consider performance of individual crops (Ventrella et al. 2012). Both of the cases consider management at farm level; however they use different approach to do so. In the first case, the main objective is to establish policy actions at regional level and the second case, is to optimise the management of the different commodities at local level. Here, we provide an analysis to define regional adaptation needs and therefore we have selected the regional approach. This approach considers statistical models of yield response to assess the sensitivity and adaptation to climate. The yield functions have been used for analysis in Spain (Iglesias et al. 2000), China (Rosenzweig et al. 1999) and globally (Lobell et al. 2008; Lobell and Burke 2010).

Given that the policy is more focused on regions rather in crops, to determine the response of crop productivity to climate variations in the different agro-climatic regions of Europe, we used the statistical models of productivity response proposed by Iglesias et al. (2012), which represent the realistic water limited and potential conditions for a mixture of crops (wheat, maize, and soybeans), the management alternatives, and the potential endogenous adaptation to climate assumed in each agro-climatic region. For each of the 247 sites in the 9 agro-climatic regions, the yield response for the 30-year intervals within the control and climate change (A2 and B2) scenarios were quantified.

The statistical models of productivity response used here are specified according to the follow relationship:

$$Y_i = \alpha^1 + \alpha^2 (CO_{2i}) + \sum_{j=1}^{12} \alpha_j^3 (T_{ji}) + \alpha^4 (T_{ai}) + \sum_{j=1}^{12} \alpha_j^5 (PP_{ji}) + \alpha^6 (PP_{ai}) + u_i , \quad (1)$$

where Yi is the crop yield (kg ha-1), Tji is the min and max temperature of the months 1 to 12 of the growing period (which varies with the location and crop, see Table 14), PPji is the total amount of water (precipitation plus irrigation) received by the crop (mm), i refers to the year, j is the month, a refers to the annual values, 1-6 are parameters, and u is the random term that allows for the residues.

Table 14 Months which the climate explain a higher proportion of crop productivity variation in the agro-climatic regions

Agro-climatic regions	Validation site	Months which climate explains a higher proportion of crop productivity variation
Boreal	Oslo	June to September and annual average
Continental North	Muenchen	May to August and annual average
Continental South	Bucharesti	April to July and annual average
Atlantic North	Cork	May to August and annual average
Atlantic Central	Dijon	April to July and annual average
Atlantic South	Lisboa	March to June and annual average
Alpine	Insbruck	June to September and annual average
Mediterranean North	Pescara	March to June and annual average
Mediterranean South	Almeria	March to June and annual average

The estimated coefficients and the standard deviations of the parameters of the statistical models of productivity response involving to monthly values of temperature and precipitation are summarised in Table 15. These functions have been derived from the process-based crop responses to management and climate by using DSSAT crop models for wheat, maize, and soybeans (Jones et al. 2003; Rosenzweig and Iglesias 1998). The selected crops have been used in several studies to characterise world food production (Hammer et al. 2005; Challinor et al. 2005) and are representative of roughly two thirds of arable land in most regions. The statistical functions of yield response have been calibrated and validated in the 9 agro-climatic regions (Ciscar et al. 2011; Iglesias et al. 2012) and then implemented in the 247 agricultural sites to provide a spatial analysis of crop yield response to climate change.

Table 15 Estimated coefficients of the statistical model of productivity response (Eq. 1) (Iglesias et al. 2012). Standard deviation is shown in parenthesis. T4 to T8 correspond to temperature in months 4 to 8, Ta refers to the annual temperature, PP4 to PP9 correspond to crop water (precipitation plus irrigation) in months 4 to 9, PPa refers to the annual crop water. R2 is the coefficient of determination.

	Boreal	Continental North	Continental South	Atlantic North	Atlantic Central	Atlantic South	Alpine	Mediterranean North	Mediterranean South
T4			0.1831 (0.0000)						
T5		0.4759 (0.0018)	0.0050 (0.0000)			-0.0059 (0.0000)		-0.2298 (0.0003)	
T6	0.0429 (0.0017)	0.0050 (0.0113)	-0.0571 (0.0045)		0.1107 (0.0069)		0.0193 (0.0462)		
T7		-0.2731 (0.0038)		-0.0056 (0.0000)			0.0564 (0.0357)	-0.0127 (0.0008)	-0.0313 (0.0004)
T8	0.2010 (0.0001)	-0.1571 (0.0009)							
Ta	0.0769 (0.0001)	0.1572 (0.0009)		0.2752 (0.0384)	0.5105 (0.0173)	-0.2014 (0.0000)	0.3401 (0.0081)		
PP4						0.0173 (0.0015)		0.0157 (0.0091)	0.0013 (0.0005)
PP5			0.0153 (0.0115)					0.0056 (0.0339)	
PP6			0.0172 (0.0200)	0.0153 (0.0013)		0.0422 (0.0401)			
PP7					0.1067 (0.0375)				
PP8		0.0041 (0.0257)		0.0102 (0.0014)					
PP9	0.0182 (0.0279)								
PPa	0.0055 (0.0032)	0.0015 (0.0265)	0.0102 (0.0138)	0.0136 (0.0104)	0.0298 (0.0264)		0.0077 (0.0001)		0.0112 (0.0000)
R2	0.62	0.71	0.83	0.72	0.60	0.69	0.67	0.89	0.78

This approach overcomes the limitation of data requirements for process based crop models using statistical functions in order to expand process-based crop models results over large areas. The methodology takes into account the impact on the mean values of productivity and also the potential risk associated with the inter-annual variability of productivity given by the coefficient of variation.

The relative changes in crop productivity as a consequence of climate change have been calculated as follows:

$$\Delta Y = \frac{Y_{CC} - Y_{CTL}}{Y_{CTL}} * 100, \qquad (2)$$

whereΔY is the variation in the crop yield (difference between crop yield under climate change scenario (YCC) and crop yield under control scenario (YCTL), in percent).

The variation in the variability of the crop productivity has been obtained by calculating the changes in the coefficient of variation of productivity of the 30 years analysed, as follows:

$$\Delta Cv = \frac{Cv_{CC} - Cv_{CTL}}{Cv_{CTL}} * 100, \qquad (3)$$

where ΔCv is the change in the coefficient of variation of crop yield (difference between coefficient of variation of crop yield under climate change scenario (CvCC) and the coefficient of variation of crop yield under control scenario (CvCTL), in percent).

In addition, this study introduces the risk analysis using indicators based on anomalies given by the changes in the probability distribution functions of the crop yield under climate change scenarios with respect to the control scenario,

Yield probability distributions functions

Climate change is expected to affect both the mean values of crop productivity and its variability (Torriani et al. 2007). Considering that these changes in crop yield could be substantial, it is possible to represent the mean and inter-annual behaviour using probability distribution functions that represent the behaviour of annual productivity. According to the changes occurring in the form of distributions, we can determine the anomalies that are generated under future scenarios with respect to the control scenario. Thus, this study considers four possible cases that take into account the changes in the average yield and the variability of productivity (Figure 37).

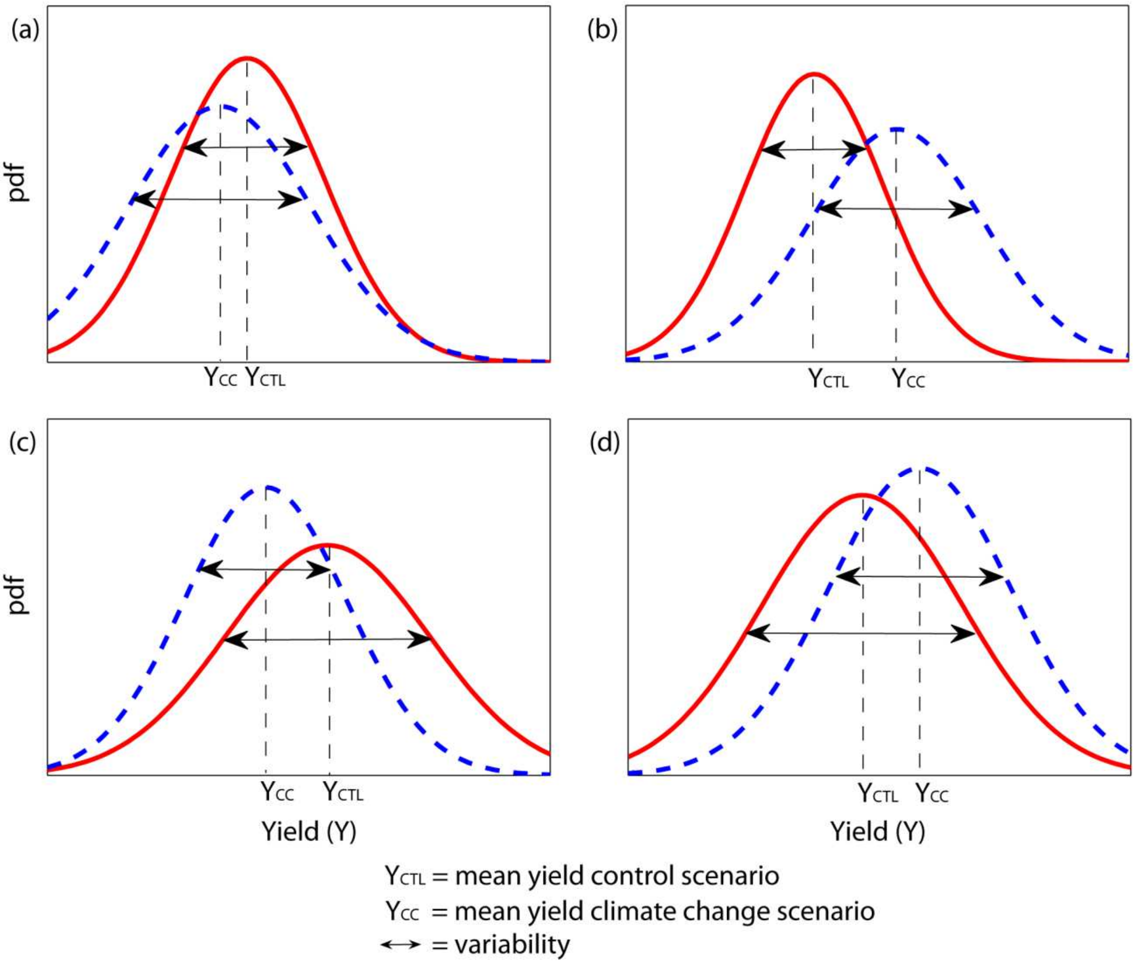


Figure 37 Probability distribution functions (pdfs) of the crop yield under the climate change scenario (dashed) and control scenario (solid). The vertical lines indicate the means, and the double-headed arrows indicate the variance: (a) lower productivity and greater variability, (b) greater productivity and variability, (c) lower productivity and variability, and (d) greater productivity and lower variability

The first case occurs when the productivity changes move the entire distribution to a lower value of productivity and greater variability. In the second case, the productivity changes move the entire distribution to a higher productivity and greater variability. The third case is characterised by the distribution shifting the mean toward a lower value of productivity and less variability. Finally, in the last case, the distribution change shifts the mean towards higher productivity and less variability. This is presented in Figure 37. The detected anomalies given by the changes in the distribution functions of productivity determine the level of impact and the risk on crop productivity under future climate change scenarios. These predicted effects and risks are used as the basis for adaptation needs based on the degree of vulnerability that characterises the different agro-climatic regions.

Example of application of the ClimateCrop model

The ClimateCrop model was developed and used in the ClimateCost project to evaluate global changes in crop productivity under 12 climate models driven by A1B assumptions of socio-economic change. The results are shown in Figure 38. The limitations of these results are the limited socio-economic scenarios used, the lack of consideration of water needs for agriculture, and the very limited adaptation analysis. In BASE we expand on these three issues and link the ClimateCrop model into the SARA modelling framework for adaptation analysis.

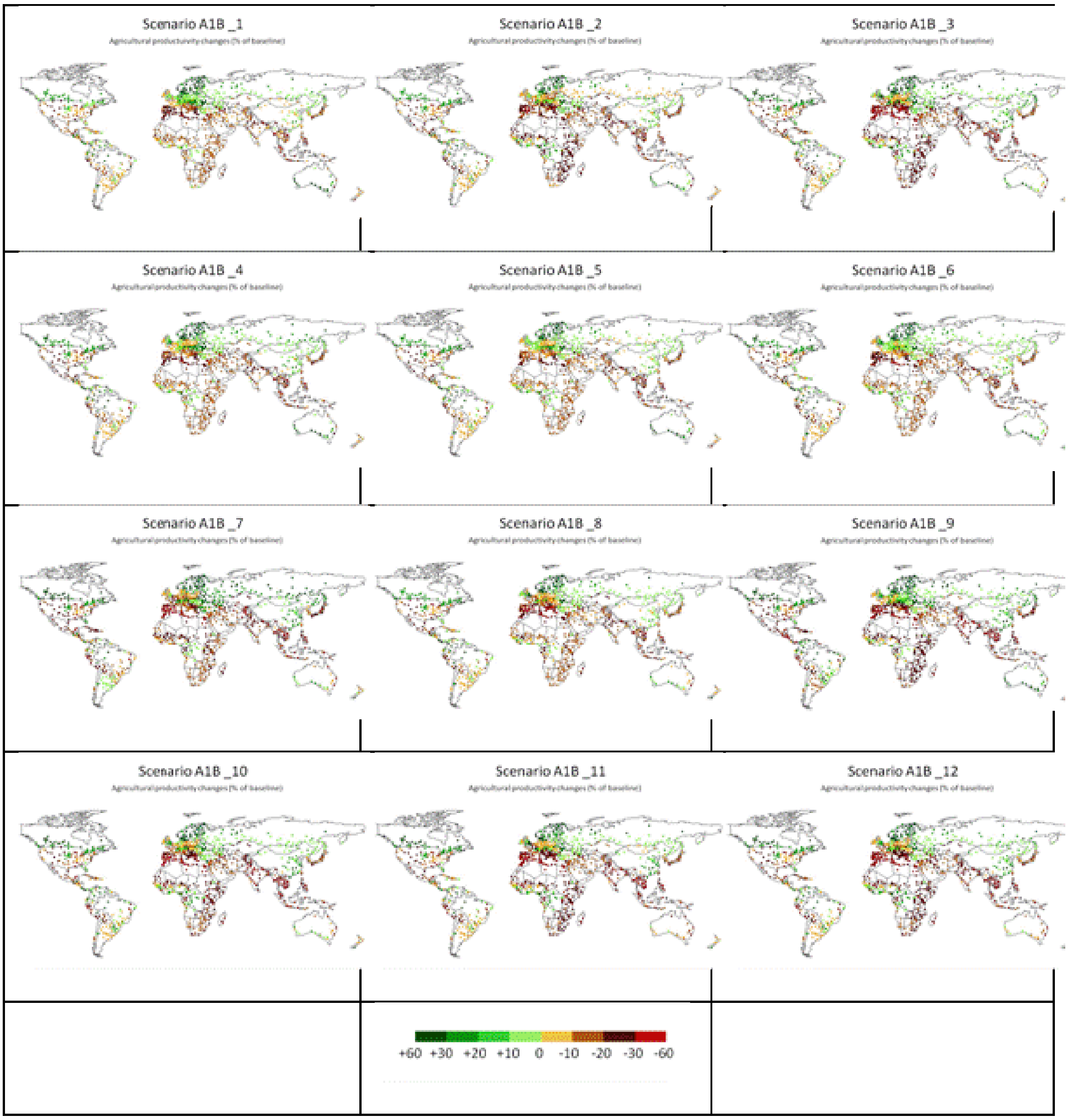


Figure 38 Projected crop productivity changes at the site level for the A1B scenarios for the 2080s.

6.6 Agricultural water demand component

Crop production response to water availability

The validated site crop models are useful for simulating the range of conditions under which crops are grown. Variables explaining a significant proportion of the yield variance are crop water (sum of precipitation and irrigation) and temperature over the growing season. Figure 39 shows an example of crop model results for three different crops (maize, wheat and leguminous) in the North Mediterranean region.

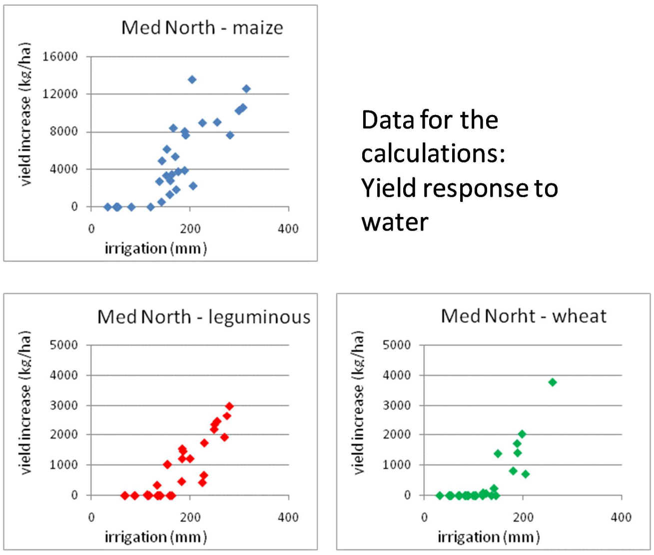


Figure 39 Example of yield response to water availability

Crop models are used to compute initial estimates of elasticities of yield to water availability. The elasticities were estimated by log-linear functions derived from model results considering 100% efficiency of the irrigation system and management.

Efficiency of the irrigation system

The initial elasticity values were modified to account for limitations in infrastructure, technology, management, and value of production. The actual efficiency of the irrigation system and management was estimated using five indicators, listed in Table 16. A country is considered to have high efficiency when it has either 3 or more high indicators, or 2 high indicators and no low indicator. A country is considered to have low efficiency when it has either 3 or more low indicators or 2 or more low indicators and no high indicator. The rest of the countries are considered to have medium efficiency.

Table 16 Assumptions to estimate real irrigation water efficiency

Indicator	High	Medium	Low
Infrastructure	Mostly pipes	Mostly open air covered canals	Mostly open air non-covered canals
Irrigation technology	> 20% localised	10 to 20% localised	< 10% localised
Irrigation advisory services	Yes, largely	Yes, some farmers	Almost none
Value of the irrigated production	More than 80% of total value of production	50 to 80% of total value of production	Less than 50% of total value of production
Land holding structure (%ownership)	More than 80%	50 to 80%	Less than 50%

The marginal productivity estimates include different sources of uncertainty. At the site level, the main source of uncertainty is inherent to the use of crop models and the implications included in them. At the regional level, the primary source of uncertainty in the estimates lies in the sparseness of the crop modelling sites to derive regional marginal productivity and the fact that the sites may not adequately represent the variability of water allocation regions, the variability of agricultural systems within a water region, or dissimilar agricultural regions. However, since the site results relate to regions that account for about 70% of the Mediterranean crop production and irrigation water use, the conclusions concerning marginal productivity estimates contained in this study are believed to be substantiated adequately.

Future water availability and impact on agricultural productivity

Quite naturally, estimates are surrounded by multiple uncertainties. Lack of information, structural model weaknesses, uncertain policy response and degree of adaptation are all factors making the evaluation of future agricultural productivity highly debatable. For these reasons, we do not aim at producing forecasts, but rather a set of not implausible scenarios, based on a consistent methodology and, sometimes, subjective judgement.

We analyze how reductions in water availability could affect the agricultural productivity. To this end, it is important to observe that (i) each country has its own mix of agricultural products, and (ii) crops may differ in terms of sensitivity to water shortages.

We consider seven classes of agricultural products: wheat, cereals, rice, vegetables and fruits, oilseeds, sugar, other products. For each crop group in each country, a water elasticity parameter has been estimated (Table 17), which expresses the percentage change in annual yield when the water input is varied by 1% (keeping all other production factors unchanged). This entails accounting for both the physical characteristics of the crop and the overall efficiency of the water delivering system.

The reduction of demand satisfaction varies yearly and therefore a water limited scenario implies greater exposure to risk.

Table 17 Water elasticities by crop for each country and an example.

	Wheat	Cereals	Rice	Veg&Fruits	Oilseeds	Sugar	Other Crops
Albania	1.0397	1.0397	0.8970	0.8970	0.6134	0.6134	0.8500
Croatia	1.0397	1.0397	0.8970	0.8970	0.6134	0.6134	0.8500
Cyprus	2.5521	2.5521	2.6145	2.6145	1.5946	1.5946	2.2537
Egypt	2.8613	2.8613	3.6493	3.6493	3.6963	3.6963	3.4023
France	3.0746	3.0746	2.1266	2.1266	1.3861	1.3861	2.1958
Greece	1.8195	1.8195	1.5698	1.5698	1.0734	1.0734	1.4875
Italy	1.8195	1.8195	1.5698	1.5698	1.0734	1.0734	1.4875
Morocco	0.2922	0.2922	1.3814	1.3814	0.7224	0.7224	0.7987
Spain	2.5521	2.5521	2.6145	2.6145	1.5946	1.5946	2.2537
Tunisia	0.2922	0.2922	1.3814	1.3814	0.7224	0.7224	0.7987
Turkey	1.8195	1.8195	1.5698	1.5698	1.0734	1.0734	1.4875
XMENA	0.2922	0.2922	1.3814	1.3814	0.7224	0.7224	0.7987

Using these parameters, changes in water availability for agriculture will be translated into changes in agricultural productivity, by sector.

Assessment of regional needs for adaptation

The magnitude of the risk indicators for crop productivity reflects the importance of the changes in the mean and variability as an individual level; however, adaptation needs are directly associated with the joint behaviour of the anomalies in both the mean values and the yield variability.

According to the adaptation needs identified in each of the agro-climatic regions in Europe, potential adaptation measures are summarised in Table 19, in order to address the four cases that involve adaptation priorities.

Table 18 Examples of adaptation strategies addressing changes in mean yield and yield variability in the different agro-climatic regions of Europe

Adaptation needs	Example of potential adaptation measures
Adaptation focus on average impacts	- Change in crops and cropping patterns - Changing cultivation practices - Increased input of agro-chemicals - Introduce new irrigation areas - Develop climate change resilient crops - Livelihood diversification - Relocation of farm processing industry
Adaptation focus on reducing variability	- Insurance - Irrigation - Shift crops from vulnerable areas - Improve soil moisture retention capacity
Adaptation focus on both changes in the mean and the variability	- Implement regional adaptation plans - Advisory services - Research: technology and biotechnology - Research: water use efficiency - Research: management and planning
Adaptation focus on eliminating barriers to potential impacts	- Adaptation plans to maintain optimal farming conditions and increased crop productivity - Expert judgment

6.7 Adaptation component: adaptation choices

Changes in irrigation requirements

Adaptation is explicitly considered and incorporated into the results by assessing country or regional potential for reaching optimal crop yield. Optimal yield is the potential yield given non-limiting water applications, fertiliser inputs, and management constraints. Adapted yields were calculated in each country or region as a fraction of the potential yield. That fraction was determined by the ratio of current yields to current yield potential.

Assumptions

It is assumed that

i. farmers follow an adjusted crop management in response to climate;

ii. irrigated areas do not increase significantly;

iii. adaptation policy scenarios may modify crop productivity and input variables;

iv. fiscal policies remain unchanged.

Because of the nature of our assumptions, our agricultural policy scenario does not impose major additional environmental restrictions beyond the ones currently implemented, nor does it take into account pollution taxes.

A major factor that may contribute to decrease or intensify impacts of climate change on water resources in semiarid regions is management of the water resources system. Adequate rules for management of irrigation systems under drought conditions can significantly offset the reduction in natural inputs. The measures of demand management can also achieve a progressive reduction of the needs far greater than the reduction of available water supply which occurs naturally as a result of climate change. This requires a coordinated series of actions in terms of awareness and education, investment in conservation, maintenance and improvement of facilities, establishment of rules for exchanging water rights and increasing the flexibility of the operation of the water resource system. The adaptation choices are summarised in Table 19.

Table 19 Some examples of adaptation measures that can be simulated with the framework and underlying policy assumptions and environmental implications

Adaptation policy	Irrigation water assumptions	Environmental implications
Adaptation 1	Demand satisfaction according to assumptions on technological capacity of the country	Optimisation of environmental water requirements
Adaptation 2	No room for changes in irrigation	none
Adaptation 3	Demand satisfaction according to assumptions on increased irrigation areas	Potential decrease in environmental flow requirements

The water demand for agriculture in our approach accounts for the following aspects:

- Water demand for agriculture is estimated by defining irrigation requirements under the climate scenarios.
- Water supply for rainfed agriculture depends on rainfall. But for irrigated agriculture depends on runoff and storage capacity.
- Water supply depends on infrastructure and regulation and these determinants are defined by environmental policy.
- We include three adaptation scenarios with different levels of water availability for agriculture. These adaptation scenarios represent different policy choices related to regulation and infrastructure.

- Streamflow variability, reservoir storage capacity and water yield reliability describe how a system is able to supply its demands and with what reliability; the estimation of these factors will be done with the WAAPA model (See section 6 of this Deliverable).

The main assumptions for estimating adaptation of crop productivity to reduced water availability are summarised below:

- If the country has a very high irrigation efficiency based on advanced technology (i.e., Israel), a reduction of water availability will imply a reduction in irrigated area while maintaining the same level of productivity per unit area (in order to maintain the competitiveness of agricultural markets)
- If a country has margin to improve its water efficiency and can afford the required technology (i.e., Spain), a reduction of water availability will be compensated by an increase in irrigation efficiency
- If a country has margin to improve its water efficiency and cannot afford the required technology (i.e., Morocco), farmers will be exposed to a loss of productivity

The reduction of demand satisfaction varies yearly and therefore a water limited scenario implies greater exposure to risk.

The adaptation policy questions are outlined in Table 20 and 21.

Table 20 Adaptation policy assumptions and indicator analysis for irrigation

Adaptation level	Assumptions on infrastructure, management, technology, and environmental protection	Consequences for agricultural outcomes	
	Rainfall index and adaptive capacity index	Crop productivity	Irrigation
1	Irrigation may increase without additional environmental constraints if the If rainfall index >800 in all countries	Potential negative impacts are completely compensated	Increase in the total amount of water to compensate potential yield reduction
	Irrigation systems may improve efficiency in countries where infrastructure and technology are already developed and the rainfall index is between 600 and 800	Potential negative impacts are compensated by one half	Increase in half of the amount of water to compensate potential yield reduction
	Irrigation systems may not improve when infrastructure and management are completely developed due to the stress under the current climate; the rainfall index is lower than 600	Potential negative impacts are not compensated, it is not possible	No increase in water for irrigation

Agro-chemical management

Table 21 Adaptation policy assumptions and indicator analysis for nitrogen fertiliser input

Adaptation level	Assumptions on infrastructure, management, technology, and environmental protection		
	Rainfall index and adaptive capacity index	Crop productivity	Nitrogen fertiliser
2	Countries with low environmental protection may apply additional nitrogen fertiliser	Potential negative impacts are compensated by 50% by increasing the N-fertilizers	Increase in the total N fertiliser applied to compensate 50% of the potential yield reduction
	Countries with high environmental protection may not apply additional nitrogen fertiliser	Potential negative impacts are not compensated, it is not possible	n.a.

6.8 Adaptive capacity

How able are people to adapt to these changes?

The ability of societies to anticipate and face an external shock is often called their adaptive capacity. When the external shock is climate change, this adaptive capacity is estimated by environmental, social and economic factors. At the same time these factors are essential components of a country's development status and of the sustainability of its socio-economic model. In other words, adaptive capacity and development are closely linked processes that feed and rely on each other. In the case of water the synergies between the two are particularly noticeable.

The key issue is to define the extent to which climate change impacts and their interactions with social systems will increase levels of vulnerability of agricultural systems. To this end we develop and apply an adaptive capacity index. Adaptive capacity is understood as the capacity of a system to cope with or recover from a potentially damaging change in climate conditions. In that sense, adaptive capacity is the combination of a number of social and economic components. (Yohe et al., 2006; Iglesias et al. 2010; IPCC 2007). Adaptive capacity is therefore a useful concept for understanding the responses of a system to future perturbations such as those associated with climate change. Here we compute an adaptive capacity index (ACI) that integrates determinants of policy in a country or region, based on the aggregate social, economic, technological, environmental, and climate components of adaptive capacity (Iglesias et al. 2010). The value of the index for any given system represents the potential adaptive capacity of that system. In other words, a higher score in the index represents a greater ability to modify future climate impacts.

Determinants of adaptive capacity

Adaptive capacity is understood as the capacity of a system to cope with or recover from a potentially damaging change in climate conditions (Smit and Wandel 2005). In that sense, adaptive capacity is the combination of a number of social and economic components. (Yohe et al., 2006; Iglesias et al 2010; IPCC 2007).In spite of the considerable associated uncertainties (Adger and Vincent 2005), a number of indices of adaptive capacity have been developed (Yohe and Tol 2002, Ionescu et al. 2009, Yohe et al. 2006, Iglesias et al. 2007b, Simelton et al. 2012) to capture different elements of social and economic vulnerability to climate change. With this in mind the adaptive capacity index (ACI) presented in this section comprises five major components that characterize the social capacity, economic capacity, technological eco-efficiency, natural capital and climate capital of a country all of which determine a system's ability to adapt to climate change.

By establishing these five components the final objective of the adaptive capacity index is to evaluate how policy affects the magnitude of potential climate change impacts and to establish the differences in adaptive capacity between Mediterranean countries. The index presented in this section provides a measure of how able societies are to adapt to climate change impacts in the water sector; in doing so it provides insights for future policy developments.

The adaptive capacity index integrates determinants of policy in a country or region, based on the aggregate social, economic, technological, environmental, and climate components of adaptive capacity (described below). The value of the index for a system represents its potential adaptive capacity, understood as a modifier of climate impacts.

Social Capacity

As suggested by Brooks et al. (2005), in large part adaptive capacity is dependent on social and political characteristics. Social characteristics depend to a large extent on the type of policies implemented in the country or region and they determine the degree of social adaptive capacity to climate change. Social adaptive strategies can range from market-based, self-sufficiency strategies to protective policies for industrialized nations where agriculture plays a marginal role. The indicators selected for this component represent several aspect of social capacity that can support or limit a region's adaptation capacity.

Some indicators (i.e. human development, collective capacity, access to resources, institutional coordination, pressure on natural resource use, literacy rate, life expectancy or access to sanitized water) imply healthier and stronger societies that can develop and implement solutions to adapt to climate change in a more efficient manner. Other indicators, like agricultural employment, have a negative correlation to overall adaptive capacity because they imply a greater dependency on a highly variable sector.

Economic capacity

The level of economic development is an indicator of the capacity of a country to invest in development technologies, food security and income stabilization. The indicators selected for this component are GDP and CO2 emissions which represent a country's technological development. These two indicators exhibit a positive correlation to adaptive capacity, while the rate of agricultural GDP shows a higher dependence on agriculture and, again, a lower adaptive capacity.

Technological eco-efficiency

The efficiency in the use of resources for production and the adoption of new technologies significantly increases a system's adaptation potential (Godfray et al. 2010). The three aspects represented in this component are general eco-efficiency, technological development and the specific level of technology applied to agriculture. The indicators selected represent the technological advancements applied to agricultural production and include GDP per unit energy use, technology exports and CO2 emissions per capita. The development of agriculture significantly decreases the sector's dependency on climatic variables and stabilizes production. Therefore these indicators have a positive correlation with the overall adaptive capacity index, as they indicate the level of independence from climatic variables.

Natural capital

One of the most relevant threats imposed by climate change projections in the Mediterranean region is higher levels of water scarcity. Adequate climate change adaptation policies in the Mediterranean region depend on the reliability and vulnerability of water resource systems in future scenarios and the availability of adequate management policies. Water management depends on factors such as infrastructure for water storage or transport, excess of demands or their mutual incompatibility, and constraints for water management (determined by policies). Indicators of agricultural water use and irrigated area show a positive correlation with adaptive capacity because the more water is used for agriculture; the easier it is to stabilize agricultural production independently from annual precipitation or distribution.

Climate capital

Climate capital represents the baseline state conditions that are not modified in the short term. Current temperature and precipitation are determinants of the potential climate policies developed in the region. This component incorporates information related to the variability of precipitation, which decreases a system's general adaptation capacity because it hampers the effectiveness of developed infrastructure. This component does not represent implemented policies but is essential as the representation of the external hazard that the regions are exposed to.

For measuring adaptive capacity we use four components as proxies for determining current vulnerability and future ability to develop adaptation strategies. Thus, the social component determines the system's dependence on agriculture and includes broader concept of social capacity also considering literacy and health. The level of economic development, on the other hand, is taken as a representation of the capacity of a country to invest broadly in technology and innovation for agriculture. The agricultural innovation component assesses a country's current level of technological advancement in the agricultural sector. Finally, the natural capacity component is a proxy for vulnerability to meteorological and physical changes, particularly relating to water. The justification for the components we have used is more extensively described in Iglesias et al., 2011. The indicators considered are outlined in Table 22.

Table 22 Components and proxy variables of the adaptive capacity index for the agriculture sector. Preliminary list of indicators.

Components	Proxy variables
Natural capacity	Average precipitation 61-90 (mm/year) Total water use(per cent of renewable) Agricultural water withdrawal (per cent of total water withdrawal) Area with salinisation by irrigation (ha) Population density (people per km2)
Economic capacity	GDP (millions of US-Dollar) GDP per capita (US-Dollar) Agricultural value added/GDP (per cent) and agricultural value added Energy use (kg oil equivalent per capita.
Social capacity	Agricultural employment (per cent of total) Life expectancy at birth (years) Population without access to improved water (per cent of total)
Agricultural innovation	Irrigated area (per cent of cropland) % of cropland that has been drained; % cropland organic soils (former wetlands); Research investments into climate resilient crops Irrigation technology (per cent drip irrigation) Fertiliser consumption (100 kg/ha of arable land) Agricultural machinery (tractors per 100 km2 of arable land)

In order to quantify the index we (a) use data from FAOSTAT and AQUASTAT databases to compute the proxy variables, (b) normalize the indicators with respect to a common baseline, (c) combine the sub-component indicators within each policy category by weighted averages and (d) quantify adaptive capacity index as the weighted average of the components.

This index has some interesting advantages such as its ordinal character allowing for monotonic transformations. The index can be calculated for different components and time periods, including climate change scenarios. The total index is generated as the average of all components. The final value of the index depends on the weight assigned to each of the components. For the baseline we present the results of the index where all components are weighted equally. For the different future scenarios we adjust the weights of the components to reflect storylines for each scenario.

In order to measure the inequality of the determinants of adaptive capacity components among the considered countries, we apply the Gini index and Lorenz curve methodology, which is one of the most widely recognised measures of inequality (Gastwirth, 1975). The Gini coefficient varies between 0 (reflecting complete equality) and 1 (indicating complete inequality) in the distribution of values. Gini index measures the extent to which the distribution of a variable (here the ACI) among individuals (here countries) deviates from a perfectly equal distribution. A Lorenz curve plots the cumulative percentages of total income received against the cumulative number of recipients. Graphically, the Gini coefficient is represented as the area between the Lorenz curve and the line of equality. The Lorenz curve plots the cumulative percentages of ACI values against the cumulative number of countries. If all countries had the same ACI, the Lorenz curve would be a straight diagonal line equal to the line of equality.

The GINI coefficient may be calculated in different ways depending on the type of data in the sample (continuous, discrete, ordered, unordered). In our case the data are unordered discrete. The Gini coefficient is most easily calculated from unordered size data as the relative mean difference, i.e., the mean of the difference between every possible pair of individuals, divided by the mean size (Dixon et al., 1987, Damgaard and Weiner 2000); therefore the ACI variability (ACID) for n countries can be measured as

$$ACI_D = \frac{1}{2n^2\mu} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| ACI_i - ACI_j \right| ,$$

which is the average ACI difference across all pairs of countries (i and j) normalized by the average value of the ACI (□).

Although the evaluation of adaptive capacity hides important local disparities, this analysis provides a first approximation of the overall capacity of a country to adapt.

The evaluation of adaptive capacity at country level hides important local disparities. However, considering that policies to facilitate adaptation are often initiated or promoted at the national level provides a first approximation of the overall capacity of a country to adapt. Because the adaptive capacity index is a component-based analysis it provides insights into a few aspects of how adaptation to climate change may be prioritised in different countries.

If there are no large investments to promote adaptation, then farmers only have a limited range of adaptation options at their disposal. These adaptation strategies include small-scale decisions such varying the time of planting for certain crops but exclude larger initiatives such as developments in irrigation infrastructure or investments in more resilient crops. This is not to say that exogenous solutions may not become available over time. Rather, our assumptions about the limited flexibility of adaptation options at the farm level allow us to shed light on the extent to which current agricultural production is at risk. If there are limited options for adaptation at the farm level, then to what extent does it make sense to discuss about prioritising adaptation? We analyse this is the following sections.

Adaptation and policy

The combination of adaptive capacity and climate impacts influences the global distribution of vulnerability (Yohe et al. 2006). This does not try to hide the fact that there needs to be an awareness of the political and economic issues that constrain efforts to develop adaptive capacity. Adapting to a particular climate impact is a much clearer issue than the actual development of adaptive capacity. Defining an emergency relief plan at the local or national setting is more profitable in terms of social and political capital than a long term plan to slowly develop the adaptive capacity of an entire country, not at least because the effects of the former are perceived to be more tangible. However, particularly for a sector like agriculture, efforts to increase adaptive capacity cannot be set aside lest future costs become unmanageable.

A measure of risk in the different agricultural areas can be defined by taking into account the two dimensions of risk: the response to an external shock, as defined by changes in projected impacts and the social vulnerability, as defined by the adaptive capacity. This simple approach aims to inform policy on the potential adaptation measures by taking into regional variation and the underlying causes of risk. Here we define broad groups of risk profiles (Figure 41). First, if a region has a projected positive potential change in productivity and the adaptive capacity is above average, the region may not face a future risk derived from global change; if the adaptive capacity is lower than average, the region may be at low level of risk since it may not be able to take advantage of the potential opportunities due to lack of adaptive mechanisms. Medium risk levels may arise from a combination of very low adaptive capacity facing a positive change that cannot be transformed into an opportunity, or from a small negative change in regions with high levels of adaptive capacity. In contrast, regions with very negative expected impacts may be at high or very high risk depending on the adaptive capacity level. Additionally, overlapping areas suggest how levels of risk may be heightened or dampened depending on the availability of water resources, among other factors. Figure 41 shows how these risk profiles are mapped onto the world given the results of our analysis. We use the data presented in the previous sections to outline regional potential risk derived from global change (Figure 40). In regions where adaptive capacity is high, negative climate change impacts will be dampened resulting in lower levels of risk, this may be the case of the Mediterranean region of Europe or Australia. On the other hand, regions such as South East Asia and Africa will be under great risk from climate change because of low levels of adaptive capacity and very negative projections of agricultural productivity. Successful adaptation policy needs to address the two risk components by supporting strategies that are region specific and provide sufficient flexibility in the face of impacts, and create synergies with development policies that enhance adaptive capacity.

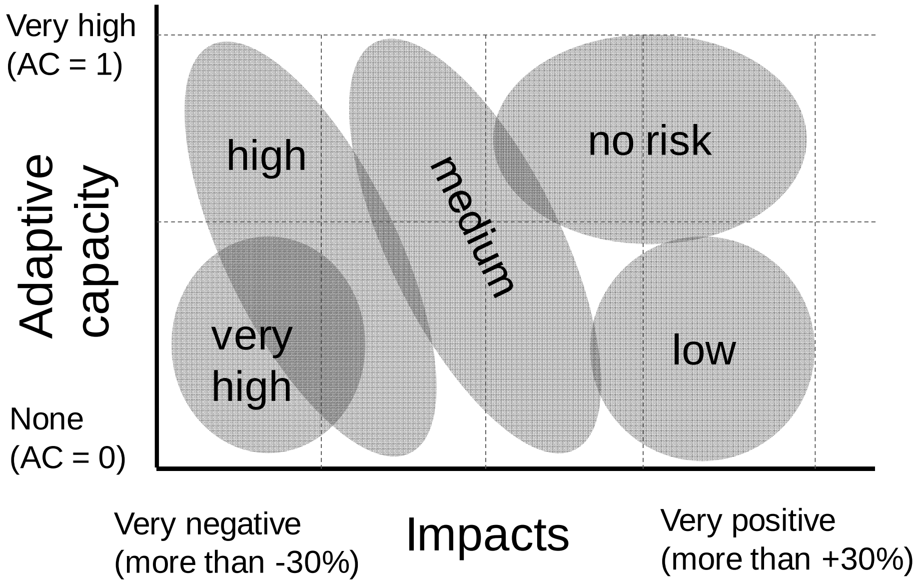


Figure 40 Definition of risk profiles as determined by projected changes in productivity and levels of adaptive capacity

6.9 Implications for European policy

Adaptation choices reflect different views about the future of societies and these choices have implications for the economy and the environment.

In contrast with farmers-only adaptation, public policies are far more uncertain and difficult to project, since do not respond only to optimising climate-crop interactions.

Agriculture is transformed through widespread land cover change, urbanisation, industrialisation, water management, and policy (Satterthwaite et al., 2010; Rosenzweig et al., 2004; Rosegrant et al., 2004; Reganold et al., 2011; Godfray et al., 2010). The benefits or costs of interventions on land productivity are often accompanied by subsequent effects on the environment and society that are not uniform.

6.10 Limitations of the methodology

Determining how farmers will adapt to climate change is a very complex dynamic process which is difficult to quantify. The study will consider that farmers optimise management under climate change scenarios but cannot implement changes that require policy intervention. How agriculture policies might react to a changing climate is another critical factor which cannot be incorporated in the simulations.

Uncertainty appears in the input side of the model (value uncertainty) and in the structural specification of the model (structural uncertainty).

Concerning the third source of uncertainty (related to the physical impact models), each sectoral physical model has its own set of uncertain parameters, and some cases have been explored.

Population and land-use dynamics and the overall policies for environmental protection, agriculture and water resource management determine, and limit, possible adaptation options to climate change.

The costs and benefits of the response adjustments will be only identified as environmental externalities. The study will not consider the potential technology that can be developed in response to change.

The modelling framework does not consider the full range of impacts that are described in the agricultural sector as consequence of climate change.

- Physiological effects on crops, pasture, forests and livestock (quantity, quality)
- Changes in land, soil and water resources (quantity, quality)
- Increased flood damages
- Increased weed and pest challenges
- Shifts in spatial and temporal distribution of impacts
- Sea level rise and changes to ocean salinity
- Socio-economic impacts are for instance (ibid):
- Decline in yields and production
- Reduced marginal GDP from agriculture
- Fluctuations in world market prices
- Changes in geographical distribution of trade regimes
- Increased number of people at risk of hunger and food insecurity
- Migration and civil unrest

7 Health risks

Aline Chiabai, Tim Taylor and Sébastien Foudi

7.1 Context

The impacts of heat waves on health have been substantially covered in the literature and ongoing projects (e.g. ClimateCost, EUROHEAT), while other impacts such as mental health risk, food-borne (e.g. salmonella, seafood diseases) and vector-borne diseases (ticks, lyme, malaria) have been less explored in an adaptation context in Europe. Here the focus will be largely on improving the existing coverage of health in the integrated assessment models and on ensuring that the model reflects the state-of-the-art in terms of health impacts and adaptation costing. The analysis will build on an exploratory analysis of secondary sources for heat stresses and work in WP4 and WP5 on food-borne and vector-borne disease in particular, as the knowledge on the impacts of these is far more advanced than is the case for mental health. The identification of uncertainties in the adaptation functions will be an important part of the research, as will the identification of any cross-sectoral linkages between health and mitigation policies. Expected outcomes will help to inform the further elaboration of adaptation cost functions inside the integrated assessment model developed by CMCC.

7.2 Introduction and objectives

This document addresses sub-task 3.3.3 on health which has the objective of improving the existing coverage of health studies in the integrated assessment models and ensuring that the state-of-the-art of health impacts and adaptation costs is properly incorporated. The results of this sub-task will be used to proceed to the estimation of the adaptation cost curve in the health sector within the AD-WITCH model in WP6. The outcomes will be also useful as input data in the development of the case study for the Madrid area assessing co-benefits in cross-sectoral adaptation strategies for water and health (in WP5).

The estimation of the health adaptation cost curve requires the following steps to be undertaken:

1. To identify climate-sensitive health risks relevant at EU level, dose-response relationships, and the total additional burden of disease by health outcome (see table 21).

2. To identify preventive and reactive measures for each selected health outcome.

3. To identify costs and/or cost-effectiveness of adaptation measures (per case or death or DALY avoided, depending on the data available).

4. To adjust the cost estimates of the measures in a format that is compatible with AD-WITCH model and to carry out new extrapolations with the participation of stakeholders when necessary.

5. To run the AD-WITCH model and estimate the adaptation cost curve (with CMCC).

The first three points are part of task 3.3.3 and will be addressed in this section of deliverable 3.2, while the last two relates to the empirical assessment within the AD-WITCH model and will be carried out in WP6. In order to address points 1-3, a literature review has been carried out on climate change impacts on health and adaptation costs, and a database in excel has been constructed with main outcomes available.

The document is organized as follows. Section 2 provides the methodological approach to estimate the health adaptation cost curve at European level as well as the challenges and main empirical issues in the modelling. Section 3 discusses the state-of-the-art of the literature with main results and drawbacks, and research gaps.It reports main results in terms of quantitative impacts on health and adaptation costs for climate-sensitive diseases, and will be used to extrapolate input data for the top-down model.

Section 4 discusses the existing literature, while section 5 presents main conclusions and next steps.

7.3 Assessing a marginal adaptation cost curve for health: methodology and modelling issues

7.3.1 Theoretical Framework

Optimising the level of adaptation requires knowledge on the shape of the total health impact cost, which is a balance between residual damages and the cost of adaptation. Figure 41 below gives a simplified overview. The objective is to minimise total health impact costs. However, there are a number of issues that need to be faced in developing appropriate adaptation policy for health. These include:

- Uncertainty over the climate change impact, and hence uncertainty over the damages (and residual damages) to health;
- Uncertainty over the future health adaptation costs – with learning likely to make costs in the future lower;
- The crucial role of discounting – as shown by the Stern report and others, discounting has a major role to play in the appropriate definition of policy; and
- The influence of non-climate change related drivers for future health (e.g. demographic change, pollution, health care systems).

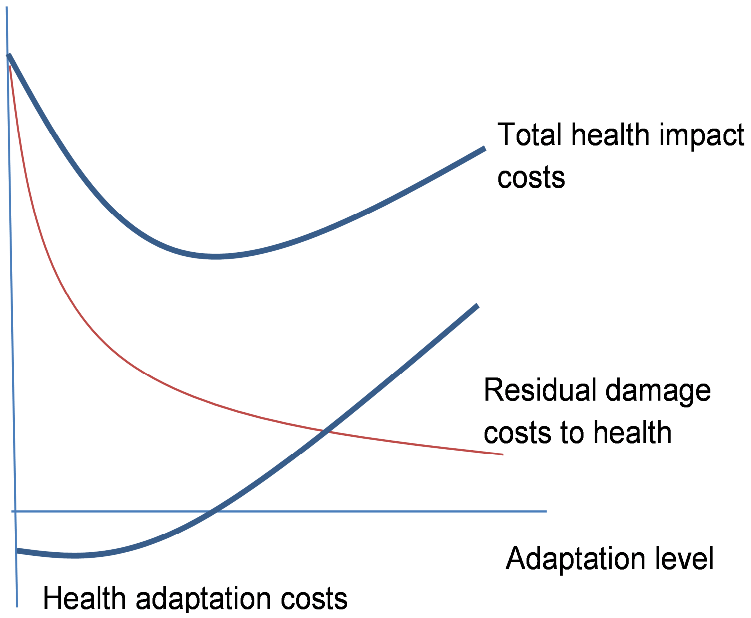


Figure 41 Optimal level of adaptation (adapted from Patt et al, 2010)

Given the uncertainty issues mentioned above, it may be appropriate to consider not just point estimates of adaptation costs, but ranges – this may lead to curves as in Figure 42 below, where THIC represents the Total Health Impact Cost, HAC the Health Adaptation Cost and RDC the Residual Damage Cost, with the subscripts representing High, Medium and Low estimates.It is important to note that this may lead to a window of optimal adaptation levels, but that the optimal mix of adaptation options may differ significantly depending on the climate scenario or adaptation cost considered.

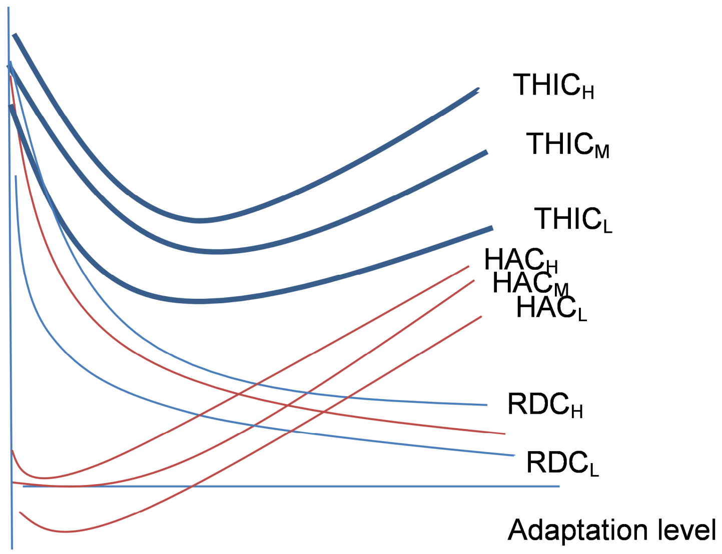


Figure 42 Uncertainty in Adaptation Cost Estimates

This paper largely targets improving knowledge on the shape of the marginal adaptation cost curve for health. In doing this, it is necessarily to first define what "adaptation costs" mean in the health context. There is need for clarifying the difference between "impacts" and "adaptation" – for example, in the correct assignment of treatment costs.

Treatment costs are considered in the literature as an adaptation (Ebi, 2008, UNFCCC 2009, EEA 2007). According to this approach, additional risks under climate change would require expanding the existing coverage of the population, which will be costly so that one could consider damages or impacts as those in the absence of action. If this is the case, the emphasis is on setting a target in budget distribution for adaptation in the health care system, and the deaths which will not be avoided through treatment would be part of the residual damage, as well as the willingness to pay of people to avoid exposure. This is the scientific approach adopted in previous literature.

From another perspective, more pragmatic, we could look at adaptation only as preventive actions. The treatment costs due to an increased incidence of disease caused by climate change would be considered as residual damage. In this case, preventive measures should be the main focus for the public health for adapting to climate change, while curative care would be seen just as a failure of the health adaptation plan.

There is also the issue of the *scope of the costs*. For the health sector it is often possible to determine costs to the health services, costs to patients and costs to society. The identification of the *unit of adaptation* is also important – i.e. the *x*-axis of Figure 1. The health impacts of climate change include both morbidity and mortality endpoints (Metroeconomica, 2004). As such, measures based solely on mortality (e.g. years of life saved/lost, lives saved/lost) are likely to be inadequate. Composite measures of health benefit such as *Quality Adjusted Life Years* or *Disability Adjusted Life Years* need to be used to account for the morbidity endpoints, though there are issues in their application for this purpose. First, QALYs are not uniformly accepted across Europe and there are strong criticisms as to methodology (see e.g. the recent ECHOUTCOME Project). There are also difficulties in transferring across contexts.

In terms of the timing of adaptation, it is possible to adapt and apply the “adaptation pathways” model of Haasnoot (2012, 2013). This model identifies “tipping points” for adaptation, and in the health context these can be seen as (see Table 23 for an exemplification of measures in each category):

- Primary interventions – before damage occurs to minimise exposure (e.g. a number of public health interventions)
- Secondary interventions – aim to prevent disease before it becomes manifest (e.g. screening tests and heat warning system)
- Tertiary interventions – applied once impacts occur.

If one take the viewpoint that adaptation refers only to preventive actions, then we should include only primary and secondary interventions in theadaptation pathways.

Table 23 Adaptation measures and their categorization in the adaptation pathway

	Adaptation measures		
Health impacts	Primary	Secondary	Tertiary
Heat stresses	Building and technical solutions. Urban planning (reforestation, green roofs, etc).	Heat health warning systems (preventive part). Educational campaign.	Heat health warning systems (reactive part). Emergency plans and medical services.
Vector-borne diseases	Healthy ecosystems (including biodiversity) Vector control (vector habitat destruction, bed nets, etc.). Information and health education.	Disease surveillance and monitoring. Vaccination.	Diagnosis and treatment (early detection)
Food-borne diseases	Food sanitation and hygiene (refrigeration, ozone treatment of drinking water, chlorination of drinking water, etc.). Food safety education.	Disease surveillance and monitoring. Zoonosis program to control disease in animals (salmonella). Microbiological risk assessment.	Diagnosis and treatment (early detection)
Water-borne diseases	Regenerate ecosystems and biodiversity e.g. wetland restoration. Improved river water quality e.g. through improved water and sanitation systems	Disease surveillance and monitoring. Information and health education.	Diagnosis and treatment (early detection).

7.3.2 Issues in the estimation

In the first instance, in order to build the cost curve, different levels of adaptation have to be identified and associated with specific costs and scenarios of temperature increase and/or precipitation change. The adaptation level refers to the risk reduction which could be achieved with the measures put in place and might in principle range from 0 to 100%, the latter entailing a complete removal of the risk/damage with return to the baseline situation. However, in the public health the normal situation will be a combination of measures to achieve a specific predetermined target of adaptation, while a scenario with 100% risk reduction might not be realistic.

This issue is also strictly related to the definition of adaptation costs, as treatment costs could be classified either as reactive adaptation or residual damage. EEA (2007) considered these measures as re-actions to climate change as they reduce the residual damage that would otherwise be higher. This approach has the advantage of simplifying the computation of adaptation costs that would otherwise become additionally complex due to the need of deciding to what extent a reactive measure is a damageor an adaptation.

An important issue in the estimation process is also the use of different metrics (cost per case, per death avoided, per DALY or QALY), which requires some kind of homogenization. Another is how to consider programs with multiple benefits. As regards water-borne diseases, for example, structural interventions such as water and sanitation programs provide also considerable non-health benefits, which should in principle affect the cost-effectiveness ratio.

The indicator chosen to represent the welfare variation has non negligible consequences on the costs. It should make explicit whether it deals with a cost of hospitalization or with more subjective values such as personal costs or social costs associated with the event (disease, flood, heat waves, etc). The choice of the indicator should be discussed with the type of cost to be estimated (direct, indirect, cost of public intervention or private actions, etc) and with the scale of the study (micro, meso, macro).

Further questions are related to the empirical estimation of the marginal cost curve using the top-down models and how to integrate data from bottom-up studies of the literature. In this context, we mention the temporal and geographic coverage as well as the climate and socio-economic scenarios. As it will appear from the literature review, the existing estimates of impacts and costs of adaptation may refer to different classifications of countries, not compatible between them or with those used top-down modelling approaches. Another issue is that different studies may provide estimates for different scenarios of temperature increase, or socio-economic contexts and demographic growth. In other cases, studies provide the costs of health interventions outside the context of climate change. All these aspects need to be homogenized and integrated appropriately.

Availability of projections of relative risk (estimated increase in risk of the disease per unit increase in exposure) for different health outcomes, geographical regions and temperature increase becomes, therefore, crucial to be able to estimate the adaptation cost curve for different levels of adaptation.

Social effects such asdevelopment, age structure of the population, access to sanitation, hygiene, etc define the vulnerability of people and the vulnerability of the area they are living in. They cannot be ruled out as they also determine how much the disease can propagate in the society. But the modelling should enable to isolate the climate effect from the social effects of vulnerability. Otherwise, it would result in overestimation of climate change impacts and prevention policies that would target climate mitigation measures whereas targeting social drivers could be more efficient for health prevention. The data source plays also an important role, as using cost estimates of intervention programs in developing countries (UNFCCC, 2009) might under-estimates the costs of interventions programs (sanitation, water access) in rich countries and thus bias the cost assessment (Hutton and Haler 2004).

Climate change already impacts human health and human exposure to vectors of diseases. Evidence of new exposure to vector species disease has been shown in Europe (Purse et al. 2005). Extreme temperature (heat, cold waves) and ozone concentration in cities affect mortality (Filleul et al. 2006). More frequent heat waves, higher ozone concentration would thus increase the risk on human health. Health impacts are also highly dependent on people and area vulnerability (DEFRA, 2003, 2006), those social factors that makes that diseases can propagate and affect people more easily or rapidly. People vulnerability refers to individuals more susceptible to be affected by natural events, like disabled, elderly people, people with pre-existing illness (cardiovascular, cerebrovascular, respiratory disease, etc), etc. The area vulnerability defines how an area is prepared to an event, it depends on the presence or absence of elements susceptible to protect people, like a warning alert system like for floods or heat waves, programs of education to face natural events, etc.

In order to move towards a better understanding of the optimum level of adaptation in health, it is necessary as a first step to identify the health impacts more relevant for Europe (see table 21), dose-response relationships and risk rates, adaptation measures and their costs (as a total cost or unit cost), and this is the purpose of the literature review reported in the next section.

7.4 Health impacts and adaptation costs: evidence from the literature

7.4.1 Introduction and background

The literature relative to the assessment of the economic impacts of climate change due to health impacted drivers basically follows 3 steps that can be diagramed as in **Error! Reference source not found.**: climate modeling, physical health impacts assessment and economic valuation of the impacts. The main challenges lie in the estimation of the climate-health relationship and the economic valuation of the physical health impacts (in the two arrows). The **Climate-Health relationship** builds a functional relationship between temperature, precipitation and health. **The economic valuation methods**are used to translate the physical impacts into economic impacts. The economic impacts can be measured at different scales: micro scales (human), meso scales (sectoral) or at macro scales (regional, country scales). The valuation method is challenging in the sense it is based on non-market values which needs to be estimated appropriately (e.g. willingness to pay, value of statistical life). In some cases, it can be referred to market values of the economic impacts using the value of labour productivity (lost revenues), or the cost of hospitalization and medicines (cost of illness), as proxies for welfare losses.

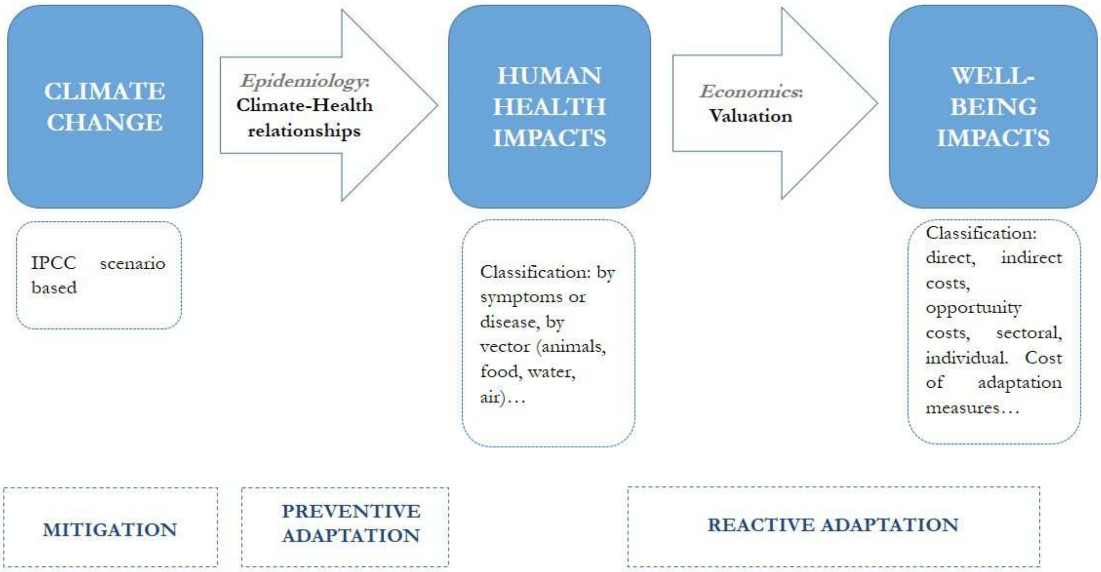


Figure 43 Basic diagram of economic assessment of CC impacts on health. Source: own elaboration

The **social responses** to heath degradation consist in implementing mitigation measures and adaptation measures in order to reduce the physical impacts on human health and the consequent economic impacts. **The mitigation measures** are not health specific measures but belong to the more general measures of CC mitigation that consists in the reduction of CO_2 concentration in the atmosphere (IPCC scenario). They will have consequences on temperatures and on precipitations and health benefits consequently. The adaptation measures are more specifically directed to the health impacts. The **preventive adaptation measures** consist in breaking the epidemiologic relationship between climate and health, i.e. measures that would stop or slow down the transmission of the disease to humans like hygiene measures, control of vector diseases for example. The uncertainty (and relative efficiency) of these measures would justify a second set of measures to treat the disease once declared. **The reactive adaptation measures** are ex-post measures to treat once declared to an individual or to a group: medical treatment for example. These measures are designed to care impacted people and to slow down the propagation of the disease to other non-impacted persons: i.e. to reduce the socio-economic impacts and thus to improve social welfare.

The following review of the literature focuses on two main groups of studies, those related to the cost of inaction on health and those related to the adaptation costs that should be supported to reduce the first. Although we tried to make a distinction between them, in practice it is difficult to discriminate between cost of inaction on health and cost of adaptation. The first measures the additional health impacts caused by climate change, when no action is taken to protect health. The second refer to interventions put in place as prevention or reaction.

The review in the next sections focuses on diseases that could potentially affect European society. Studies outside Europe are taken into account when providing information about the dose-response relationships or the unit cost of health interventions. Non-climate-oriented studies (outside the adaptation context) are also included as they provide relevant interventions on costs and benefits of water-health intervention programs. Actually, these types of measures are technically the same in both contexts. The papers related to the health impacts follow essentially the theoretical framework described in Table 24. For a worldwide context review of the literature see also Markandya and Chiabai (2009), Chiabai and Spadaro (2014). More details on the papers are provided in the excel matrix joined with this deliverable's contribution. The list of European projects which have addressed or are addressing health and climate change are reported in Table2 below.

Table 24 Projects related to health

Acronym	Project name	Sector	Funding	Website
cCASHh	Climate change and adaptation strategies for human health in Europe	Health	FP5	http://ec.europa.eu/research/environment/pdf/env_health_projects/climate_change/cl-ccashh.pdf
ClimateCost	The full cost of climate change	Many, including health	FP7	http://www.climatecost.cc/
Climate-TRAP	Training, adaptation, preparedness of the health care system to climate change	Health	EAHC	http://www.climatetrap.eu/
ClimSAVE	Climate change integrated assessment methodology for cross-sectoral adaptation and vulnerability in Europe	Water and floods (check if applicable for health)	FP7	http://www.climsave.eu/ climsave/index.html
EDEN	Emerging diseases in a changing European environment	Health	FP6	http://www.eden-fp6project.net/
EDENext	Biology and control of vector-borne infections in Europe	Health	FP7	http://www.edenext.eu/
EuroMOMO	The European mortality monitoring project	Health	DG SANCO	http://www.euromomo.eu/
PESETA	Projection of economic impacts of climate change in sectors of the European Union based on bottom-up analysis	Many, including health	JRC	http://peseta.jrc.ec.europa.eu/
PREEMPT	Policy relevant assessment of socio-economic effects of droughts and floods	Water	DG ECHO	http://www.feem-project.net/preempt/
Water2Adapt	Resilience enhancement and waterdem and management for climate change adaptation.	Water	IWRM-net funding intiative	http://www.feem-project.net/water2adapt/index.html
FLOODsite	Integrated flood risk analysis	Water	FP6	http://www.floodsite.net/

	and management methodologies			
PHEWE	Assessment and prevention of acute health effects of weather conditions in Europe	Health	FP5	http://www.epiroma.it/phewe/

7.4.2 Health and economic impacts with no adaptation

The studies reviewed in this section report the costs and physical impacts of climate change in the absence of planned adaptation.

Watkiss and Hunt (2012) estimate health and economic impacts of climate change on coastal flooding consequences, food borne diseases and temperature related disease, in Europe. Their research has been conducted within the PESETA project. They build the assessment under two IPCC scenarios, A2 and B2 for the sub period 2011-2040 and 2071-2100. The CC-health relationship is based on epidemiological studies that relate temperature with disease (Baccini et al. 2008, Menne and Ebi 2006, Kovats et al. 2006) and on flood related studies (Bosello et al. 2011). The physical indicators of changes are mortality for temperature-related stresses and floods, hospital admissions and salmonella cases. For heat stresses, significant increases are expected in the period 2071-2100, while in the shorter term, 2011-2040, the impact will be much lower. An increase of 60,000-165,000 deaths per year is expected by 2080 due to heat waves, without adaptation and physiological acclimatization, while cold-related mortality would experience a larger decrease, of around 60,000-250,000 deaths by 2080, compensating the negative impacts on heat stresses. Flood-related events are expected to increase the number of deaths per year of about 650 in A1B scenario and 185 in E1 mitigation scenario, though coastal adaptation measures would lead to a smaller impact. As for mental health, a significant increase in the number of cases is expected in the high sea level rise scenario (A2) by 2071-2100, with 5 million additional cases of mental stresses per year. Finally for salmonella, an increase of 20,000 cases per year is expected by 2020, reaching 40,000 cases per year by 2080, while in the period 2071-2100 the projections of 50% additional cases would be due mainly to population changes.

The economic indicators used are the cost of treatment, the loss of productivity and the dis-utility experienced. They use the Value of Statistical Life (VSL) and the Value of a Life Year (VOLY) to value death and productivity indicators. The estimates vary for each disease with the climate scenario, the human acclimatization to CC and the time horizon. Then, for the larger time horizon, they estimate the cost of temperature-related impacts would vary between 0 and 177,870 million euros per year (VSL) and 0 to 76,322 million euros per year for VOLY index. For salmonellosis infections, the cost would vary from 69 million to 177 million euros. For flood related impacts, it varies from 0.2 million to 1,408 million euros.

Kovats et al. (2011) in the ClimateCost project provide estimations of health impacts and costs under the A1B and E1 IPCC scenarios, with and without human acclimatization, for Europe (EU27) at horizons 2020, 2050 and 2080. They focus on similar diseases as in Watkiss and Hunt (2012): heat wave, salmonellosis and flood related deaths. As regards heat stresses, under scenario A1B, 26,000 additional deaths per year are projected in the period 2011-2040, which will increase to 127,000 deaths per year in the period 2071-2100, with no adaptation. Under scenario E1 69,000 additional deaths per year are estimated by 2080. As for flood-related deaths, the projections show an increase of 130 deaths per year by 2050 and 650 by 2080 in scenario A1B, while in scenario E1 the increase would be of 100 deaths per year by 2050 and 185 by 2080. Finally for salmonellosis an increase of 7,000 cases per year by 2020, 13,000 by 2080, and 17,000 by 2080, in scenario A1B. While for the first outcomes figures are comparable to those estimated by Watkiss and Hunt (2012), the numbers for salmonella are considerably lower in the study of Kovats (2011).

They also use the VOLY and VSL indicators. For heat wave related they estimate the losses to vary between 829 million and 3,992 million euros under A1B and between 917 million and 2,202 million euros under E1 for VOLY index. For salmonellosis the costs would vary between 36 million and 88.8 million euros under A1B and between 44 and 56.4 million euros under E1. For flood related, it varies between 33.9 million and 720 million euros under A1B and between 31.4 million and 183 million euros under E1. Losses of productivity are estimated to vary between 76 and 743 million euros under A1B and between 111 and 145 million euros under E1.

Bambrick et al. (2008) estimate the impact of CC on health in Australia under 7 climatic scenarios: 3 unmitigated scenarios (A1FI emissions path + different temperature, rainfall distribution) and 4 mitigation scenarios (3 based on the 550ppm Co2 equivalent stabilization + different temperature, rainfall distribution and 1 based on the 450 ppm Co2 equivalent stabilization). The projections are at the horizon 2020, 2050, 2070 and 2100. They focus on temperature related disease, gastroenteritis and mosquito-borne disease (dengue). The climate-health relationship is estimated through functional forms with threshold relating temperature or humidity with physical impacts on health. The economic valuation is based on hospitalization cost, lost work day due to hospitalization and productivity indicators or life lost (Year of Life Lost YLL). The estimate thus varies with the scenario, the horizon, the city population in Australia for each disease. For gastroenteritis, the estimates varies from 41070 AUD to 906616 AUD.

Hunt (2008) investigates the impact of climate change on health in the UK in terms of heat and cold mortality and morbidity under four climate scenarios, drawing on the UKCIP02 work. This used the HADRM3 ensemble simulation for A2 emissions and applied scale factors to reflect different HADCM3 global temperatures for A1F1, B1 and B2. Four different UKCIP socioeconomic scenarios were also linked to appropriate climate change scenarios – world markets for A1F1, national enterprise for A2, global sustainability for B1 and local stewardship for B2. In terms of valuation, estimates of £15,000 for a life-year and £1.2million for a fatality were used, based on UK policy appraisal guidance at that time. The health costs for summer mortality identified were valued at <£1 million per year in the 2020s (irrespective of scenario), rising to £2million (L, M-L, M-H) or £3million (H) in the 2050s. By the 2080s the costs vary more, with estimates of £3million (L, M-L), £4million (M-H) or £8 million (H). For reduced winter deaths, the benefits range from £4million (L, M-H) in the 2020s to a maximum of £15 million in the 2080s (H).

Alberini and Chiabai (2006) use a contingent valuation approach to estimate the value placed on health risks of heat waves and air pollution for the case of Italy. They find that the monetized mortality damages of excess mortality associated with heat in the absence of adaptation are €193million for the city of Rome alone in 2020 (2004 prices).

In addition, the study of Rosenzweig et al (2011) reports on climate change impacts for the New York State, where different sectors are analysed among which the public health. The study is discussed here as it may provide an interesting comparison with similar studies for Europe. A number of climate models (ClimAID) are run under A2 and B1 scenarios to assess temperature-related mortality from 2010 to 2100 in New York County. The results show that the increment in heat mortality will offset the cold-related mortality and that a net increase will be expected as a result of the temperature increase. The costs associated with heat waves in the USA over the past 30 years have been calculated to range from 1.3 billion $ to 48.4 billion $. As regards health impacts related to ozone exposure, the models project a 7.6% increase in 2050 (relative to 1990) under scenario B2 and 4.6% increase under scenario A2.

D'Ippoliti et al (2010) estimated the health impacts of heat waves on the elderly differentiating by gender, cause and age, using a single definition of heat waves to be applied in different European cities and Generalized Estimating Equations models. Two main European regions are considered taking into account geographical and climatological criteria, the Mediterranean region (Athens, Barcelona, Milan, Rome and Valencia) and North-Continental region (Budapest, London, Munich and Paris). Impacts for the period 1990-2002 and 2004, except year 2003 which has been analyzed separately, show an increase in mortality during heat waves ranging from 7.6% in Munich to 33.6% in Milan, with the highest increment recorded for respiratory diseases and among women of 75-84 years.

Table 25 summarizes the main impacts of climate change on health expected in Europe, based on the findings of the literature.

Table 25 Health impacts related to climate change in Europe

Health impacts	Description	Geographical distribution
Heat stresses	Heat waves are projected to become more frequent and more intense over the 21st century. Small increase in heat stresses in 2011-2040 to significant increase in 2071-2100.	Most affected Mediterranean and Southern Europe and Central-Eastern countries.
Cold stresses	Small decrease in cold stresses in 2011-2040 to significant decrease in 2071-2100. Decrease in cold stresses expected to compensate the increase in heat stresses in Europe.	Most affected Northern Europe.
Air pollution and ozone related mortality and disease	Quantification of future ground-level ozone is uncertain due to complexity. Synergistic effects between high temperature and air pollution (PM10 and ozone) observed during hot weather.	Increased average summer ozone concentrations in Southern Europe and decreased levels in northern Europe and Alps.

Flood-related deaths and injuries	Significant increase of deaths and injuries by 2080, though reductions with coastal adaptation.	Most affected northern Mediterranean, and northern and western Europe. According to ClimateCost 2/3 of projected deaths expected in Western Europe.
Mental stresses	Flooding associated with increased rate of anxiety and depression. Significant increase in number of cases by 2100, though important reductions with adaptation. The persistence of the health impacts is directly related to the intensity of the flood.	Most affected northern Mediterranean, and northern and western Europe.
Vector-borne diseases		
Mosquito-borne diseases	The Asian tiger mosquito important vector in EU, transmitting dengue and chikungunya. Climate-related increase in population of this mosquito could lead to a small increase of dengue in Europe, but further modelling is required. Risk of chikungunya may increase. Malaria vectors present in Europe, few cases of local transmission occur annually in travellers. Re-establishment of malaria in Europe not expected, also due to appropriate public health care.	Not endemic in Europe. Climatic suitability for Asian tiger mosquito projected to increase in central and western Europe and to decrease in southern Europe.
Hantavirus	Unclear the risk under climate change, but not considered high.	Higher risk in northern and central Europe and decreased risk in southern Europe.
Leishmaniasis	Projected to slightly increase, expansion constrained however by the limited migration of sand-flies. The distribution of the vector could extend to higher altitudes. In places where the climate will be too hot and dry the disease might disappear.	Central Europe might become more suitable for the vector, while the risk of transmission may decrease in southern Europe. Cases reported from Albania, Bosnia and Herzegovina, Bulgaria, Croatia, France, Greece, Hungary, Italy, Malta, Monaco, Portugal, Romania, Spain and Serbia and Montenegro.
Lyme borreliosis	Lyme could increase slightly with climate change and human behaviour for increased contact with ticks in leisure time.	Endemic in Europe. Highest incidence in central Europe.

Tick-borne encephalitis	Endemic areas could extend to higher altitudes and latitudes with climate change.	Endemic in Europe, mostly common in Northern and Central countries.
Water and food-borne diseases		
Salmonellosis	Floods and heavy rainfall may disrupt water treatment and sewage systems and contribute therefore to increase exposure to salmonellosis.	Largest increase in UK, France, Switzerland and Baltic countries.
Campylobacter	Use of rainwater might increase during droughts and campylobacter in untreated run-off water might contribute to increase the disease in animals and humans.	Northern Europe more exposed with the projected increase in heavy rainfall and risk of groundwater contamination (rural areas more prone).
Cryptosporium	Increase in rainfall (and preceding dry weather) is predicted to increase cryptosporidiosis, due to infiltration of drinking water reservoirs from springs and lakes.	–
Norovirus	Heavy rainfall and floods might cause wastewater overflow with risk of contamination of shellfish farming, and increased risk of norovirus infections.	–
Vibrio	The infection is linked with the increase of summer water temperatures and extended summer seasons, but the disease is projected to increase only modestly due to the current low incidence.	Baltic sea.

Source: results from PESETA (Watkiss and Hunt, 2012, Watkiss et al., 2009); ClimateCost (Kovats et al., 2011); cCASHh projects (Menne and Ebi, 2006, EEA, 2012a)

Finally, the health impacts are also sensitive to the Climate model used for projection. Aström et al. 2013, studies the impacts of climate change on respiratory hospital admission (RHA) under scenario A1B and A2 and for 4 different climate models: CCSM3, ECHAM4, ECHAM5, HadCM3. The Climate-health relationship is derived from the PHEWE project (Michelozzi et al. 2007), the respiratory hospitalization admission depends on the population exposed, the RHA per capita, the relative risk and, air temperature and dew point temperature. Results shows an average increase of 0.21% in RHA due to heat from the baseline (1981-2000) to the period 2021-2050. In the future 0.4% of the RHA was estimated to be due to heat, (0.18% in the baseline period) for EU27. Within EU, they evaluate places where the increase of risk would be greater. Mediterranean countries are found to be those whose risk will increase the more (compared to their current situation). In addition, their results show large estimate differences among the 4 climate models. In extreme cases, RHA estimates under A2 scenario (high emissions) are even smaller than under A1B (middle of the road scenario), which seems to be contradictory to the expected forecast of temperature increase by IPCC: temperature would be higher under A2 than under A1B. Regional climate modeling (downscaling, upscaling) has therefore significant impact on projections.

Bosello et al. (2006) depart deeply from the literature using a Computable General Equilibrium (CGE) model (GTAP-EF) in order to estimate the impacts of climate change on health. They focus on 6 diseases: malaria, schistosomiasis, dengue fever, diarrhea, respiratory disease and cardiovascular disease. They project climate change in 2010, 2030 and 2050 and use the baseline of 1997. For 2050, the scenario is a 1.03ºC increase in temperature. They use a linear relationship between per capita income and diseases from Tol and Heinzow (2003) to predict heath impacts. They consider the direct effect of climate on health via mortality and morbidity due to the 6 diseases but also labor productivity changes and health cares.

CGE models are models used to analyse the direct and indirect effects of a shock in the sectors of the economy. The effect are estimated in GDP variation compared to a baseline. Results reveals a decrease of morbidity and mortality at the horizon 2050 and imply less costs in health cares, more labour productivity, GDP and household welfare(see Ackerman and Stanton (2008) for a comment on Bosello et al. (2006) and Bosello et al. (2008) for a reply.)

7.4.3 Costs of health measures

Most of the existing studies focus on the physical and economic impacts of climate change on health, while there is very limited information about the costs of adaptation. Some estimates exist on heat warning systems but only for specific locations (and very difficult to be up-scaled or re-calculated at a larger scale) (Ebi et al., 2004), while changes in infrastructures are more expensive and quite complex to estimate. There is therefore a strong and urgent need to fill this research gap.

Ebi (2008)monetized the adaptation costs related to malnutrition, malaria and diarrheal diseases for 3 climate scenarios: unmitigated emissions IS92, stabilization of emissions at 750ppm CO2 equivalent (S750) and stabilization of emissions at 550ppm of CO2 equivalent (S550). She used the climate-health relationship developed by McMichael (2004) who estimates the change in relative risk for these diseases under the IS92, S750 and S500 climate scenario at horizon 2030. The physical impacts are measured with 2 population health indicators: the disability Adjusted Life Year (DALY) and the mortality. In order to isolate the CC effect from social effect of contamination, she keeps constant the yearly number of affected cases based on historical data from the Global Burden of Disease of the WHO and estimates the cost of annual increase in affected cases. Adaptation measures are assessed using the cost of some preventive measures as well as interventions to treat the diseases. The total costs estimates vary for each disease with the CC scenarios, the time horizon and the relative risk and the localization (3 categories for Europe according to mortality indexes for child and adult). For Europe, the impact of CC on diarrheal disease is estimated to vary between 12 and 206 millions of euros in 2030. The mitigation scenarios of IPCC do not always result in a significant decrease of affected cases compared to less developed areas. Therefore some thresholds of social development related to hygiene might exist and reduce the propagation of the disease (virus, bacteria). Intuition would then say that adaptation policies (promoting hygiene) would be preferred to mitigation policies for developed countries.

Other studies are outside the climate change contexts, but they can provide useful information on costs of health intervention.

Hutton and Haler (2004) propose a CBA of policy intervention programs to improve access to safe water and sanitation, i.e. to reduce exposure to water borne and water washed diseases like infectious diarrhea (cholera, salmonellosis, intestinal infections, etc). Their study is outside the context of climate change, as they assess the cost of improving water and sanitation programs in order to achieve the targets stated in the MDG for 2015, and not the cost of adaptation. They do not project costs under climate change risks. Nevertheless, they provide useful information on the unit cost of interventions which are the same, whether are they used in a climate change context or not.

They analyse 5 different grades of policy intervention to reduce exposure. The grades vary with the water and sanitation services offered and with the population targeted. They use the DALYs physical indexes (cases and death avoided). The economic benefits of the intervention are classified as: direct benefits (avoided expenditure of treatment), indirect benefits (loss of productivity) and non-health benefits (opportunity cost or dis-utility related like time to collect water). The economic benefits is the sum of the health sector avoided costs of treatment, the patient expenses, value of death avoided, value of time savings, value of productive days, value of days of school attendance, value of child days gained.

For Europe (regions EUR-A, EUR-B1, EUR-B2, EUR-D) the targeted population would vary between 24 million and 508 millions of people according to the grade of intervention, and the total annual cost would range from a minimum of 77 (with 1% of avoided cases) to 9,464 million dollars (with 49% of avoided cases). The number of cases avoided would vary between 112,000 and 27.9 million. More specifically clean drinking water and improved sanitation (program 4) would avoid more than 19 million of infections and with a better sewerage systems the avoided cases would be around 27 million for respectively an annual cost of 226 million of dollars and 4.2 billion of dollars. The total benefits of the five intervention programs would vary between 46 million and 5.3 billion of dollars. Cost-benefit ratio for the five programs is greater than one which indicates that such intervention programs can be economically justified.

In terms of more regional or national estimates it is important to make use of these where possible, as we realize the information base on the topic of adaptation costing is not extensive. Such estimates will need to be carefully assessed as to their transferability to the European regions or other world regions.

Desjeux, Galoisy-Guibal and Colin (2005) conduct a cost-benefit analysis of the vaccination of French troops in the Balkans against Tick-Borne Encephalitis. The cost-benefit analysis was based on costs of vaccination compared to costs for the treatment of TBE, including rehabilitation, compensation costs for disability and death, and lost productivity. The midpoint compensation costs range from €60,000 to €0.72 million (range €2,000 to €1,190,000) – which are lower than the VSL. There is also no accounting for pain and suffering. The overall net benefit was -€5.68 million.

This study is reported as part of the literature review as it addresses interventions for climate-related diseases. Vaccination, as well as other many other health interventions, has benefits outside the climate change context as well. This issue is related to programs with multiple benefits, which is discussed in the next section.In our model, in principle we will not take vaccination into account. Data inputs which will be used for AD-WITCH model are the costs of interventions and a measure of the cost-effectiveness ratio. Benefits are not taken into account.

The Euroheat project identified a number of measures that can be taken to reduce the impact of heat stress and heat related mortality. These include a range of actions that may be taken autonomously (e.g. taking a shower, using air conditioning), drug interventions and heat warning systems. Costs were collected for different heat warning systems, as shown in Table 22. Cost-benefit analysis was not conducted, though the study suggests this would be "interesting" (WHO, 2009).

Table 26 Costs of Heat Warning systems

Location	Cost	Notes
France	€0.14 per protected person	Those protected considered to be those less than 1 and older than 75
Catalonia	€9.2 per vulnerable person	€923k for public health element of heat-health action plan, €3.4 million for additional medical personnel, €3mn for Dept of Welfare
England	€215k for printing information materials	No additional costs estimated

Source: WHO, 2009

Ebi et al. (2004) estimate the number of life saved and the economic benefit of a heat watch and warming system based on historical data, in Philadelphia. They estimate that the warming system saved during 1995-1998 an average of 2.6 life per day of heat. Only the elder vulnerable population is considered, ie the more than 65 years old. They show that warning system are relatively costless compared to the value of a life saved. Using a VSL between $4 million and $6.12 million (varies with age structure, VSL falls with age according to Krupnick et al. 2000), they show that the warning system produced a net benefit of $468 million over this 3 year period (for the cost they used the direct cost of medical wages of emergency services). They also moderate their findings with the mortality displacement effect. This occurs when death are brought forward in time because of the heat, i.e. when an individual dies during a heat while he would have died anyway in the few days after the heat. This reveals that a discussion is required to isolate the climatic effect from other effects like vulnerability of people.

For salmonellosis, The WHO uses a classification for control measures, as follows:

- Pre-harvest – control in the food producing animal (eg vaccination, hygiene conditions, clean food stuff etc)
- Harvest – hygiene improvement during slaughter (eg of the slaughter-house and cutting rooms, decontamination of carcasses etc)
- Post-harvest – food preparation (eg hygiene in food services operation – guidance and enforcement, guidance and education for consumers

It should be noted that, to some extent, control measures would be needed in the absence of climate change. However, climate change will impact on the extent of possible damages and potential benefits of actions.

An overview of costs of different options to reduce salmonella is given in Table 27. As can be seen from the table, cost-benefit analysis of options to date, with adjustments for climate change and socioeconomic scenarios, largely suggests that pre-harvest control options are not optimal policies.

Table 27 Adaptation Costing in Context of Salmonellosis

Adaptation option	Study/Measure	Cost estimates	Avoided Damage Costs	Notes
Public Health campaigns	UK Foodborne Disease Strategy 2001	£5.5 million over a five year period to a publicity campaign directed at the general public.	No specific cost-benefit analysis of such campaigns has been conducted.	Public health campaigns often assumed to be low cost options yielding high benefits. Original measures not specifically for adaptation purposes.
Improving standards of biosecurity, cleaning and disinfection and rodent control in poultry	Interventions in parent breeders (stags and hens), in pre-breeders (replacement breeding stock) and in the commercial growing stock for turkeys (VLA, 2009)	Costs range from €28.2 million to €31 million (Taylor, undated)	Avoided damages depending on climate scenario of €1 million to €25.38 million. If underreporting taken into account, this could increase values significantly. (Taylor, undated)	Original measures not specifically for adaptation purposes
Measures to reduce salmonella in slaughter pigs	This costs a range of interventions, ranging from increased sampling and the creation of a support unit to significant improvements in slaughterhouses and transport (FCC Consortium, 2010).	Different scenarios presented, ranging from Establishment of a support unit and some increased sampling (€287 million) to clean replacement pigs or food control measures, plus transport measures (£1458 million)	Under climate change scenario A2, only one option passes cost-benefit analysis – that of one variant of the cheapest option. This only has a benefit-cost ratio of 1.25 (Taylor,undated)	Original measures not specifically for adaptation purposes

7.5 Discussion on the existing literature

The review reveals a number of critical uncertainties and research issues which need to be addressed when building a marginal cost curve of adaptation for health. As a first issue, we highlight the importance to delineate the difference between costs of impacts (or costs of inaction) and costs of adaptation. As a matter of fact, treatment costs can fall into one category or the other depending on how we consider them. The issue is relevant and no choice has been done till now, as this will be part of the next steps to feed the model with appropriate inputs.

Secondly, the studies reviewed on adaptation show a limited coverage, both geographically and per health outcome. More studies are needed in this context, covering different health outcomes and countries, and possibly following a protocol in order to be able to construct an adequate database of studies, from which to draw information on impacts and adaptation costs. Available studies focus mainly on the costs of adaptation, with less or no information on the benefit side (see Watkiss, 2012), so that it is important in general to expand the focus of the review and include studies costing the health interventions outside the climate change context, as well as information on cost-effectiveness of health measures. The issue of their transferability to a climate change context is assessed taking into account the estimation of additional risks under climate change, while the unit costs provide useful information as they are usuallyindependent of the context.

Third, when addressing the cost-effectiveness of measures, there is the issue of the indicator to be used to compare different interventions and their effectiveness, if a cost per avoided death, or a cost per case or DALY/QALY. The latter have the advantage to incorporate both measures of mortality and morbidity. Regardless, the existing studies use different indicators and are therefore difficult to compare, though a choice must be made in building the framework for the marginal adaptation cost curve.

Co-benefits within cross-sectoral adaptation measures should be another important factor to consider. Cost effectiveness analysis might play a role but the main issue relates to the use of a common metrics for benefits coming from different areas (health and non-health). Cost-benefit analysis, on the other side, would have the advantage of using one common metrics for all the benefits. Multicriteria analysis, finally, could be a further option when local stakeholders are involved.

Lastly, we have to mention the substantial uncertainty surrounding estimation of the health impacts and costs of adaptationin the current literature. Sources of uncertainty tend to amplify each other, but sensitivity analyses should be the minimum request so that results could inform policy decision making.

7.6 Conclusions and next steps

Taking into account the findings of the literature review, the assessment of the marginal adaptation cost curve will be based on a number of decisions addressing the main critical issues discussed above, as well as choices regarding key health outcomes to consider in Europe, specific adaptation options, measurement of unit costs and assumptions on population coverage. The main choices are discussed here below together with the key steps under development.

Final selection of key health outcomes for Europe based on the results of the literature review

The health outcomes which will be selected for the assessment at European level include heat stresses, deaths, injuries and mental health related to extreme weather events (flooding), water-borne diseases (diarrhea), food-borne diseases (salmonella), and tick-borne diseases, which represent the main impacts for Europe (see also Table 21).

Identification of health risks inquantitative terms

Additional risks estimated in the literature (as reported in the present deliverable) will be translated into burden of disease under different climate change, population and economic growth scenarios, and for different geographical categorizations in Europe (Northern, Southern, Eastern and Western). For this purpose, we will use information on the current incidence of diseases, the increased risk of occurrence due to climate change and the growth rate of population and income by country.

Identification of adaptation options

Adaptation options will be selected taking into account availability of data on unit costs. The appropriate classification will be used, preventive and reactive, if curative care is considered as adaptation, or just prevention on the opposite case.

The allocation of costs will be done independently from the source of expenses. This means that the selected measures will include those financed by the health sector, as well as those outside the public health when providing mainly health benefits (e.g. water and sanitation systems).As stated by Hutton (2000), "*the Ministry of Health is unlikely to consider the costs and benefits arising to other agents or ministries, despite the importance of these costs and benefits arising from many environmental health interventions*". From an economic point of view, interventions providing important health impacts should be included in the costs assessment even if funded by other Ministries (Markandya and Chiabai, 2008).

Differentiating cost of adaptation and residual damage

A decision will be taken on how consider treatment cost, if to follow the scientific approach in the literature or the most pragmatic one.

Identification of unit costs in terms of cost-effectiveness

For preventive measures a cost per avoided cases will be used as a first step, and possible conversion into a cost per DALY will be also explored. The evaluation of reactive measures (if it will be considered as adaptation) will be based directly on a cost per avoided DALY or QALY. This would allow us to consider both mortality and morbidity rates within one unit of measurement.

Assumptions about coverage of population and portfolio of options in public health

Specific assumptions will be made about the coverage of population for preventive and reactive measures: high, medium and high coverage, for example 25%, 50%, 80% and 100%, with different proportions for prevention and reaction. Final decision will be taken based on WHO guidelines and/or consultation with stakeholders. Considering different levels of coverage we will be able to find out also to analyze trade-offs between preventive and reactive adaptation.

Estimation of total annual adaptation costs per health outcome

Adaptation will be defined as “additional adaptation” including all the measures which are additional to those already existing in a baseline scenario. Preventive measures aim at reducing the additional risk of occurrence of disease due to climate change (avoiding the impact), while reactive adaptation is used to reduce the residual health impacts, which cannot be completely avoided.

If both preventive and reactive measures are considered, the following two-step approach will be used to assess the total cost of adaptation in the health context for a specific year. We first estimate the cost of a set of preventive measures in vulnerable areas to protect additional population at risk following different levels of coverage as discussed in the previous point. In as second step, the residual impact will be calculated taking into account that the proposed preventive measures will bring a reduction of the impact based on the cost-effectiveness of each measure considered. A set of reactive measures based on treatments will be selected to cure the residual number of cases expected. Total preventive costs will be estimated by multiplying the unit costs by the population expected at risk, while total reactive costs will be assessed by multiplying the unit costs by the residual number of cases expected after prevention has been put in place. Different levels or degrees of adaptation will be considered for both preventive and reactive measures, in terms of different coverage of the population.

Table 28 reports the health outcomes which will be explored as a preliminary step in estimating the marginal cost curve, their geographical coverage, initial set of selected adaptation measures and definition of unit costs.

Table 28 Health outcomes selected, geographical coverage and adaptation options.

Health outcome	Geographical coverage	Adaptation measures	Portfolio of adaptation measures
Heat stresses	Selected number of European cities	Primary, secondary and tertiary	Heat warning systems Medical treatment and hospitalization
Deaths and injuries due to flooding		Secondary	Alert warning system (*) Surveillance
		Tertiary	Evacuation plans First aid and medical treatment
Water-borne diseases (diarrhea)		Primary	Water and sanitation programs(**)
		Secondary	Surveillance
		Tertiary	Medical treatment
Food-borne diseases (salmonella)		Secondary	Surveillance
		Tertiary	Medical treatment
Tick-borne diseases		Secondary	Surveillance
		Tertiary	Medical treatment

(*) We do not include structural measures in the preventive adaptation, as these are providing mainly material benefits.

(**) Water and sanitation programs are planned outside the public health but they provide mainly health benefits

In conclusion, within BASE, the work on the health sector will contribute to improve the knowledge on the shape of the marginal adaptation cost curve for health within the AD-WITCH model.The improved knowledge will be based on the input data provided to run the model. These data will be provided in terms of annual cost of adaptation for selected health outcomes, and for different points in time and different increase in temperature, as well as in terms of cost-effectiveness of measures. The analysis will probably lead to a window of optimal adaptation levels depending on the climate scenario and adaptation measures considered.

8 Wider economic impacts of adaptation in urban areas

Dabo Guan

8.1 Introduction

Some recent large-scale disasters such as the 2003 heat wave that struck Paris and other European cities, hurricane Katrina in New Orleans US in 2005, 2012 flooding in Germany shows the urgency of understanding and then preparing for such hazards, including their impacts and effects to the regional economy and other connected economic bodies. Research indicates that economic losses caused by such events have been on the rise in the last few decades (Munich Re, 2001). Especially, along with the growth of population and assets, the metropolitan areas become particular concentrations of vulnerability to such disasters. Adaptation of the climate extremes can provide benefits of damage avoid in event impact regions but also production supply chain protection which can benefit further damage in other regions or sectors.

Economic analysis of disasters is based on the distinction between so-called ‘direct’ and ‘indirect’ costs or damages. The costs associated with damages to factories, houses and other buildings, infrastructure, etc., are known as direct costs. They are often highly visible, basically being a ‘stock’ variable. However, there also is a second type of costs which are a consequence of the highly interdependent production structures of modern economies. Interdependency means that if part of the structure is incapacitated, this will also affect other parts of the economy, and even may spill over into areas other than the one under consideration. These phenomena thereby cause indirect costs, which, in contrast to the damages to buildings, etc., have a ‘flow’ character. Indirect costs are, in general, less visible than the direct costs; they consist of business interruption, production losses during reconstruction and service losses in the housing sector. Together, the direct and indirect costs make up total costs.

Among the modelling, a number of well-known methodologies including Computable General Equilibrium (CGE), Econometrics and Input-Output (IO) Analysis are frequently used. However, no distinct advantages of any are seen. For example, CGE is considered to be overly optimistic on market flexibility and overall substitution tendencies (Rose, 1995), while IO analysis doesn’t take into account productive capacity and producer and consumer behaviours, and therefore loses much flexibility for the economic modelling (Hallegatte, 2008). Econometric models are more prevalent at national level, while IO models are the major tools of regional impact analysis (Richardson, 1985). Moreover, econometric models which are based on time-series data that may not include any major disasters, appear ill-suited for disaster impact analysis (Okuyama, 2009) and cannot easily distinguish between direct and indirect effects (Rose, 2004). On the other side, econometric models are statistically rigorous, which can provide stochastic estimates and have forecasting capabilities. IO analysis is grounded in the technological relations of production and provides a full accounting for all inputs into production (Rose, 1995), which is in contrast to some large econometric models expressing quantities only in terms of primary factors of production. Meanwhile, IO analysis is a powerful tool to assess the economic effect of a natural catastrophe at a regional and sectoral level through intermediate consumption and demand. Although IO analysis is mainly a model of production, it's fully capable of analyzing households and other institutions (Batey and Rose, 1990). Moreover, its simplicity and integration ability with engineering models and data add its popularity.

Literature (e.g., Okuyama, 2009; Tsuchiya et al., 2007; Rose and Liao, 2005; Rose, 2004; Cochrane, 2004; Green, 2003; Haimes and Jiang, 2001; Brookshire et al., 1997; Cole, 1993) seems to suggest that there is no generally accepted formula for the representation of a post-disaster economy development, and no general way in which economic agents will adjust and an imbalance economy will change. Steenge and Bočkarjova (2004, 2007) suggest a basic equation by designing a closed IO table integrating with a so-called Event Accounting Matrix (Cole et al., 1993). They assume that the economy recovery of a post-disaster will have two steps to restore pre-disaster conditions: the first is to reach 'as fast as possible' the targeted output proportions and the second is to bring the economy back to the pre-disaster scale of operation. However statistics have demonstrated that the imbalance may persist during a post-disaster period and economic agents have to adapt themselves in a very dynamic manner. Hallegatte (2008) applies the IO analysis to the landfall of Katrina in Louisiana by taking into account changes in production capacity due to productive losses and adaptive behavior in disaster aftermaths. However the impact of housing destruction and labour constraint on production capacity is neglected, which may essentially influence the recovery process; and the paper also implies the assumption of two-step recovery process of Steenge. Meantime, rarely are studies found on the influence of hypothetical future shocks to a regional economy, which is vital for decision planning.

In BASE, we develop a regional adaptive input-output model (ARIO) to estimate the total economic impact of preventing any climate event (e.g. flooding) along the production supply chains.

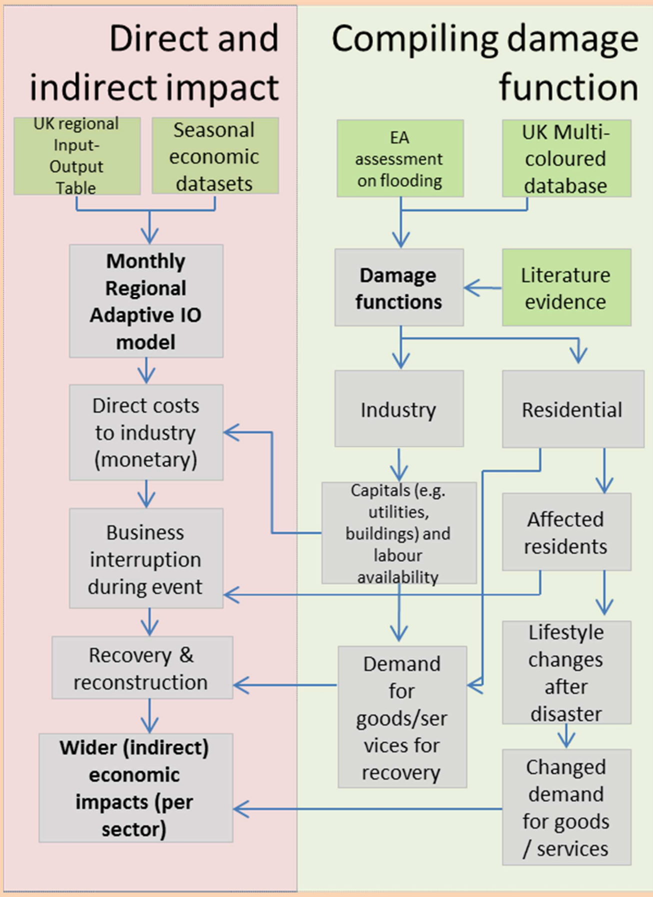
8.2 ARIO model development

8.2.1 General modelling framework

In order to estimate the total (direct + indirect) economic impact induced by an event, there are two steps. Firstly, event damage functions are required. These functions measure the economic cost or damage per area (following a disaster) as a function of the intensity of the disaster. Here 'intensity' can be measured in several different ways. For example, a bigger flood may translate into a larger surface area of a city being inundated, or the water surface reaching a higher level. If available, damage functions provide a representative estimate of the costs or damage inflicted by catastrophes of varying intensity on e.g. public buildings, factories or houses However, the methodologies based on these functions are still somewhat preliminary. Secondly, those damage functions will be integrated into the macroeconomic analysis framework (e.g. IO model). Such action would link different spatial dimensions from impacted region at local scale to the city / regional / international scale levels.

Here we show an example of compiling and interlink the damage function to study direct and indirect economic impact of a UK national flooding event (e.g. 2007 floods).

The key dataset for compiling the damage functions are from the Environmental Agency (EA) reports on 2007 flooding (e.g. report entitled by "cost of 2007 floods"); the EA funded handbook of "The benefits of flood and coastal risk management – A handbook of assessment techniques" (so-called Multi-coloured manual); and evidence from the literature.



The damage function would have three outputs:

- Industry capital loss – including infrastructure damage, building and production capital loss.
- Labour productivity and availability during and after the event.
- Residential capital loss – including houses and household appliances.
- Affected population – death and hospital visits and admission.

In order to estimate the direct and indirect impact to wider economic systems, a monthly regional adaptive input-output model is constructed. The data required are the UK regional input-output model and seasonal national / regional accounts data.

The outputs from the damage function will feed into the regional input-output model to estimate the direct economic costs in 40+ production sector details, business interruptions due to capital and labour loss, and finally the cascading effects via economic supply chains to the disaster region and beyond (e.g. national or EU scale).

8.2.2 Modelling processes

We use a regional adaptive input-output model following the approach developed by Hallegatte (2008) and Li et al. (2013). ARIO model is capable of assessing the impact of a natural disaster on the level of a regional economy, accounting for interactions between industries through demand and supply of intermediate consumption goods with a circular flow – a set of inputs which should match, given certain restrictions, with a set of outputs that subsequently becomes a set of inputs in the next round. No prior economic balance will be assumed during the period of recovery in the model.

Assume a regional economy consisting of *n* industries that exchange intermediate consumption goods and services in order to sustain the production processes, and final demand categories that include final consumption goods and services for local household, government, fixed investment and export. It is struck by a natural disaster, which damages household physical assets, industrial capitals and stocks and the transportation system, thereby affecting people travelling.

The ARIO model is derived from a standard input-output model that reflects a detailed flow of goods and services between producers and consumers. All economic activities are assigned to production and consumption sectors. An economy with *n* sectors in pre-disaster condition can be presented in the following standard input-output relationship:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f} \qquad (1)$$

where vector **x** represents sectoral production output, vector **f** represents final demand and **A** is a matrix of technical coefficients, of which a coefficient a_{ij} refers to the amount of input from a sector *i* required by a sector *j* for each unit of output.

A standard input-output model is a solely demand-driven open model. While the post-disaster economy condition is analyzed, the limitations in supplies become important constraints for production capacity. On the other hand, Leontief closed models allow for tracking the supply and demand of each individual good and those that are considered as primary inputs such as labour in an open model. Let us introduce a labour constraint to equation 1:

$$\begin{bmatrix} \mathbf{A} & \mathbf{f}/l \\ \mathbf{l}' & 0 \end{bmatrix} \begin{pmatrix} \mathbf{x} \\ l \end{pmatrix} = \begin{pmatrix} \mathbf{x} \\ l \end{pmatrix} \qquad (2)$$

or

$$\mathbf{M}\mathbf{q} = \mathbf{q}, \text{ where } \mathbf{M} = \begin{bmatrix} \mathbf{A} & \mathbf{f}/l \\ \mathbf{l}' & 0 \end{bmatrix} \text{ and } \mathbf{q} = \begin{pmatrix} \mathbf{x} \\ l \end{pmatrix} \qquad (3)$$

with

- $l = \mathbf{l}'\mathbf{x}$ (4)

where *l* is a scalar of total regional employment, while $\mathbf{l}'$ is a row vector of direct labour input coefficients. Equations 2-4 describe an economy in equilibrium with a closed Leontief model, which is the so-called 'basic equation'. The left-hand side of equation 3 stands for the totality of inputs, and the right-hand side for the totality of outputs.

Let's introduce time dynamics and a damage fraction (i.e., Event Accounting Matrix) into the equations step by step, firstly:

$$\mathbf{x}_{td}^{t} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}^{t},\ (t > 0) \tag{5.1}$$

$$\text{or,}\quad \mathbf{x}_{td}^{t} \approx \mathbf{A}(\mathbf{I} - \mathbf{\Gamma}^{t})\mathbf{x}^{0} + \mathbf{f}^{t} \tag{5.2}$$

where in equation 5.1 $\mathbf{x}_{td}^{t}$ simulates the degraded total demand determined by final demand $\mathbf{f}^{t}$ over time, and *t* refers to a time step (we denote the pre-disaster time as *t=0*, and *t=1* as the first period right after the disaster); in equation 5.2, $\mathbf{x}_{td}^{t}$ is calculated based on the intermediate demand met by the current production capacity, and total final demand. However, the equation needs to be balanced between $\mathbf{A}(\mathbf{I} - \mathbf{\Gamma}^{t})\mathbf{x}^{0}$ and $\mathbf{f}^{t}$. In equations 5.1 and 5.2, **I** is an $n \times n$ identity matrix. The matrix **Γ** is the damage fraction matrix – an *n* dimension diagonal matrix which changes with time:

$$\mathbf{\Gamma}^{t} = \begin{pmatrix} \gamma_1^t & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \gamma_n^t \end{pmatrix} \tag{6}$$

Meantime, let us introduce dynamics into equation 4:

$$\mathbf{x}_{l}^{t} = \mathbf{l}_{e}^{t}\ ./\ \mathbf{l},\ \text{where}\ \mathbf{l}_{e}^{t} = (1 - \gamma_{n+1}^{t})\mathbf{l}_{e}^{0} \tag{7}$$

where $\mathbf{x}_{l}^{t}$ simulates the degraded labour production capacity, $\mathbf{l}_{e}^{t}$ represents the employment in sectors at the time *t*, and the parameter $\gamma_i^t (0 \le \gamma_i \le 1;\ 1di \le n+1)$ indicates the fraction of the production capacity lost in industry *i* $(1\ i \le n)$ as shown in equation 6 or labour $(i = n+1)$ at the time step *t* as shown in equation 7 (Here, we assume that the impact of employment by disaster on each sector is equally distributed). Equations 5 and 7 are constrained by the following equations at each time step,

$$\mathbf{x}_{tp}^{t} = (\mathbf{I} - \mathbf{\Gamma}^{t})\mathbf{x}^{0} \tag{8}$$

$$\mathbf{M}\mathbf{q}^{*(t)} = \mathbf{q}^{*(t)},\ \text{where}\ \mathbf{q}^{*(t)} = \begin{pmatrix} \mathbf{x}^{*(t)} \\ l^{*(t)} \end{pmatrix} \tag{9}$$

$$\mathbf{q}^{*(t)} = \begin{pmatrix} \mathbf{x}^{*(t)} \\ l^{*(t)} \end{pmatrix} \leftarrow \mathbf{q}^{(t)} = \begin{pmatrix} \mathbf{x}^{t}_{tp|td|l} \\ l^{t}_{tp|td|l} \end{pmatrix} \quad (10)$$

where $\mathbf{x}^t_{tp}$ simulates the degraded total production. Equation 9 refers to a balanced economy in a closed model, while the balance (i.e., $\mathbf{q}^{*(t)}$) can be calculated by equation 10 through $\mathbf{q}^{(t)}$. Here we use $\mathbf{q}^{*(t)}$ to represent a balanced total output and labour force, distinct from $\mathbf{q}^{(t)}$ which represents an imbalanced input-output condition. $\mathbf{x}^t_{tp|td|l}$ and $l^t_{tp|td|l}$ represent the balances of total output and labour are required between total production capacity, total demand and labour production capacity at time step *t*. As there are restraints during the recovery between these factors (for example, the labour production capacity may not meet or may exceed the capital production capacity), a balance is needed. There are many ways (represented by the label '$\leftarrow$' in equation 10) to adapt $\mathbf{q}^{(t)}$ to a balanced input-output condition.

From the equations shown above, there exist a few inequalities in the context at each time step. Let us consider a condition at time step *t* during the recovery. Then, the inequalities may be shown below,

$$\begin{cases} \mathbf{x}^t_{td} \neq \mathbf{x}^t_{tp} \\ \mathbf{x}^t_{td} \neq \mathbf{x}^t_{l} \\ \mathbf{x}^t_{tp} \neq \mathbf{x}^t_{l} \end{cases} \quad (11)$$

and,

$$\mathbf{M}\mathbf{q}^t_{deg} \neq \mathbf{q}^t_{deg} \quad (12)$$

where the $\mathbf{q}^t_{deg}$ represents the degraded total economic output and the labour force within a closed model at the time *t*. The condition holds unless $\mathbf{q}^t_{deg}$ is proportional to $\mathbf{q}^0$, which shows the case that the economy is shrinking proportionally. Even though the balance or proportion may occur at some time steps, the dynamic inequalities may still appear at subsequent time steps as total production capacity, final demand and labour capacity vary disproportionally. In practice, the economy only has a "tendency" during the recovery period to move back towards pre-disaster conditions.

Imports and exports during the disaster and recovery period are not only affected by the severity of a disaster, especially reflected in damage to the transportation infrastructure, but also affected by disaster aid policies and actions. The modeling of these two factors highly depends on the assumptions designed according to real disaster scenarios. In this framework, we study the case of Yorkshire that was stricken by a flooding in November of 2012. As a result, economic structure was disrupted, which was reflected in labour and production capacity losses, and final demand reductions.

In the modeling we assume that the labour recovery path (expressed as $\mathbf{l}_e^t$) is taken exogenously. The ARIO model simulates the total final consumption adaptation process (expressed as $\mathbf{f}^t$) based on the consideration of a long term tendency back to the pre-disaster economic condition and short term tendency to a balanced economy. Household consumption pattern changed during the disaster and subsequent recovery period, the household demand had a sudden drop, and increases gradually thereafter but not exceed the level of the pre-disaster condition. Immediately following the disaster, we assume that households switched their consumption pattern to more basic goods and services. We also introduce a distinction between sectors according to whether the substitution of local production by external providers is possible (e.g., one cannot substitute an external provider for electricity or local transportation).

The recovery process is modelled on a monthly basis with three steps at each time interval. Firstly, the labour loss is captured by the percentage of labour not available for travelling, the percentage of labour delayed for work because of transport damage and corresponding delay hours. The labour production capacity - $\mathbf{x}_l^t$ is calculated based on equation 7. The capital production capacity - $\mathbf{x}_{tp}^t$ recovery is captured by the damage demand through the local production. It corresponds to the dynamic equation 8. Then, the production capacity of labour and capital surviving are compared with the current total demand - $\mathbf{x}_{td}^t$ resulting from the final demand change to determine how much could be locally produced based on constraints between the three factors (reflected by equations 9 and 10). A rationing scheme (either a proportional rationing, or a priority system, or a mix of these) is applied to the intermediate consumption, and a new total production is calculated. Thirdly, if the three elements, i.e., new total production capacity, the total demand, labour production capacity and the pre-disaster total production are met, the economy recovers from the post-disaster conditions; otherwise a new total demand is calculated based on the new total final demand adjustment (corresponding to equation 5). Then the three steps repeat with a new time step and the labour and capital production capacity are re-calculated.

9 Modelling linkages

Ana Iglesias, Francesco Bosello

9.1 Top-down and bottom up integration

The models will be used to evaluate the needs for adaptation; this will be done in WP6 and will be described fully in WP6. This report only very briefly addresses the elements of adaptation that are considered in model development.

In order the fulfil its objectives WP3 proposes to apply different top-down and bottom-up integrated assessment modelling approaches to quantify costs and benefits of adaptation in specific domains – namely: water, agriculture, ecosystems, the urban context and health. Moreover, by adopting a holistic perspective, it investigates complementarily and trade-off between mitigation and adaptation.

Further, WP3 aims at improving existing quantitative tools for a more realistic description of adaptation dynamics.

The specific activities under WP3 are therefore to:

1. Critically evaluate modelling frameworks and contexts currently applied to adaptation;
2. Establish a consolidated quantitative top-down integrated assessment model which builds on previous work but makes some new developments;
3. Establish new developments in quantitative sectoral assessment models (water, agriculture, ecosystems; urban context and health) and their integration into the top-down integrated assessment models; and
4. Develop methodologies to deal with uncertainty and scaling. Uncertainty could be addressed through extensive sensitivity analysis (e.g. related to the scale of climatic impacts, social preferences, different assumptions on adaptation cost and benefits) or through the introduction of stochastic elements.

To guarantee comparability and the possibility to consistently integrate results, all the analyses above will be performed using a common reference climate change scenario. The choice of this common framework and the practical quantification of the associated climatic information (e.g. temperature and precipitation) is also one of the main tasks of WP3.

9.2 Modelling adaptation in the context of sustainability

The models developed in BASE will:

- Produce variables that can then be used to estimate costs and benefits. Some of the variables can then be used to produce monetary estimates. However, some costs and benefits are intangible effects on society and the environment.

- Need to have a common set of assumptions to enable the integration in the top-down model Ad-Witch also in WP3 and to analyse integrated adaptation pathways in WP6.

Here we summarise the main concepts included in the adaptation framework that guide the model development reported in this Deliverable D3.2. Complete adaptation framework information is included in D6.1.

The key analytical practice in modelling should be transparency about the used baseline. For practical purposes, no adaptation may be an easier baseline to use in the case studies. Business as usual baseline could include for example autonomous adaptation, which may be difficult to predict in specific case study settings.

Key elements of the adaptation pathway approach are:

- The use of critical thresholds called adaptation tipping points (ATP) allows to link climate impacts can be linked to (sectoral) policy goals.
- Consideration of a wide portfolio of options (measures/strategies/actions) for adaptation.
- Consideration of more than one climate and economic growth scenario.

Adaptation will take place in the context of sustainability. All models developed in BASE include some element of socio-economic or environmental sustainability. Therefore the role of the models is to ensure greater robustness of the economic assessments and thus ensure socio-economic and environmental sustainability.

The following elements are considered in the modelling framework:

Sustainability: Sustainability is explicitly considered in each model - i.e. how the model may represent some aspects of economy, ecology and society.

Risk: Might consider the spectrum from imminent disaster risk reduction to long term gradual adaptation and the format of the models how they support these different needs - i.e. model parameterization in terms of temporal and spatial scope - as needed for all models.

Uncertainty: The models are applied with the aim of contributing to reducing uncertainty in the estimation of damages from climate change and benefits from adaptation. The models will be applied in the context of scenarios to contribute to uncertainty evaluation. An important element of the research is that models are validated with the case studies and therefore include the knowledge from the stakeholders.

9.3 Linking models to research in the Case Studies

The sectoral models and the case studies are mutually supportive for developing adaptation pathways. There are two key points of interaction across scales:

- The models are applied and further developed and calibrated within one or more case studies.
- The case studies are and the models are interacting through a feed-back process that includes the following steps:

1. Inform the Case Study on the vulnerability and adaptation needs projected by models.
2. Validate model results with local participatory knowledge.
3. Propose adaptation strategies that could be evaluated with the models.

Data and information needs from case studies:

a. Agricultural systems: crops, technology, inputs, etc

b. Water infrastructure: reservoirs, irrigation, etc

c. Socio-demographic characterisation of the rural population

9.4 A summary of the case studies that will link to model implementation

A summary of the contribution of the case studies to the assessment of adaptation is found in Deliverable D4.1. Here we firefly summarise the case study aspect that will link to the quantification of the adaptation needs.

Denmark

The Danish case studies will contribute to model development evaluating barriers and opportunities to climate change adaptation, focusing on policy coherence/integration vertically and horizontally. Thus key questions concern the interaction between local climate adaptation responses and the strategies at local, regional, national and EU level and the use of knowledge in decision-making processes regarding climate adaptation among key actors at the local level. The Danish case study uses document analysis, in-depth interviews with key stakeholders and develops of a questionnaire to the farmers in the two municipalities – it is planned to have some similar questions to farmers in the Danish and the Czech case studies to make comparisons possible, and maybe in the Portuguese case too.

Czech Republic

The Czech case studies in Ústí Region and South Moravian region aims to investigate current and potential adaptation measures (with special focus on ecosystem-based approaches) and strategies in the agricultural (particularly hop growing, respectively wine growing regions) and water sector to deal with the changing climate. The case studies will investigate perceptions of local stakeholders as well as barriers and opportunities of adaptation policies. If possible, the case studies will try to investigate costs and benefits of adaptation measures, particularly related to drought and water availability. Semi-structured interviews with relevant stakeholders and questionnaire-based survey to the farmers (developed together with Danish Case Study) are planned.

Portugal

The Portuguese case study will analyse the adaptation to drought in the Alentejo region as a case study with several projects that are implementing measures for the adaptation to Droughts and Water Scarcity. The replication potential is high since the adaptation measures from farms, organic farms and Eco-Communities can potentially be adapted to and applied in all farms in the Alentejo and Mediterranean region. The case study will seek answers to questions (based on the Alentejo Region) like: How can the Mediterranean region best adapt in an integrated and sustainable way to extreme events such as droughts? How can food security be improved and food production made more resilient in the Mediterranean region? How is Climate Change perceived in the Alentejo region by the stakeholders that have intervention on the landscape? How can communication and decision processes on mitigation and adaptation for Agriculture and Forestry be developed to become more transparent and legitimate? The case study will provide qualitative data on adaptation measures to drought and quantitative and qualitative evaluation of the full costs and benefits of such adaptation measures. Methodologically, information based on questionnaires to farmers and relevant stakeholders will be gathered. The case study will also use participatory methods.

Tagus basin

The case study of the Tagus River Basin in Spain addresses adaptation from the water demand and supply point of view. Agriculture in the Tagus basin suffers the most adverse effects from water scarcity as it is by far the largest water consuming sector in the entire country and in the basin. As climate change impacts are expected to notably worsen conditions the adaptation of agriculture has recently received increased attention in the scientific and policy debate. However, the situation becomes more complicated when water needs for agricultural and natural systems exceed the total water availability and the attempt to satisfy the total agricultural water need is the main cause of natural protected areas having poor ecological conservation status. When this occurs the optimal provision of ecosystem services for both agricultural and natural systems cannot be reached separately and therefore it should be pursued for both systems as a whole rather than independently. The work in the Tagus basin relies on the assessment of adaptation strategies with the purpose of building resilience to water scarcity by combining modelling with the consultation of experts and principal stakeholders. Table 29 indicates some key research questions that will be addressed in the case study.

Table 29 Tagus basin Case Study

Research question in the Tagus case study	Main implications for building resilience to water scarcity
How do stakeholders perceive the need to adapt to an increased water scarcity?	Agreement on perceptions of water scarcity risks and choices for water allocation
What are the best adaptation options to ensure resilience to water scarcity?	Maximizing ecosystem services provision and other relevant socio-economic criteria

9.5 Information provided by the case studies

There are strong links from the agricultural, water, and urban case studies to BASE sectoral models as all case studies will be addressing some of these aspects.

9.5.1 Water in the Case Studies

In BASE the adaptation studies of water management are closely inter-linked with the agricultural and rural development studies, and include:

- Climate adaptation in the Tagus River Basin of Spain and Portugal, a transboundary case study that also incorporates urban areas and health.
- Climate adaptation responses to flooding problems in two Danish predominantly rural municipalities.
- Climate adaptation responses to drought and water availability problems in two regions of the Czech Republic. Water availability refers to an imbalance between supply and demand. If demand is too high, even in non-drought conditions there will be water availability problems. Maybe put the figure. Drought adaptation in the region of Alentejo in Portugal.

Water management is becoming increasingly complex in developing and developed countries. Water resources provide employment opportunities to rural population, support ecosystems and food production. However, water is an increasingly scarce resource in many regions. Water management include a large range of technical, economic and social factors. Rainfall (green water) is water in its natural condition and it is therefore highly exposed to natural variability. Water in rivers or storage in reservoirs (blue water) is also exposed to natural variability but can be managed. The debate on water for agriculture and water for nature is an environmental problem that has been in the centre of policy debates in and has generated media attention, often focusing on perceptions and personal values. Adding the climate change aspect, environmental beliefs become more complex and public opinion is further polarized (McCright and Dunlap, 2011, Dietz et al., 2007).

Climate change is only one of many pressures faced by water management today and in the future. However climate change is a very significant pressure since it has a direct impact on all aspects of water for people and ecosystems.

The challenges of climate change will have to be met through adaptation. Adaptation here is defined as the adoption of actions that have significant potential to reduce the impact itself or the influence of the driver on the impact. Understanding the adaptation strategies for water management as a whole requires a multi-dimensional analysis at the global level that requires information on: a measure of the potential impacts and a measure of the potential limits (social and physical) to adaptation.

Evaluating adaptation of the water resources sector to climate change is not an easy task, due to the broad range of objectives of water policy – from social choices for the allocation of water to technical alternatives. Society is becoming increasingly concerned about environment as population water needs continue to grow, and climate change imposes further limitations.

Water is increasingly becoming limiting factor for sustainable economic growth and development. Its allocation has significant impacts on overall economic efficiency, particularly with growing physical scarcity in certain regions. Greater water supply variability further increases vulnerability in affected regions. Water also has become a strategic resource involving conflicts among those who may be affected differently by various policies (Wechsung and Naumann, 2008).

Efforts to develop adaptation policies have been met with a lack of concrete local measures that are understood and supported by citizens. Even in areas of strong environmental commitments, the success of various policy proposals has been mixed, reflecting a perception that the public views adaptation to climate change as opposed to economic development.

Defining the adequate strategies requires multiple efforts from the understanding of impacts to the selection of alternatives that respond to local development priorities. As result there are many different methods for evaluating the needs for adaptation. Modelling the system at risk provides a measure of the potential need for adaptation and the benefit of the intervention. At the same time, the implementation methods range from expert judgement to cost-benefit analysis.

The case study aims to identify possibilities to achieve climate proof river basin management plans (RBMP) and flood risk management plans (FRMP) according to Floods and Water Framework Directives. The case study focuses on comparing alternative management choices and their impacts in Kalajoki river basin in Western Finland. The case study supports on-going planning processes. The research questions are: What is the adaptive capacity of river basin and flood risk management measures? How to find synergies between flood risk and river basin management? What are the costs and benefits of flood risk management measures? What is the acceptability of measures among stakeholders and citizens? What are the possible future adaptation pathways in flood risk management?

The case study contributes to BASE project by providing data on costs and benefits of different adaptation measures in water sector. Additionally, the case study offers examples and experiences on involving stakeholders in adaptation planning. Kalajoki case study has also strong links to BASE case studies dealing with human settlements and infrastructure as well as biodiversity and ecosystem services.

In order to allow comparability and consistency across the analysis performed by case studies, all cities and infrastructure case studies need to answer four overarching research questions:

- What are the main drivers and triggers of adaptation and of adaptation strategy?
- Which adaptation options and pathways are considered and assessed?
- What are the costs and benefits of adaptation?
- How and what adaptive actions are implemented and what are the main drivers of implementation?

In BASE the adaptation studies of water management are closely inter-linked with the agricultural and rural development studies (see the case studies above and in the agriculture section below).

9.5.2 Agriculture in the Case Studies

The agricultural case studies of BASE make important contributions:

- Climate adaptation responses to flooding problems in two Danish predominantly rural municipalities.
- Climate adaptation responses to drought and water availability problems in two regions of the Czech Republic.
- Drought adaptation in the region of Alentejo in Portugal.
- Climate adaptation in the Tagus River Basin of Spain.

The agricultural case studies will provide an overview of the status and the focus of climate adaptation efforts in case communities and countries, indicating what kinds of risks and opportunities farmers are aware of, respond to and how they respond. Likewise they will provide a state of the art review of national and EU adaptation responses for the agricultural sector and its effect on the ground.

The agricultural case studies will add to the sparse literature on costs and benefits of climate adaptation in agriculture. Some of the case studies will provide knowledge on specific industries - hop and wine production in the Czech Republic, and sugar production in Denmark.

9.5.3 Data from the stakeholders in the case studies

The agricultural subgroup is planning to share stakeholder interview guides for qualitative interviews among the BASE partners in the subgroup. Part of the content in these interview guides will be the same across countries, while some aspects will be country specific. The Czech and the Danish case studies will perform quantitative studies by sending surveys to farmers in the case study regions/municipalities (in Denmark there might be performed a national survey among farmers too). The Portuguese case study will contain a questionnaire too addressing many of the same subjects mentioned above – the prime focus in the Portuguese survey will be what innovative drought adaptation measures the farmers are implementing. The Tagus basin case study will also be addressing some of the above mentioned aspects by focusing on farmer perception (and other stakeholders' perception) on the need for adaptation to climate change. In the Spanish case study this is assessed through qualitative interviews. Studying farmers and public support for agricultural adaptation policies can play a key role in successfully adapting the sector to climate change. Thereby, the case studies will address support for adaptation policies.

The responses of the stakeholders will then be used in two ways. First, to define adaptation actions in the models and second to validate the modelling results. The key insights will be:

- How do farmers perceive climate adaptation and the need for climate adaptation actions? What is their risk perception? How are farmers motivated?
- What climate adaptation actions have farmers already taken (if any)? And what are the costs? Are there any experienced benefits? (this information is needed for WP3 and WP6)?
- Do farmers experience any conflict between climate adaptation policies and other policies (e.g. in the CAP)? (for WP2)

9.6 Linking sectoral models to the AD-WITCH

This very brief section aims to provide summary information about the linkages of the sectoral models to the top-down AD-WITCH model. This is described with greater detail in Deliverable D3.3.

The AD-WITCH model will use to "estimate" the costs and benefits (in broad sense, not in monetary sense in most cases) of adaptation derived from the sectoral models.

Ability to respond to climate change scenarios

The models developed respond to changes in climate. The scenarios used summarize climate change and socio-economic projections describing a range of plausible external contexts for the system considered in the case studies and model exercises.

BASE Deliverable D3.1 includes extensive information on scenario development and on the choice of the BASE consortium for the modelling analysis. Here is a brief summary.

The Socioeconomic pathways (SSPs) framework is built around a matrix that combines climate forcing on one axis (as represented by the Representative Concentration Pathways or PCRs) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated. BASE selected the SSP2 and SSP5 and associated them respectively to RCP4.5 and RCP8.5. SSP2 represents a sort of business as usual that can allow to characterize adaptation needs and challenges in a world were both social-economic and environmental concerns evolve following current trends. SSP5 is expected to quantify the cost of inaction in mitigation policy not only in terms of higher damages, but especially of higher adaptation expenditure. The choice of the SSP-RCP couplets, is thus motivated by scientific interest and relevance for the questions BASE tries to answer. Therefore the models need to include the assumptions of these two SSPs.

Modelling costs and benefits of adaptation

The sectoral models will be used to assess the costs and benefits of adaptation. In most cases the benefits will be estimated as avoided damages. The cost estimation will be further developed in WP6.

All negative effects of an adaptation option compared to a baseline option, which is usually the business-as-usual-option. The most important cost components are:

- Investment costs to implement a certain adaptation measure.
- Transaction costs, i.e. costs associated with the design and implementation of measures are part of it.
- Running costs, operation and maintenance costs.
- In addition, negative side-effects, possible negative effects in another sector, such as negative environmental and social effects of the measures. I.e. building a dike reduces flood risk but could also have negative impacts on floodplain ecosystems or on the spatial quality of a city front.

All positive effects of an adaptation option compared to a baseline option, which is usually the business-as-usual-option. The most important benefit components are:

- Avoided damages (at buildings, yields, insured persons, environment, treatment costs in health care);
- Positive side benefits (possibly for other BASE sectors) such as change of recreational function, tourism change of potential for development, change of biodiversity and ecosystem services , change of values of goods or land.

10 Concluding comments

This Deliverable D3.2 describes the models developed in BASE that is, the experimental setup for the sectoral modelling. The models described in this deliverable will then be implemented in the adaptation and economic analysis in WP6 in order to integrate adaptation into the economic assessments. At the same time, the models will link to the case studies in two ways. First, they use the data in the case studies for model validation and then they provide information to inform stakeholders on adaptation strategies.

The models will be used to evaluate the needs for adaptation; this will be done in WP6 and will be described fully in WP6. This report only very briefly addresses the elements of adaptation that are considered in model development.

In order the fulfil its objectives WP3 proposes to apply different top-down and bottom-up integrated assessment modelling approaches to quantify costs and benefits of adaptation in specific domains – namely: water, agriculture, ecosystems, the urban context and health. Moreover, by adopting a holistic perspective, it investigates complementarily and trade-off between mitigation and adaptation.

Further, WP3 aims at improving existing quantitative tools for a more realistic description of adaptation dynamics.

The specific activities under WP3 are therefore to:

- Critically evaluate modelling frameworks and contexts currently applied to adaptation;
- Establish a consolidated quantitative top-down integrated assessment model which builds on previous work but makes some new developments;
- Establish new developments in quantitative sectoral assessment models (water, agriculture, ecosystems; urban context and health) and their integration into the top-down integrated assessment models; and
- Develop methodologies to deal with uncertainty and scaling. Uncertainty could be addressed through extensive sensitivity analysis (e.g. related to the scale of climatic impacts, social preferences, different assumptions on adaptation cost and benefits) or through the introduction of stochastic elements.

To guarantee comparability and the possibility to consistently integrate results, all the analyses above will be performed using a common reference climate change scenario. The choice of this common framework and the practical quantification of the associated climatic information (e.g. temperature and precipitation) is also one of the main tasks of WP3.

Hydrology and Flood Risk

Flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide and floods are, together with windstorms, the most frequent natural disasters (Munich Re, 2010; UNISDR, 2009). It therefore has a prominent place in the GAR2011 report, where flood hazard is based on a methodology published by Herold and Mouton (2011). Here the methodology is further developed and updated.

In BASE we have developed a flood risk modelling framework for Europe that is able to project changes in flood risk due to climate change and socio-economic developments. We build upon the global flood risk estimation method, presented by Winsemius et al. (2013) and Ward et al. (2013) to fit the needs of European scale flood risk assessment. The model has a cascade of components sand functionalities. The impact module will be further tailored and developed, to fit the data availability and requirements of the case studies in BASE.

For the BASE project, we will simulate daily discharges and flood volumes (0.5◦× 0.5◦) using the global hydrological model PCR-GLOBWB (Van Beek and Bierkens, 2009; Van Beek et al., 2011), and its extension for dynamic routing, DynRout (PCR-GLOBWB-DynRout). Discharge arises from flood-wave propagation; in each cell the associated flood volume is stored in the channel or on the floodplain in case of overbank flooding. The suitability of these models is discussed in Winsemius et al. (2013). In brief, the model runs on a daily time-step, which is sufficiently short for runoff generation and flood propagation. Two other important features are that the runoff scheme resolves infiltration excess as a non-linear function of soil moisture; and the routing differentiates river flow from overbank flow dynamically. PCR-GLOBWB is forced by meteorological fields (precipitation, temperature, potential evaporation).

In BASE, further improvements will be to apply to Europe our downscaling scheme to 3” (about 90 meter) resolution. Additionally, experiments are performed to solve the dynamic equations fully at 90 meter resolution instead of at the 0.5 degree scale. A feasibility study is being performed at the time of writing and if successful, this approach may be applied in the BASE project as well.These activities would allow producing flood hazard maps across case studies for different return periods and combine them with damage models.

The impact model for flood risk assessment for BASE on a set-up with key elements being: a) vulnerability data (exposure of people and assets); b) hazard information (data on flood characteristics coming from the hydrological model, described above); and c) damage functions relating the flood characteristics to impacts (e.g. damages).

Previous studies have also assessed the benefits and costs of flood prevention in Europe, for instance Rojas et al. (in press) for river basins, and Hinkel et al. (2010) for coastal floods. Rojas et al. (in press) estimate the costs for upgrading river dike systems in the EU to be around 8 billion Euros by the 2080s, under the A1B emission scenario. Their approach for assessing these costs relies on an assessment of average benefit-cost ratios, whereby investment costs are related to the avoided damages, and the level estimated from a fixed average b-c ratio of 4.

We propose to also assess actual costs related to the adaptation measures, based on unit costs available from other research. For instance, for dike systems we will rely on estimates produced for the Netherlands (Kind, in press). For local damage reducing measures in businesses and households, cost estimates are available for the required efforts. These include measures to reduce flood damage to heating systems, electricity systems, and floors, for which cost estimates are available (e.g. Thieken et al., 2006), as well as the potential response of citizens to implement such measures (Botzen, et al., 2006). For retention areas, costs are more difficult to assess, but examples of costs for creation of retention and management of the retention system will be used. These estimates, together with the possible costs for damage compensation will be used to scale up from single examples to the European scale and the number of measures required for this adaptation type.

Environmental flows

Europe's water resources and aquatic ecosystems are impacted by multiple stressors, which affect ecological and chemical status, water quantity and ecosystem functions and services (Hendriks et al., 2013).

For BASE, we have selected the IHA method developed by Laizé et al. to analyse the impacts of the future changes in flow regime. A method that provides insight in flow regime change is most suitable for BASE, not a method that sets environmental flow requirements and quantified deviations. This means that both the IHA method and the method by King and Brown are relevant. Europe's river discharge regimes however are not suitable for King and Brown's method, because often there is no clear wet and dry season. Therefore, Laizé's method will be applied to analyse the changes in the hydrological regime of rivers due to climate change, land use change and catchment management, including the water retention measures. We will focus on the changes in ecological requirements with respect to magnitude and timing of hydrological patterns (Figure 10).

The method by Laizé et al. is based on the Range of Variability Approach (RVA) and uses indicators of Hydrological Alteration. The predicted changes in environmental flows for Europe due to climate change (based on simulations with the CMCC scenarios) will be a component of WP6.

Water availability and policy

European countries are diverse from various points of view including their socio-economic development, climate, water availability, infrastructure levels, or social and ecological pressures natural resources. However, the region as a whole is undergoing rapid social and environmental changes which may harbour negative implications for current and future sustainability. In the water sector, institutions, users, technology and economy cooperate to achieve equilibrium between water supply and demand in water resource systems.

The Water Availability and Adaptation Policy Assessment model (Garrote et al., 2011) links water supply, demand and management and is used to analyse policy options. We have developed a modelling approach to compute water availability and reliability as result of implementing climate or policy scenarios. The models will be used to compute water availability and demand-reliability curves, which provide a simple way to evaluate water availability under different policy and climate change scenarios.

The proposed methodology to identify and evaluate climate change adaptation policies within the BASE project is presented in this section. The methodology is based on the development of a GIS-based model, called Water Availability and Adaptation Policy Assessment (WAAPA), which computes net water availability for consumptive use for a river basin taking into account the regulation capacity of its water supply system and a set of management standards defined through water policy. WAAPA model provides a simple way to account for the influence of socioeconomic factors (hydraulic infrastructure and water policy) on climate change impacts on water resources.

Defining future water availability is a basic step for water policy formulation. We provide a platform for determining policy responses at the basin level. This evaluation helps define the sensitivity of a system to external shocks and to identify the most relevant aspects that can decrease the level of risk posed by climate change. With this modelling activity we will assess water availability resulting from different climate scenarios and multiple adaptation pathways. We will incorporate the local adaptation measures selected in the case-studies. If requested water availability maps can be made available to the case-study partners.

The WAAPA model may be used to compute the water availability and demand-reliability curves, which provide a simple way to evaluate water availability under different policy and climate change scenarios. WAAPA simulates the joint operation of all reservoirs in a basin to satisfy a unique set of demands. Basic inputs to the WAAPA model are the river network topology, the reservoir characteristics (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates), the naturalized stream flow series entering different points of the river network, the environmental flow conditions downstream of reservoirs and monthly values of urban and agricultural demands for the entire basin. The model is based on the mass conservation equation, and main assumptions refer to how reservoirs are managed in the system: to supply demands for any given month, water is preferentially taken from the most downstream reservoir available, since spills from upstream reservoirs can be stored in downstream ones.

Ecosystem services

The ecosystems provide goods and services that make a considerable contribution to human welfare and provide an environment, in which ecological processes take place (Costanza et al., 1997; de Groot et al., 2002). Ecosystem services measures can be applied as indicators of the functioning and change in the land system, and therefore the analysis could be an important tool for management-relevant communication concerning recent, past or potential future states of human-environmental systems (Rounsevell et al., 2012; Muller and Burkhard, 2012). Climate change will alter the provision of ecosystem services that we rely on today. In order to design suitable adaptation and mitigation responses, it is necessary to understand how ecosystems and ecosystem services respond to climate change (Lawler et al., 2011).

In BASE we use InVEST to evaluate adaptation needs to maintain ecosystem services in the Case Studies and across Europe and therefore define adaptation needs at different scales. The simulations will be done with the CMCC scenarios and will be presented in WP6.

InVEST modelling approach could be also applicable on the European level. However, data availability could become the main challenge with respect to future land use European-wide land use scenarios that involves the adaptation component. Challenging data requirements cover future land use scenarios that reflect climate change and adaptation on the European level. This type of land use scenarios is not at the moment available for us. Therefore, possibility of European-wide modelling would need to be further explored.

Agriculture

Food production faces some serious challenges in the coming decades: competition for water resources, rising costs due to environmental protection policies, competition for international markets, loss of comparative advantage in relation to international growers, changes in climate and related physical factors and uncertainties in the effectiveness of current European policies as adaptation strategies.Many of these threats are directly or indirectly influenced by climate change.

Adapting agriculture to climate change raises four challenging questions about regional systems, land productivity, water requirements and adaptation choices, both planned and autonomous. We address these questions for agriculture in a changing climate in BASE within a modelling framework that is closely linked to local case study information and provides data to the macro-economic model.

SARA (Supporting Agricultural Modelling in Regions for Adaptation to climate change) is the modelling framework developed in BASE to support adaptation choices in the agricultural sector. The main components of SARA are outlined in Figure 33.

Our approach considers that the main determinants of crop changes include: changes in agroclimatic regions and land use, crop productivity, water requirements, and adaptation management (autonomous and deliberate adjustments).

With the SARA modelling activity we assess the land productivity choices resulting from different climate scenarios and multiple adaptation pathways.

The framework allows for the development of adaptation scenarios in four dimensions: Local to National and private to public. Local adaptation measures selected in the case studies can be implemented.

The outputs include: maps of changes in agricultural productivity, water demand, nitrogen fertiliser application, adaptive capacity, that can be aggregated to one value in the different EU-27 countries as requested by Ad-Witch.

If requested, the agricultural productivity maps can be made available to the case-study partners.

Crop productivity modelling: AU will focus on the agroclimatic analysis and land use modelling in selected areas in Europe.

Crop productivity modelling: UPM will focus on the analysis of climate change impacts on EU-27 using the global scale agricultural model Climate-Crop (global, 1300 sites) and a subsequent interpolating at the country scale.

Water requirements modelling: UPM will focus on the analysis of climate change impacts on EU-27 using marginal productivity estimates at the country and crop level developed for the BASE project. The irrigation component will be linked to the water availability modelling.

Adaptive capacity modelling: UPM will focus on the evaluation of adaptive capacity under current climate and climate change scenarios.

Adaptation pathways: AU and UPM will focus the evaluation of planned adaptation and adaptation policy with a dialogue with the case studies and the macro-economic modellers. Adaptation strategies and measures will be collected from those case-studies focussing on agriculture. The adaptation measures will be aggregated and integrated in the European model to assess potential benefits under different climate scenarios. A Cost Benefit analysis of different adaptation options could be assessed in different case studies. A policy analysis of tradeoffs between adaptation (1 or 2 adaptation policy scenarios) and mitigation could be developed at the EU-27 level.

End-product: The results will be European maps of agricultural productivity and water requirements for different climate scenarios and adaptation paths. The irrigation component will be linked to the water availability modelling (See section 6 of this Deliverable). The final set of maps will be adjusted as required by Ad-Witch (See Deliverable 3.1).

Health

The impacts of heat waves on health have been substantially covered in the literature and ongoing projects (e.g. ClimateCost, EUROHEAT), while other impacts such as mental health risk, food-borne (e.g. salmonella) and vector-borne diseases (e.g. lyme disease, malaria) have been less explored in an adaptation context in Europe. Here the focus will be largely on improving the existing coverage of health in the integrated assessment models and on ensuring that the model reflects the state-of-the-art in terms of health impacts and adaptation costing. The analysis in BASE will build on an exploratory analysis of secondary sources for heat stresses and work in WP4 and WP5 on food-borne and vector-borne disease in particular, as the knowledge on the impacts of these is far more advanced than is the case for mental health. The identification of uncertainties in the adaptation functions will be an important part of the research, as will the identification of any cross-sectoral linkages between health and mitigation policies. Expected outcomes will help to inform the further elaboration of adaptation cost functions inside the integrated assessment model developed by CMCC.

The estimation of the health adaptation cost curve requires the following steps to be undertaken:

- To identify climate-sensitive health risks relevant at EU level, dose-response relationships, and the total additional burden of disease by health outcome (see table 21).
- To identify preventive and reactive measures for each selected health outcome.
- To identify costs and/or cost-effectiveness of adaptation measures (per case or death or DALY avoided, depending on the data available).
- To adjust the cost estimates of the measures in a format that is compatible with AD-WITCH model and to carry out new extrapolations with the participation of stakeholders when necessary.
- To run the AD-WITCH model and estimate the adaptation cost curve (with CMCC).

The review presented in this deliverable will be built on in Deliverable 3.3 and in Work Package 6 in terms of the construction of health adaptation cost curves.

Wider economic impacts in urban areas

Some recent large-scale disasters such as the 2003 heat wave that struck Paris and other European cities, hurricane Katrina in New Orleans US in 2005, 2012 flooding in Germany shows the urgency of understanding and then preparing for such hazards, including their impacts and effects to the regional economy and other connected economic bodies. Research indicates that economic losses caused by such events have been on the rise in the last few decades (Munich Re, 2001). Especially, along with the growth of population and assets, the metropolitan areas become particular concentrations of vulnerability to such disasters. Adaptation of the climate extremes can provide benefits of damage avoid in event impact regions but also production supply chain protection which can benefit further damage in other regions or sectors.

Economic analysis of disasters is based on the distinction between so-called 'direct' and 'indirect' costs or damages. The costs associated with damages to factories, houses and other buildings, infrastructure, etc., are known as direct costs. They are often highly visible, basically being a 'stock' variable. However, there also is a second type of costs which are a consequence of the highly interdependent production structures of modern economies. Interdependency means that if part of the structure is incapacitated, this will also affect other parts of the economy, and even may spill over into areas other than the one under consideration. These phenomena thereby cause indirect costs, which, in contrast to the damages to buildings, etc., have a 'flow' character. Indirect costs are, in general, less visible than the direct costs; they consist of business interruption, production losses during reconstruction and service losses in the housing sector. Together, the direct and indirect costs make up total costs.

ARIO model development. In order to estimate the total (direct + indirect) economic impact induced by an event, there are two steps. Firstly, event damage functions are required. These functions measure the economic cost or damage per area (following a disaster) as a function of the intensity of the disaster. Here 'intensity' can be measured in several different ways. For example, a bigger flood may translate into a larger surface area of a city being inundated, or the water surface reaching a higher level. If available, damage functions provide a representative estimate of the costs or damage inflicted by catastrophes of varying intensity on e.g. public buildings, factories or houses However, the methodologies based on these functions are still somewhat preliminary. Secondly, those damage functions will be integrated into the macroeconomic analysis framework (e.g. IO model). Such action would link different spatial dimensions from impacted region at local scale to the city / regional / international scale levels.

11 Planned papers

The following Table outlines the papers planned as result of the effort in model development.

Table 30 Planned papers

Sector	Suggested planned paper and papers in preparation
Hydrology and flood risks	Analysis of hydrological extremes in Europe under climate change (Bouwer et al) Implementing and assessing adaptation options to hydrological extremes in Europe (Bouwer et al)
Environmental flows	Environmental flow analysis in the Danube basin (Meijer et al) Climate adaptation and environmental flows: analysis framework (Meijeret al)
Water availability and policy	A policy analysis of water availability in Europe under climate change (Garrote et al) Participatory water adaptation choices in the Tagus basin (Garrote et al)
Ecosystem services	Ecosystem services and biodiversity in a Central-European mountainous (Lorencová et al)
Agriculture	SARA (Supporting Agricultural Modelling in Regions for Adaptation to climate change) (Iglesias, Termansen, et al) How able are farmers to adapt to climate change in Europe? (Iglesias, Termansen, et al)
Health	Towards a marginal adaptation cost curve for health: A theoretical framework (Chiabai, Taylor et al)
Wider economic impacts of adaptation in urban areas	A regional adaptive input-output model to estimate climate change impacts in urban areas (Guan et al)
Modelling linkages	Integrating top-down and bottom- up perspectives in adaptation assessment (Bosello, Iglesias, et al) Linking models to assess adaptation to climate change in Europe (Bouwer et al)

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