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D2.7 Overview of river ESS demand and delivery in selected case studies under different scenarios of climate change and barrier management.

This is version 1.0 of D2.7 'Overview of river ESS demand and delivery in selected case studies under different scenarios of climate change and barrier management'. This document is a deliverable of the AMBER project, which has received funding from the European Union's Horizon 2020 Programme for under Grant Agreement (GA) #689682.

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DISCLAIMER

Executive summary

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River barriers are important elements of the landscape for two reasons – they change the water balance of the area and as a consequence, they cause shifts in land uses, and also eventually habitat structure within the direct catchment of a reservoir, as well as in river valleys up and downstream of the barrier. Additionally, both water balance and land use drive other impacts, like water pollution or erosion, or biodiversity decline. The construction or removal of barriers therefore has consequences reaching far beyond the riverbanks. There are also a number of stakeholders and sectors affected by the (de)construction process, and the level of impact mirrors the level of dependency on the ecosystem services and disservices as delivered by the reservoirs and impounded rivers. The complexity of the human-water-service interaction is amplified by climate change. Thus, dam construction/removal lies at the core of the land-water-energy nexus, being perceived as a problematic and on occasion, even unsolvable, issue.

For these reasons, it is difficult to anticipate what the stock and allocation of natural capital in the absence of the dam would be, particularly in the case of those dams that have operated over decades, for example, the Nieszawa dam (Poland) since the 1960's, the Poutès dam (France) since the 1940's, or the Guadalhorce dam (Spain) since the 1970's. These dams have already led to the establishment

of new steady states defined by water demands, new habitats, crop production standards and demand, energy delivery, etc. Therefore, in the following report, we focused on the status of potential (natural capital) and realized ecosystem services and their spatial allocation in relation to the barriers and reservoirs, with the aim of locating hot-spots, and, through the modelling of climate change impact on the area, anticipate the threat to ecosystem services and the potential role of barrier management in reducing the threat. Referring to the outcome of task 2.6.1, we also attempted to identify the groups of stakeholders whose wealth may decrease due to climate change and natural capital decline.

This report is an outcome of bridging AMBER project with the methodology of H2020 NAIAD (http://naiad2020.eu), namely the application of two global models Co$ting nature (http://www.policysupport.org/costingnature) and WaterWorld (http://www.policysupport.org/waterworld). The models allowed a decrease in data intensity implied by other models and tools, for example, InVest, offering a number of imbedded databases and scenarios.

The report is to be extended at a later date with modified RESI (River Ecosystem Service Index) methodology applicable to small scale demonstration cases and foreseen as a basis for high IF publication.

Authors

Kinga Krauze (ERCE), Kamila Belka (ERCE), Daria Sikorska (ERCE), Małgorzata Łapińska (ERCE).

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1 INTRODUCTION

Globally, we observe an increasing need for water resources, food and energy. Inevitably, delivery of those resources is interconnected through an already created land-energy-water nexus (OECD, 2017). For example, by 2050, a 70% increase in food production will be required in order to feed the world's pupulation (FAO, 2011). Simultaneously, the World Energy Council (WEC) projects a 100% increase in energy supply (WEC, 2007). Total global water withdrawals for irrigation are projected to increase by 10% by 2050 (Keeler et al. 2012). Simultaneously, aquatic ecosystems (rivers, lakes, groundwater coastal waters, seas) directly support the delivery of such goods and services as fish production, water and recreation. Key supporting and regulatory ecosystem services are also connected to the hydrological cycle in the river basin, for example, water purification, water retention and climate regulation. Those services cannot be directly appreciated by people and quantified, thus are less evident. Maes et al. (2018), Keeler et al. (2012), and Brauman et al. (2007) carried out comprehensive analyses of ecosystem services provided by aquatic and water-dependent ecosystems. They include habitat provision, sediment retention, flood and flow regulation, carbon storage, mineralization or decomposition, nutrient regulation, climate regulation, and spiritual, symbolic, educational and other human-nature interactions.

Provision of ecosystem services is dependent on the status of the environment. While the European Environmental Outlook (EEA, 2011) already proved that during preceding decades, substantial progress has been achieved in the areas of the use of natural resources regarding waste recycling and decoupling economic growth from resource use, much less has been achieved in meeting nature and biodiversity targets. The conservation status of valuable habitats has been maintained unchanged, however Member Countries failed with pressures control, for example, eutrophication and urbanization, and with preventing biodiversity decrease in all three domains of ecosystems: terrestrial, freshwater and marine.

Focusing on water systems, the Water Blueprint (EEA, 2012) initiative pointed out that after over the 10 years of implementation of the Water Framework Directive, the most severe pressures are still changes in hydromorphology (which affect 50% of water bodies) resulting in altered habitats, and diffused pollution (affecting almost 40% of water bodies) that impacts water trophy. The EEA (2009) also mentions water stress as an additional and significant stressor. According to estimates, 26 European river basins are under permanent water stress, while another 43 experience it seasonally. According to projections, these numbers are going to increase by approximately 30% by 2030 and the impact will extend to Northern European rivers.

Awareness related to loss of quality rivers does not follow the reality of the situation. The EEA report (2015) indicates that over 70% of rivers offer unfavourable conditions to animal and plant species, however, less than 30% of the European population is concerned with shortage of drinking water or species extinction (EC, 2014). The Eurobarometer on biodiversity and ecosystem services (EC, 2015) reveals also that on average, less than 20% of the European population believes that biodiversity decline already impacts their lives, while less than 40% consider that loss of biodiversity will affect them later.

1.1 Ecosystem services and service bundles

The last decade has seen increasing attempts to assess the relationships among different ecosystem services, and led to the establishment of the ecosystem service bundle concept (Bennet et al, 2009; Raudsepp-Hearne et al., 2010; Maes et al. 2012; Renard et al., 2015). An ecosystem service bundle has been defined as a ''set of associated ecosystem services that repeatedly appear together across time or space" (Renard et al. 2015). Certain categories of ecosystem service often co-vary positively (even synergistically) with one another, while others co-vary negatively (i.e., they tend to be in competition). The phenomenon of ecosystem service bundles has several possible causes: it may be because the co-delivered services originate from a shared underlying condition, which is not substantially altered by the enjoyment of the benefit. Antagonistic services, however, may require different conditions, or their production may modify the environmental basis for the delivery of other services (Howe et al., 2014).

Bundles capture how different ecosystem services interact. They are distinct from inventories of ecosystem services that can be added up to obtain a total quantity of services, because adding the services within a bundle would both double count ecosystem services that interact and ignore varying social values placed on different ecosystem services (de Groot et al. 2002).

The recognized ecosystem service bundles are presented in **Table 1**.

Table 1. Ecosystem service bundles according to literature review (orange –conflicting; green – synergic) (Kong et al. 2018; Baró et al. 2017; Howe et al. 2014; Martín-López and Iniesta-Arandia 2012).

	biodiversity	C sequestration	water regulation	soil formation	flood mitigation	water purification	wind erosion	crop production	meat production	climate regulation	recreation	air quality	erosion control	fishing	hunting	forest production	aesthetics	noise attenuation	water provision	N regulation	P regulation
biodiversity		green		green		green	green	orange	orange				green					green		green	green
C sequestration	green		green	green	green	green		orange	orange	green		green			green	green		green		green	green
water regulation	green	green		green	green	green		orange	orange				green	green	green	green			green	green	green
soil formation	green	green	green		green	green		orange	orange			green				green	orange				
flood mitigation		green	green	green				orange	orange												
water purification	green	green	green	green			green	orange	orange											green	green
wind erosion prevention	green					green		orange		green		orange				green					
crop production	orange	orange	orange	orange	orange	orange	orange		green	orange	orange		orange				orange			orange	orange
meat production	orange	orange	orange	orange	orange	orange		green		orange	orange	orange					orange				
climate regulation		green					green	orange	orange		green	green	green	orange			green		green		
recreation									orange	green			green	green			green	green			
air quality	green	green		green			orange		orange	green	green		green			green					
erosion control	green		green					orange		green	green	green								green	green
fishing			green							orange	green										
hunting		green	green													green					
forest production		green	green	green			green					green			green			green		green	green
aesthetics				orange				orange	orange	green	green										
noise attenuation	green	green									green					green					
water provision			green							green										green	green
N regulation	green	green	green			green		orange					green			green			green		green
P regulation	green	green	green			green		orange					green			green			green	green	

1.2 Ecosystem services and climate change

Most ecosystems are vulnerable to climate change even under low and medium-range scenarios of global warming (Scholes et al. 2014). They are likely to be affected by gradual changes in temperature or precipitation and climate-related disturbances (for example, flooding, drought and wildfire), in association with other threats which accompany climate change (i.e. rising CO_2, land use change, air and water pollution, intensifying natural resource use, loss of biodiversity and overexploitation of resources (Scholes, 2016)). Pedrono et al. (2015) list seven types of impact of climate change on ecosystems: species extinction, novel ecosystems, coastal flooding, increase of cyclone frequency, reduction of freshwater resources, failing crop yields and disruption of animal, plant and human health. Those changes and disturbances will affect the abundance, production, distribution, and quality of ecosystems. Therefore, ecosystem services such as climate stabilization through carbon sequestration, the provision of forage for livestock and wildlife species, the delivery of water that supports fishing, the provision of critical habitat for biodiversity, and many other types of ecosystem service, are likely to change (Locatelli et al. 2008). For example, the ability of forests to sequester carbon and thus limit climate change could be constricted because forest productivity decreases and fire frequency and/or intensity increases with rising atmospheric temperatures (Shaw et al. 2011). Ecosystem vulnerability has consequences for the global climate, if changes and disturbances release carbon into the atmosphere, vegetation-climate feedback will amplify global warming (Canadell et al., 2004). Local and regional ecosystem services may also be affected by climate change, such as water regulation or timber production, with direct implications for dependent societies (Shaw et al. 2011).

The summary review of the impact of climate change on ecosystem services is provided by Sholes (2016) in **Figure 1**.

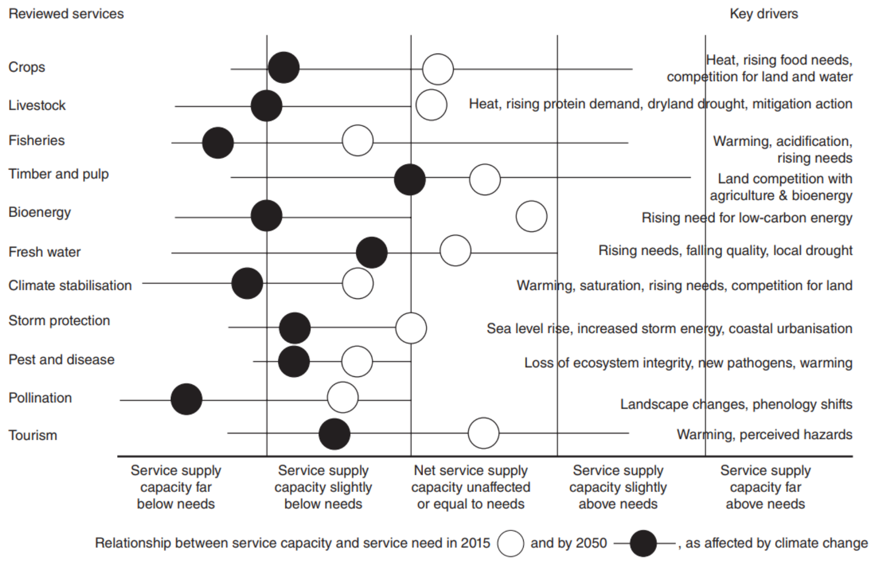

Figure 1. A visual summary of the relationship between supply and demand for the ecosystem services surveyed in this review, both at the present time (open circles) and as affected by the climate (after Sholes, 2016).

Climate change translates into change for the way governments, companies, and citizens realize their needs. Many projects and programs are contributing to effective mitigation and adaptation strategies, mostly through the conservation of biodiversity and ecosystem services (World Bank, 2009), though these rarely consider a comprehensive approach built upon three dimensions: ecosystem-based mitigation, ecosystem-based adaptation, and adaptation for ecosystems. To ensure that ecosystems mitigate climate change and help people adapt, management must reduce current threats to ecosystem services (for example, wetland or forest degradation) as a first step (Locatelli, 2016).

2 METHODOLOGY

2.1 Site selection

This study has been carried out for three AMBER demo sites: the Włocławek Dam and Reservoir (Poland), the Guadalhorce (Spain) and the Neckar River sluice system (Germany). The selection of sites was based on the availability of data related to ecosystem service delivery, as well as GIS information enabling remote analysis of the area. Considering the scale of operation of both Waterworld and Co$tingNature models (1km^2), sites needed to reach a critical size.

2.2 Co$ting Nature modelling

Co$ting Nature (http://www.policysupport.org/costingnature), is a web based tool for analysing the ecosystem services provided by natural environments, identifying the beneficiaries of these services and assessing the impacts of human interventions. This Policy Support System (PSS) is a testbed for the development and implementation of development and conservation strategies focused on sustaining and improving ecosystem services and their environmental foundations. The PSS incorporates detailed spatial datasets at 1km^2 and 1ha resolution for the entire world, and spatial models for biophysical and socioeconomic processes along with scenarios for climate and land use. The PSS calculates a baseline for current ecosystem service provision and allows a series of interventions (policy options) or scenarios of change to be used to understand their impact on ecosystem service delivery (Mulligan et al., 2010). The workspace data are listed in Annex 1.

Co$tingNature incorporates ecosystem service provision and benefits information into conservation prioritisation and planning. It focuses on water, carbon and tourism related services, and on defining the magnitude and geographic pattern of these as potential services, and as those realised (used) by local and global beneficiaries. Co$tingNature starts by mapping 13 ecosystem services and then allows combining them with analysis of current pressure, future threats, biodiversity and delphic conservation priority, to produce an assessment of priority areas for conservation and careful (sustainable) management on the basis of these factors. This is done first using baseline datasets representative of the current situation. When in possession of relevant data, users may apply land-use scenarios or valuations and examine the impacts, in terms of change in ecosystem services, and implications for beneficiaries. Users may also carry out economic valuation by using the economic valuation customisation and completing the economic valuation matrix.

The model produces a series of summary metrics as maps. By default, Co$tingNature normalises all service values as a means of defining a common unit of priority (value) from 0 (low) to 1 (high). Aggregate metrics, such as the Bundled Ecosystem Services Index, by default bring the individual services together with equal weighting, meaning all services are considered of equal priority. The weights for individual services can also be specified by the user when there is relevant local information available. For output in relative units (0-1 in the study area), the potential and realised values (tonnes) are normalised between the first and 99th percentile. In relative units, Co$tingNature maps 13 potential and 13 realised services (Mulligan, M., 2018): timber (softwood, hardwood), fuelwood (softwood, hardwood), grazing/fodder, non-wood forest products, water provisioning (quantity, quality), fish catch, carbon, natural hazard mitigation (flood, drought, landslide, coastal inundation), culture-based tourism, nature-based tourism services, environmental and aesthetic quality services, wildlife services (pollination, pest control) and wildlife dis-services.

Calculation of relative disservice value is an important and interesting feature of Co$tingNature. The negative impacts on people include pests, diseases and crop raiding, as well as other forms of human-wildlife conflict, however, this is mostly focused on agriculture. Thus, wildlife disservices are assumed to affect both croplands and pastures. They are calculated for non-urban areas only and are assumed proportional to the inverse of the productivity of non-agricultural (i.e. non-cropland and non-pasture land) on the basis that low productivity of natural land will tend to drive wildlife into agricultural areas as pests, bringing disease and raiding crops and livestock. For this service to be realized, there needs to be non-agricultural land to produce it and agricultural land nearby to make use of it. Thus, the realized service is zero for pixels in which there is no non-agricultural land to provide the service, and scales from the potential service value to zero as the distance to the nearest agriculture increases (Mulligan 2018).

In this study, the information about ecosystem services has been aggregated and mapped as: Relative Pressure Index, Relative Total Potential Bundled Services Index, and Relative Total Realised Bundled Services Index. Potential value is the value of services from all ecosystems whether these services are used now or not (i.e. potential value includes value to future beneficiaries everywhere that the service could be supplied), thus, it reflects natural capital of the area. Realisable value is the value that could be realised if all of the accessible service (based on current infrastructure and population) were consumed at the maximum sustainable rate (a function of investment, practice and policy). Realised value is the value currently realised (extracted) per year on the basis of the current distribution of population, infrastructure, investment, policy and practice (Mulligan 2018). A brief description of each index is provided in Annex 2.

Co$tingNature also produces a Relative Pressure Index. It is given as the combination of relative population, relative fire frequency, relative grazing intensity, relative agricultural intensity, relative dam density and relative infrastructural density. Relative population is calculated on the basis of population density. Relative fire frequency is based on an analysis of the mean burn frequency from 2001-2010 from the MODIS burnt area product (Mulligan 2010). Grazing intensity is calculated according to head of cattle for managed grazing and wildland grazing after Wint and Robinson (2007). Agricultural intensity combines the fractions of cropland and pasture in each pixel. Pressure from dams is calculated as the cumulative upstream number of dams using the Global Dams Database

(Mulligan et al., 2009). Infrastructural pressure is calculated from the location of dams, mines, oil and gas, roads and urban infrastructure. Relative pressure is again scaled from 0-1.

2.3 WaterWorld modelling

Hydrological and climatic data have been generated with the Waterworld model (http://www.policysupport.org/waterworld) licenced with non-commercial hyperuser access. Waterworld is a web based policy support system (PSS) based on the FIESTA hydrological model (Mulligan and Burke 2005; Mulligan et al., 2010; Bruijnzeel et al., 2011) and previous policy support systems, for example, DESURVEY PSS. The PSS is a testbed for the development and implementation of land and water related policies. It incorporates detailed spatial datasets at 1km^2 and 1ha resolution globally and spatial models for biophysical and socioeconomic processes along with scenarios for climate, land use and economic change. The workspace data used for scenario building is listed in Annex 3. A series of interventions (policy options) are available, which can be implemented and their consequences traced through the socio-economic and biophysical systems. The model integrates with a range of geobrowsers for immersive visualisation of outcomes, for example, google earth or google maps.

This study applied 1km^2 resolution to run the PSS for each out of the three chosen AMBER sites, to generate a climatic and hydrological baseline, and only for the climate change impact analysis was the information filtered and scaled down to the area of a single demo site.

Waterworld has been developed with reference to the IPCC Fourth Assessment Report (IPCC AR4 SYR (2007) and IPCC SRES (2000). Out of AR4, we have chosen the group of A2 scenarios assuming more or less business as usual and the most severe climate change. The A2 family of scenarios is characterized by: a world of independently operating, self-reliant nations, continuously increasing population, regionally oriented economic development and low emissions, that, in terms of climate change, considers a temperature rise of 3.4^{0}C, with a likely range of 2.0 to 5.4^{0}C, sea level rise likely ranges from 23 to 51cm. The other scenario groups consider more ecology-friendly developments, significant technological changes, and/or limited population growth. Thus, the choice of A2 scenarios allows visualisation of the uppermost impact of climate on water resources and environment. The projections have been focused on barrier-influenced area (in terms of microclimate, surface water impoundment and groundwater table). The climate change modelling has been done with GISS Model E20 Russel by the NASA Goddard Institute for Space Studies, with a forecasting time horizon of 2041-2060. As the PSS did not allow for deriving cumulative information, i.e. monthly water balance or annual temperature and precipitation change, three months have been chosen for detailed investigation: May – important for the spawning and nursing of many European fish species, July – important from the point of view of agriculture, when intense precipitation or drought can lead to significant economic losses, and September – important from the point of view of fish feeding and fitness, but also because autumn is considered as the season with the projected highest temperature increase across Europe. For each of these three months, we have generated maps of percentage temperature and precipitation change comparing to the baseline. The areas with the highest increase of temperature and drop in precipitation have been considered as threatened with negative water balance.

2.4 Pros and cons of adopted approach

There are several broadly adopted methods of assessing natural capital and ecosystem services. Those commonly applied and well documented are: InVest (https://naturalcapitalproject.stanford.edu/invest) Integrated Valuation of Ecosystem Services and Trade-offs) by the Natural Capital Project; open-source software models used to map and value the goods and services from nature, MAES methodology (Maes et al., 2018); using a number of indicators and proxies to estimate ecosystem services at large scales, Ecosystem Services Review (ESR) (https://www.wri.org/blog/2012/02/re-introducing-corporate-ecosystem-services-review-version-20) by The World Resources Institute and World Business Council for Sustainable Development, TESSA (http://tessa.tools/); a basic toolkit to identify which services may be significant at a site of interest, what data are needed to measure them, what methods or sources can be used to obtain the data and how to communicate the results, RESI (https://www.resi-project.info/en/projektbeschreibung/) the River Ecosystem Service Index; developed under the BMBF funding program "Regional Water Resources Management for Sustainable Protection of Waters in Germany (ReWaM)" to assess, evaluate and visualize potential and used ecosystem services provided by rivers and their floodplains, or recently advanced Knowledge innovation project (KIP) on Accounting for natural capital and ecosystem services by DG Environment and EEA (http://ec.europa.eu/environment/nature/capital_accounting/pdf/KIP-INCA-ScopingPaper.pdf). There are also some other tools like ARIES or ERS, described in Table 2. The common feature of all those methods is high data and labour intensity not feasible to the AMBER project. The goal was therefore to adopt an approach that could compensate for lack of data and manpower, and still generate useful information, which allows the attraction of attention to catchment hotspots in terms of natural capital and ecosystem services, and to conclude on services and disservices of barriers and reservoirs to a variety of users. A special challenge was linking that information with climate change scenarios in order to draw conclusions on potential positive or adverse effects of barriers under changed water balance.

The choice of the Co$tingNature policy support system as a core methodology was a result of cross-cutting work and collaboration between two H2020 projects – AMBER and NAIAD (http://naiad2020.eu/; EU Insurance Value of Nature), and pragmatic compromise between the expectations of both data access and analytical feasibility. Co$tingNature also enables the continuation of work and increasing accuracy of assessments and forecasts whenever more detailed, local information can be uploaded to the system, allowing precise zones of interests (ZOIs) to be delineated.

Thus the advantages of using the Co$ting Nature PSS include:

- Spatially explicit, public-domain tool;
- Rapid analysis of climatic/biophysical/biotic conditions based on global data, that compensates for scarcity of local information;
- Ability to make projections about water availability (precipitation/temperature) under a number of climate change scenarios;
- Use of hydrosheds as a working unit, that complies with the AMBER approach;
- Fast identification of catchment hotspots of natural capital and ecosystem services, based on 13 services presented as bundles;
- Possibility to extend assessment with economic valuation of services/capital whenever basic economic information can be uploaded for individual ZOIs.

The disadvantages of the method are:

- Large scale of operation that makes analysis of the impact of small barriers (single sluice, culverts, levees) impossible;
- Coarse resolution of data that leads to high generalization of outcomes;
- Does not support mapping of individual services and their trade-offs;
- Does not focus on water-based services;
- Partially documented, that may influence quality of data interpretation;
- Divergent functionalities of Co$ting Nature and WaterWorld that means that influence of climate change on services cannot be modelled in parallel to hydrological characteristics.

In their review of models and tools for ecosystem service assessment, Bagstad et al. (2013) emphasises that, contrary to many other tools, Co$tingNature can be rapidly applied in terrestrial environments globally and well serving as a low-cost, spatially explicit screening tool for identifying potential ecosystem service hotspots. Such preliminary assessments could be used as a broader analytical ‘frame’ for more granular analyses with other mapping and modelling tools (
Figure 2). The functionalities of different models are compared in **Table 2**.

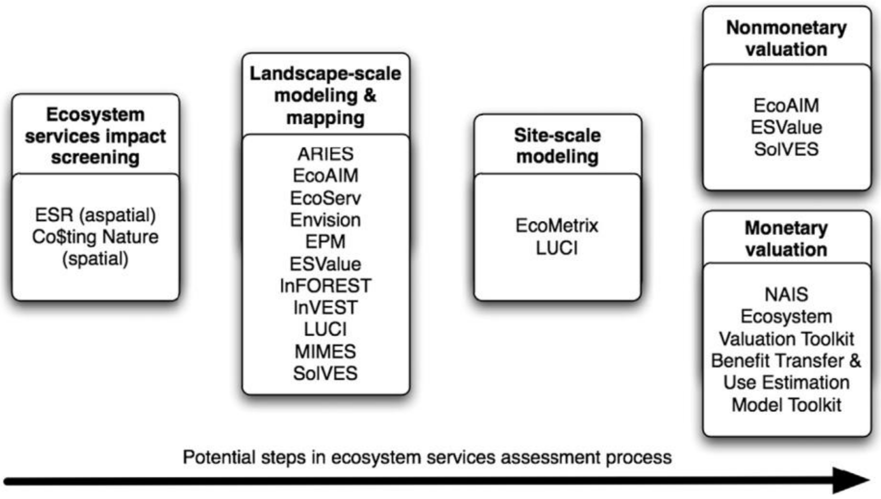

Figure 2. Applicability of different tools along the ecosystem services assessment process (after Bagstad et al. 2013).

Table 2. Comparative characteristics Comparative characteristics of selected ecosystem service models and tools (after Bagstad et al. 2013, modified)

Tool	Quantifiable, approach to uncertainty	Time requirements	Capacity for independent application	Level of development & documentation	Scalability	Generalizability	Nonmonetary & cultural perspectives	Affordability, insights, integration with existing environmental assessment	Reference
ESR	Qualitative	Low, depending on stakeholder involvement in the survey process	yes	Fully documented	Multiple scales	High	Novaluation component	Most useful as a low-cost screening tool	http://www.wri.org
InVEST	Quantitative, uncertainty through varying inputs	Moderate to high, depending on data availability to support modeling	yes	Very broad and detailed documentation	Watershed or landscape scale	High, though limited by availability of underlying data	Biophysical values, can be monetized	Spatially explicit ecosystem service trade off maps; currently relatively time consuming to parameterize	http://www.naturalcapitalproject.org
ARIES	Quantitative, uncertainty through Bayesian networks and Monte Carlo simulation	High to develop new case studies, low for pre existing case studies	Through web explorer or stand-alone software tool	Fully documented	Watershed or landscape scale	Low until global models are completed	Biophysical values, can be monetized	Spatially explicit ecosystem service tradeoff, flow, and uncertainty maps; time consuming for new applications	http://www.ariesonline.org
Co$ting Nature	Quantitative	Low	yes	Well documented with videos, some unclarities are related with incorporated models and datasets	Landscape scale	High	Outputs indexed, bundled ecosystem service values	Rapid analysis of indexed,bundled services based on global data, along with conservation priority maps; important functionalities accessible only with licence	http://www1.policysupport.org
Benefit Transfer and Use Estimating Model Toolkit	Quantitative, uncertainty through varying inputs	Low	yes	Fully documented	Site to landscape scale	High	Dollar values only	Low cost approach to monetary valuation	http://www.defenders.org
RESI	Quantitative	High, requires in-site verification and measurements	yes	Fully documented in German; some ambiguities remains	River and floodplain scale	Low, tool operates on very precise local data	Some services can be monetized	Fully integrated with WFD, data intense and referring to German policy documents and databases	https://www.resi-project.info
EcoServ-GIS	Quantitative, uncertainty through varying inputs	High to develop new case studies, low for existing case studies	yes	Under development	Site to landscape scale	Low until global or national models are completed	Biophysical values, can be monetized	In development, will offer spatially explicit maps of ecosystem service trade offs; tested in England, Scotland and Wales	https://ecosystemsknowledge.net/ecoserv-gis

3 RESULTS

3.1 The Włocławek Dam, Poland

The Włocławek Dam is located on lower the river Vistula (km 674.850) in Central Poland. The dam, constructed in 1968, creates a large dam reservoir of 70,4km^2 surface area. It was built as the first part of a 10 large reservoir plan at that time, but has remained to date the only one built. The dam was equipped with six electric turbines (Kaplan type) and a technical step-pool fishpass.

The Włocławek Dam (the Nieszawa Reservoir) (**Figure 3**) was to reduce the risk of fluvial flooding to the City of Włocławek while provide energy the the local users and triggering tourism and water transport. It however had a crucial impact on migratory fish species, as the dam cut off the majority of the river Vistula catchment that was the main historical spawning ground for sea trout, Atlantic salmon, vimba bream and sturgeon. However, sturgeon and Atlantic salmon became extinct in the Vistula River catchment even before the Włocławek Dam construction due to overexploitation and loss of spawning grounds. Populations of sea trout and vimba bream declined dramatically after dam construction. Species composition and abundance of local fish assemblages also significantly changed (https://amber.international/portfolio-item/the-wloclawek-dam-poland/).

Figure 3. The Włocławek Dam located on the river Visula, Poland.

The goals of the construction were not fully achieved, and there are ambiguities related to its overall influence on the catchment. Although it significantly reduced flood risk to Włocławek, its positive influence on agricultural production is difficult to prove, i.e. it both supplied and drained agricultural land over its history, depending on land location. It does contribute to energy production, however, simultaneously imposed tremendous risk to downstream settlements because of bottom erosion caused by the dam, which endangered the construction of the barrier. Finally, construction destroyed habitats of species protected under the Habitat and Bird Directives and those located downstream are continuously threatened by dam operation, while it has never positive influence on tourism.

To prevent the dam failure, the water authorities created a stabilizing stone ramp two meters high, 500m below the dam to prevent bottom erosion. This slowed down the erosion, but created a new obstacle for fish migration, especially at low water flows. Now, there are plans to build a new dam located about 20km downstream of the existing one to stop the bottom erosion and ensure safety of the existing dam. A new dam and reservoir will create an additional barrier for fish migration, further elimination of birds' nesting areas and many water dependent ecosystems.

3.1.1 Natural Capital and Ecosystem services

The Włocławek demo site is located in the plains of Central Poland and surrounded by agricultural land. Although Central Poland is densely populated, the floodplain of the river Vistula and its valley remains relatively natural. They are covered either by extensive agriculture, mostly wet meadows and forests, or by areas under different conservation schemes from reserve to Natura 2000. This explains why the relative pressure index remains low in proximity of the river and increases west and east. The other gradient can be observed along the North-South axis (**Figure 4**). Low-pressure areas coincide with areas of high importance for natural capital and ecosystem service delivery that prove generally sustainable management practices. The areas are distributed almost evenly along the Włocławek barrier impact zone (**Figure 5** and **Figure 6**).

The bigger hot spot patches appear in proximity of the three big cities in the area: Nieszawa, Włocławek and Płock. The stocks of natural capital correspond with ecosystem service donor areas and reveal high, unused potential.

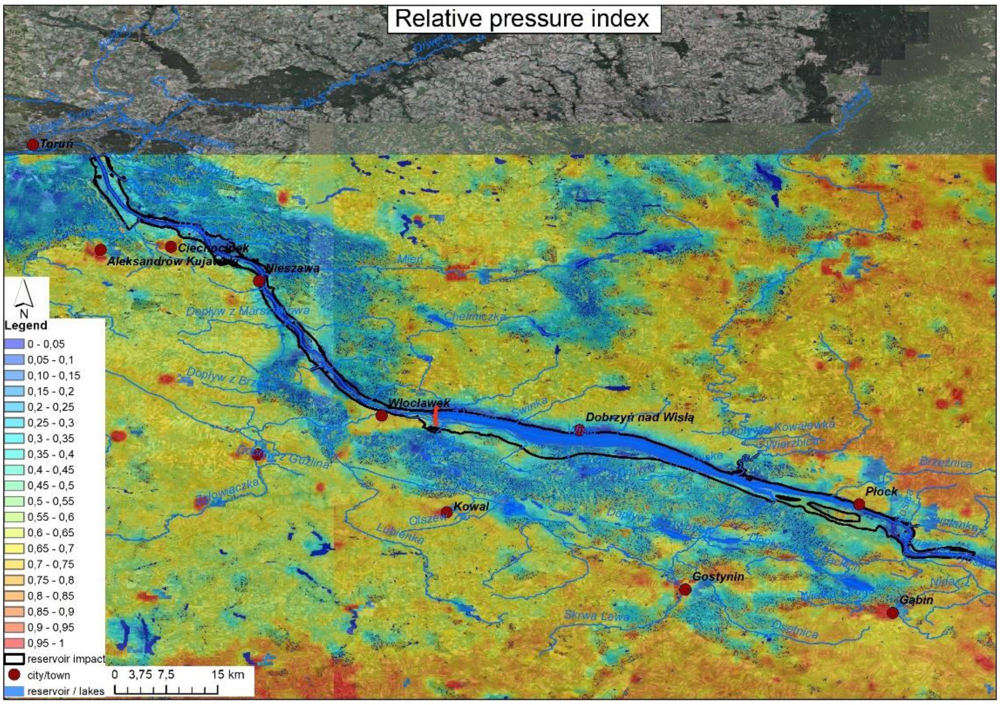

Figure 4. Current pressure according to population, wildfire frequency, grazing intensity, agricultural intensity, dam density, and infrastructure (dams, mines, oil and gas, urban) density.

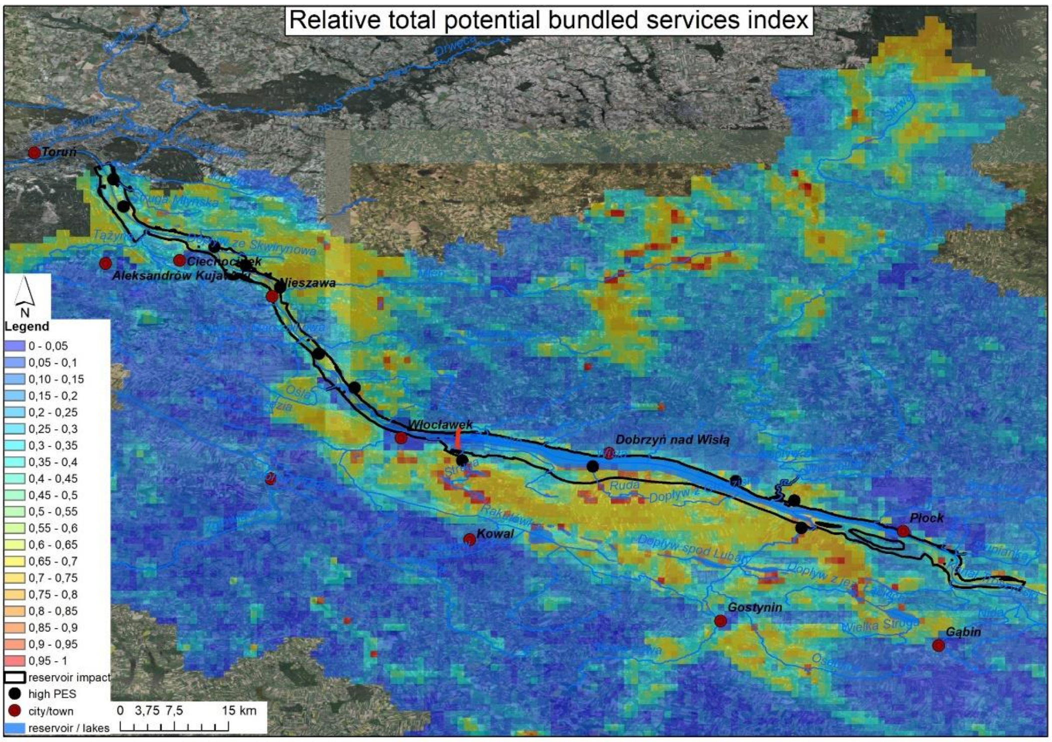

Figure 5. The allocation of potential ecosystem service bundles along the Włocławek dam impact zone (natural capital hot spots).

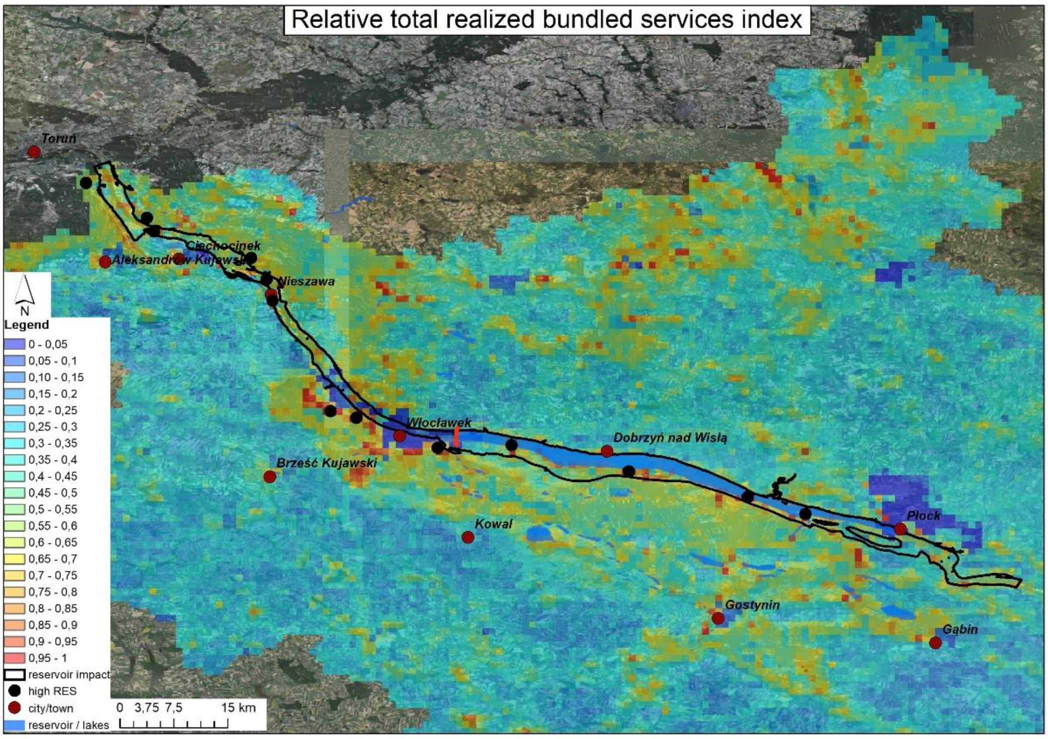

Figure 6. The allocation of realized ecosystem service bundles along the Włocławek dam impact zone (ecosystem service hot spots).

Modelled delivery of ecosystem services revealed a switch in relative contribution of services to the ecosystem service bundles below, and along the reservoir as well as along the backwater area. However, the whole area of actual and historic floodplain is an important donor of ecosystem services.

The river Vistula, maintaining its natural character (location of Natura 2000 habitats) below the Włocławek barrier, contributes the most to habitat formation and angling, ecological regulation, pollination, pest control, carbon sequestration, environmental quality and nature-based tourism. The potential services (natural capital) having the greatest contribution to the bundles are: water provisioning services, non-wood forest products and inland fisheries both commercial and artisanal.

Considering the Nieszawa City region (point 2 on **Figure 7** and **Figure 8**), also located downstream of the Włocławek barrier, and considered as the location of the new barrier and reservoir, there is a clear indication of high both potential and realized services. They are to be lost in a case of the dam construction. The service stock is higher than realized services. It provides opportunity for non-wood forest products, water provisioning, and fisheries, while realized services include carbon sequestration, wildlife services, timber and non-wood forest products. Interestingly, potential service hot spots are located further north than realized ones.

Similarly, in the area of the City of Włocławek (point 3 on **Error! Reference source not found.** and **Figure 8**), the potential services that could be used include water provisioning, angling and fisheries and grazing. The four actual most used services are fuelwood, non-wood forest products, carbon sequestration and timber production.

The significant decline of both natural capital and ecosystem services can be observed on the left side of the Włocławek Reservoir. It results from the way the reservoir has been constructed. It reflects the shape of the gutter lake with relatively fast flow (short water retention of approximately 5 days). Whereas the left side area is flattened and rich in oxbow lakes, the right side bank is steeper with limited influence of the reservoir on groundwater and habitats.

The natural capital significantly outweighs the services realized within the direct impact zone of the Reservoir (compare **Figure 7** and Error! Reference source not found.**,** points 4 and 5 respectively). It comprises non-wood forest products, water provisioning, inland commercial fisheries and inland artisanal fisheries value, hazard mitigation, hard and soft fuelwood, hard and soft commercial timber, wildlife services, grazing services and carbon sequestration, in the order of relative contribution to the bundle.

There are relatively few services delivered by the reservoir itself (point 5 on **Figure 8**), and those include energy production and limited extended transportation (both not considered by Co$tingNature), fuel wood and non-wood forest products play an important role and carbon sequestration is the third most weighted service. The majority of realized services are associated with the neighbourhood of Włocławek.

There are two important disservices, not considered by Co$tingNature*,* however, these are crucial from the perspective of reservoir management: accumulation of organic matter including toxic substances, and greenhouse gas emission. It has been calculated that organic matter accounts for 11.5% of dry mass of sediments, that causes greenhouse gas emission of approximately 400 mg of methane for every $1m^2$ (aproximately 841ml $m^{-2}day^{-1}$) (Trojanowska et al., 2009).

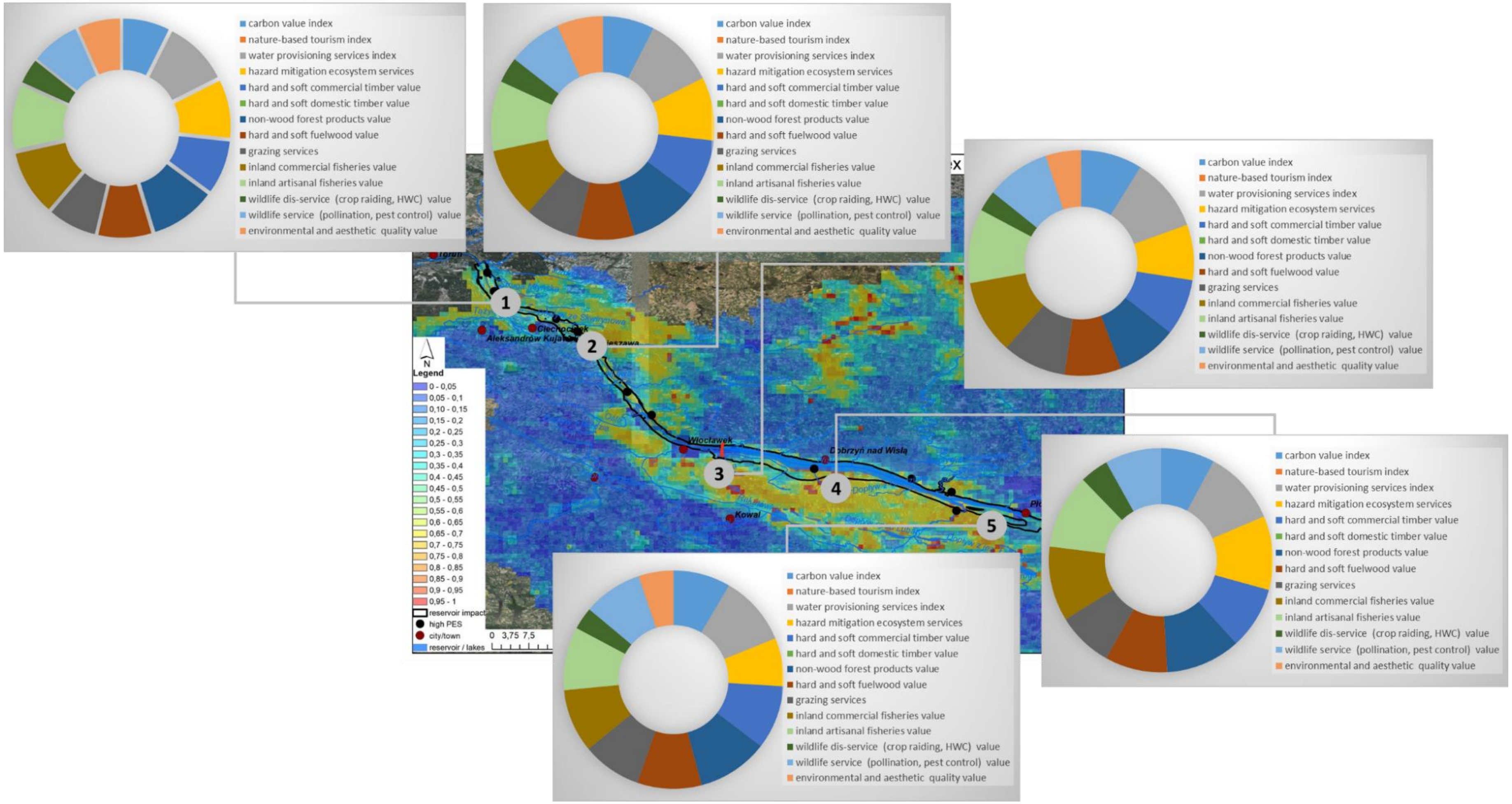

Figure 7. Ecosystem service bundles of the Włocławek hot spot areas. Relative contribution of 14 ecosystem, services to the weight of the hot spot area according to the potential ecosystem service bundle index.

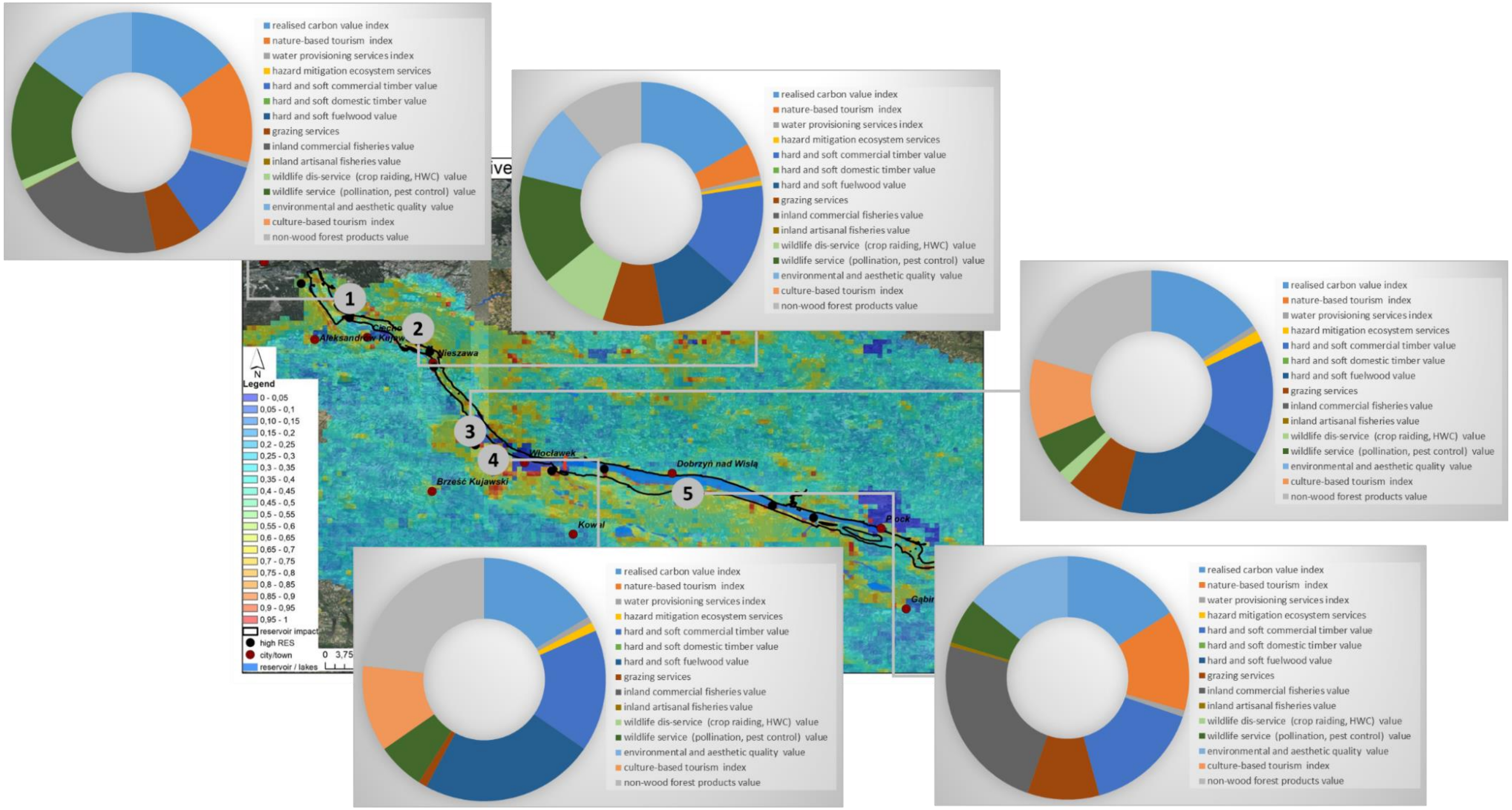

Figure 8. Ecosystem service bundles of the Włocławek hot spot areas. Relative contribution of 14 ecosystem services to the weight of the hotspot. According to the realized ecosystem service bundle index.

3.1.2 Impact of climate change

There is a generally higher uncertainty of predictions of the precipitation variability due to climate change than temperature in Poland. Temperature is less affected by local phenomena and is more homogeneous in space, unlike precipitation, which can be more affected by local conditions such as topography. For instance, winter and spring precipitation changes by ESD projections are expected to be about 16% and 14%, respectively, whereas the bias-corrected DD projections indicate higher increases of about 116% and 118%, respectively. An exception is made for winter, which shows a similar order of magnitude. Projected precipitation for autumn also differs depending on the downscaling method. The ESD projections show almost no changes (0% - 8%) in the ensemble mean by 2071–2100, assuming the intermediate emission scenario, whereas the bias-corrected DD projections suggest an increase of about 7% in monthly sums of precipitation, with a range between 23% and 117% (Mezghani et al., 2019).

Co$tingNature modelling showed a decrease of May precipitation by 2041-2100 of around 5-10% in the whole Włocławek region. The summer precipitation is to increase by around 10% below the Włocławek barrier. Finally, the autumn precipitation is not showing a major difference for the upper Włocławek region and slight decrease in precipitation downstream (**Figure 9**).

A forecast made by both the dynamical downscaling and ESD-Com based projections, suggests increasing temperature in the future across Poland. The annual mean temperature in Poland is expected to rise by 1.0 and 2.2^{0}C for the period 2021– 50, and by up to 4.7^{0}C for the period 2071–2100, assuming the RCP 4.5 and RCP 8.5 (Mezghani et al., 2019).

According to Co$tingNature predictions, temperature will not show bigger deviations from the baseline for the period 2041-2100. On average, it is to increase by about 1-2^{0}C (**Figure 10**).

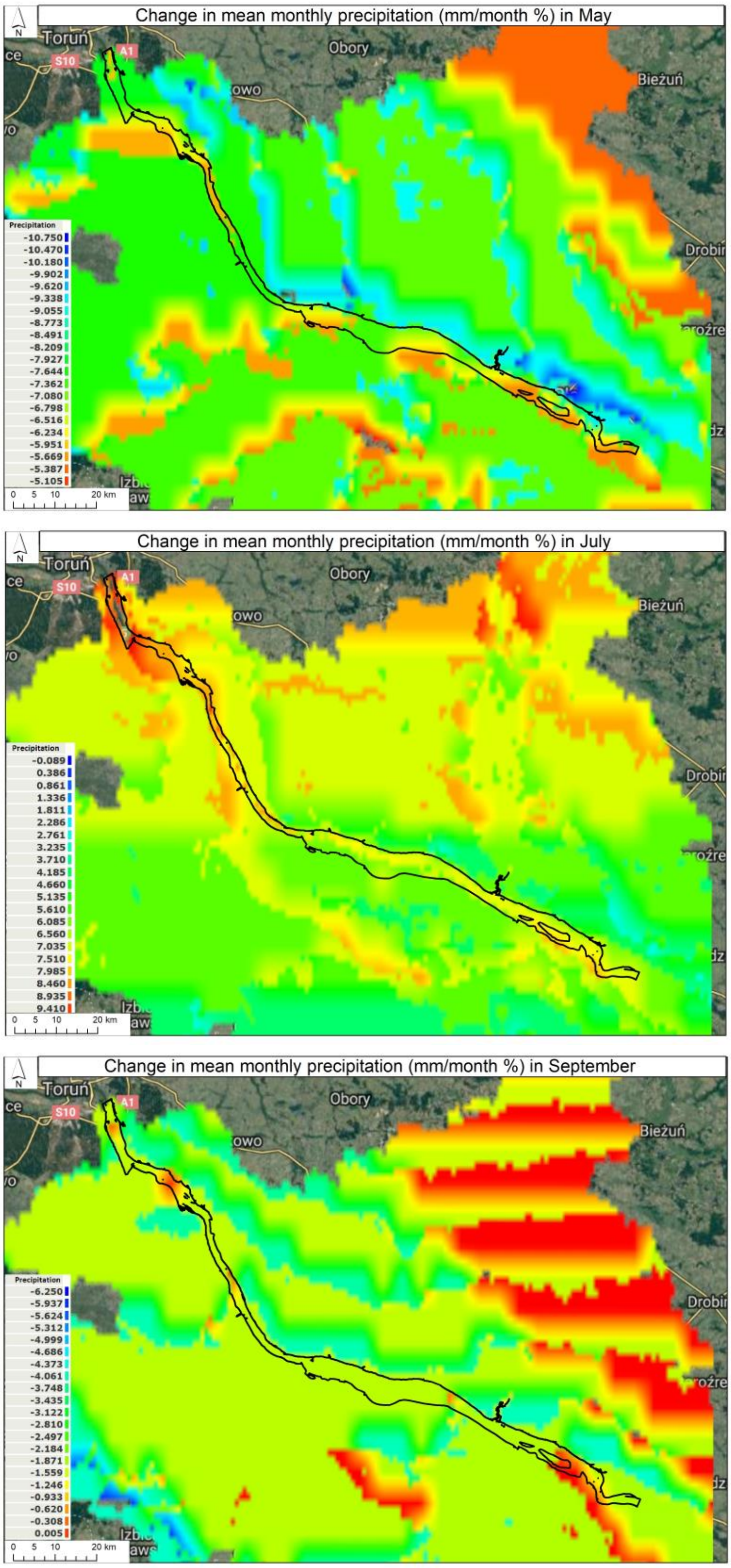

Figure 9. The change in mean monthly precipitation for May, July and September, respectively, in the Włocławek area (in mm/month %).

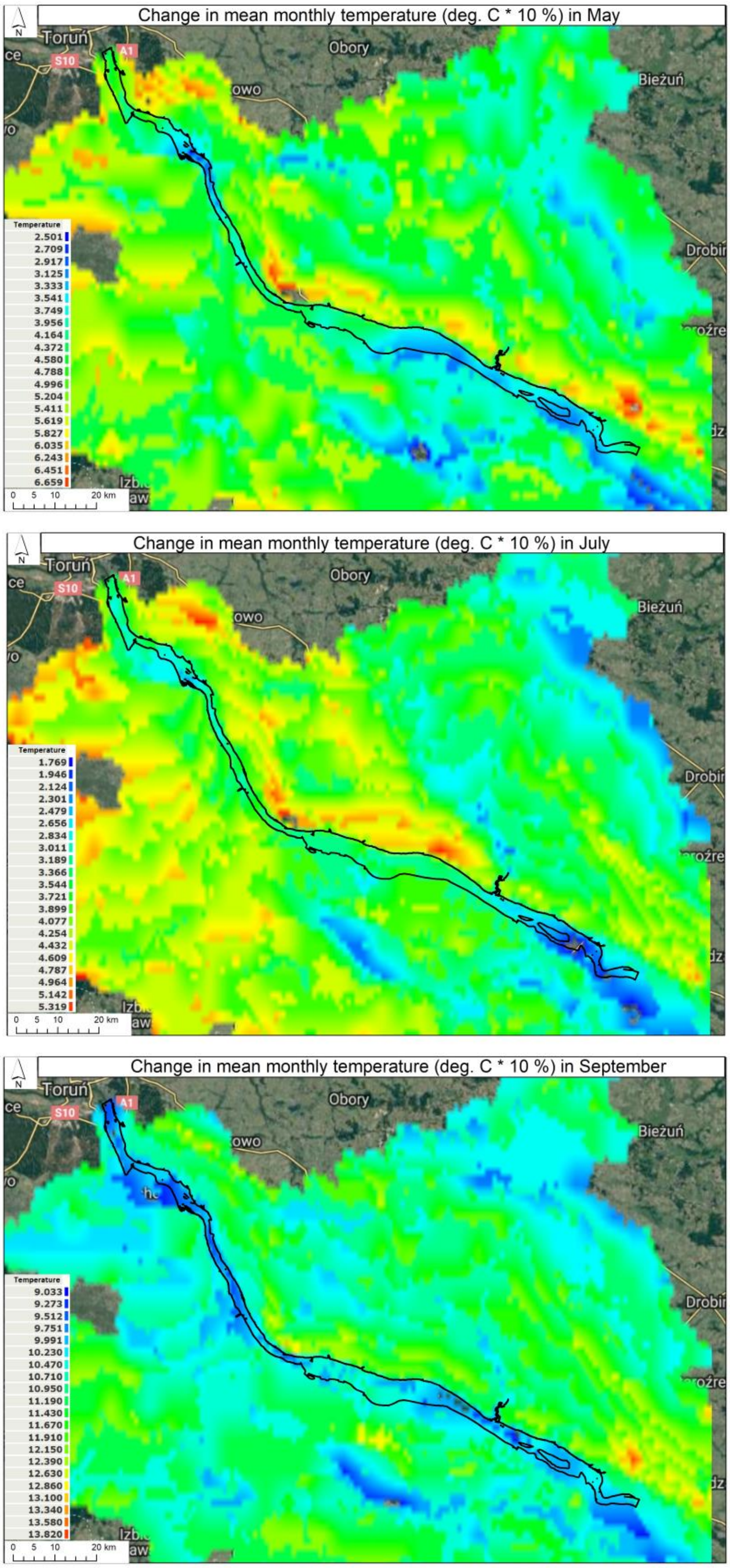

Figure 10. The change in mean monthly temperature for May, July and September respectively in the Włocławek area (in deg. C *10 %).

Considering the location of both climate change and ecosystem service delivery hotspots, the overlap is observed mostly in the area of the direct catchment of the Włocławek reservoir and its upstream impact zone (**Figure 11**). As no adverse effects of climate change are projected, neither natural capital nor realized services are exposed. In May, precipitation is projected to slightly decrease, however, temperature is to stay similar to the baseline. It may adversely affect water balance as a consequence of superimposed effects of lower precipitation and rapid vegetation growth. The Włocławek dam operation can play an important role in stabilizing water conditions above and below the barrier.

In summer, conditions are not projected to vary significantly, which is important as it is a stable situation below the Włocławek barrier. Projected precipitation increases may even compensate for the disturbances of the Vistula flows caused by the dam. Services like crop production, water provision, habitat provision, timber and non-wood forest production or carbon sequestration may be even better supported by positive water balance (precipitation – evapotranspiration).

The impact of climate change on ecosystem services may be more negative in autumn. The temperature is projected to increase by approximately 10%, while precipitation will drop by approximately 3%. Increased temperature will cause extension of the vegetation period while precipitation may not be enough to support ecosystems. Again, however, the climate impact zones and ecosystem service hotspots overlap mostly around the reservoir backwater area. This means that dam operation will play an important role in sustaining the services.

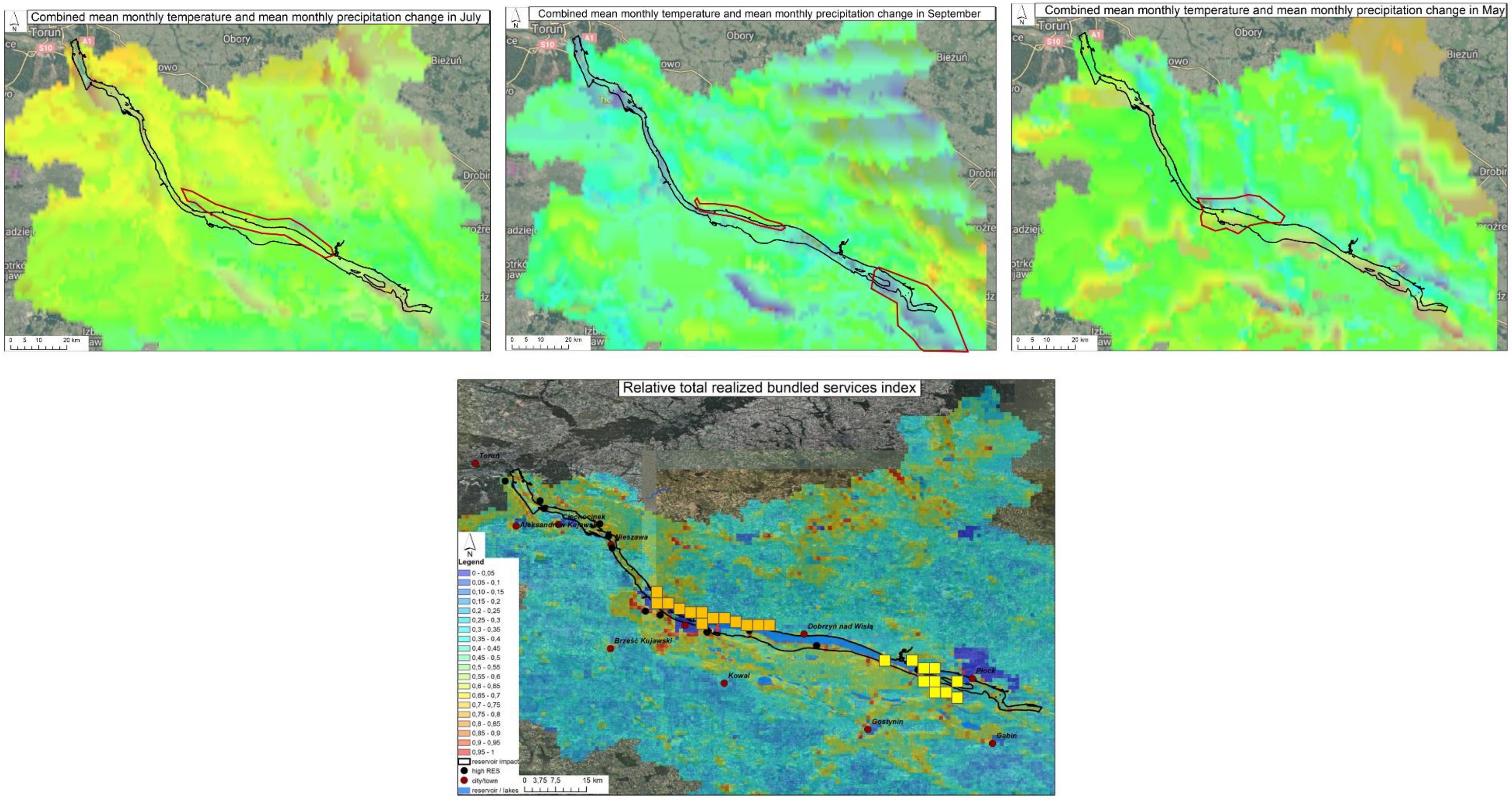

Figure 11. Areas within the Włocławek Demo most affected by effects of climate change (increase of temperature vs decrease of precipitation) - May, July and September respectively vs hotspots of ecosystem service delivery.

3.2 The Guadalhorce Dam, Spain

The river Guadalhorce is 149 kilometres long and is the longest river in the southern basin. There are five reservoirs in the Guadalhorce catchment, with little distance between them. They were built in different years to supply water to the city of Málaga and to the crops of Guadalhorce's valley, regulate water flow and provide electricity to the city via four hydropower stations. Count Guadalhorce Reservoir is in the river Turón, and Gualdalteba Reservoir is in the river Guadalteba. Both rivers are tributaries of the river Guadalhorce. There are three other reservoirs in the river Guadalhorce; Guadalhorce Reservoir (connected to the Guadalteba Reservoir when there is a high level of water in both reservoirs), Gaitanejo Reservoir and Tajo de la Encantada Reservoir.

The consequence of damming of the Guadalhorce River is an irregular flow regime, characterized by severe droughts and flash floods that have caused extensive damage in recent years. River engineering and flood defences have been built at the city of Malaga to minimize flooding risks, but dams and reservoirs also reduce the characteristic Mediterranean-climate droughts.

The main economic activities in the region are agriculture and tourism. Guadalhorce valley has 10,000 hectares of crops and the population of the region increases significantly in summer. Therefore, water supply, hydro-electrical power and recreational activities are necessary and provided by these reservoirs. On the other hand, the connectivity along the river Guadalhorce and its tributaries has been interrupted by the multiple reservoirs and associated power plants (https://amber.international/portfolio-item/river-guadalhorce-spain/)

The catchment contains many elements of social importance and historical relevance, including: 'El Caminito del Rey', a natural and touristic route through Gaitanejo defile; the Guadalhorce Wetland, a Special Protection Area (SPA) for migratory birds with relevant dune vegetation which contains species that are almost extinct from other littoral places of the region; and the Phoenician archaeological site known as 'Cerro del Villar' classified as an element of cultural heritage in the BIC catalogue.

3.2.1 Natural Capital and Ecosystem services

The Guadalhorce is the most important river in Málaga, both in terms of its length and the size of its catchment area. It has a vast basin of 3,160 km^2, covering almost every geographical area of Malaga's territory. Two other important tributaries of the Guadalhorce are the rivers Guadalteba and Turón. The former is joined by incipient streams that spurt from the easternmost foothills of the Serranía de Ronda and, from this point on, it flows through another part of the Intrabaetic Basin, surrounded by small limestone mountains and non-irrigated land, representing one of the most interesting agricultural landscapes of the provincial geography. The river Turón, on the other hand, feeds on some of the waterfalls from Ronda's Spanish fir forest, in the heart of the Sierra de las Nieves Natural Park, and flows through very different environments before lending its waters to the Conde de Guadalhorce reservoir. The mouths of the Turón and the Guadalteba on the Guadalhorce were linked together in the 20th century through one of Andalusia's most important hydroelectric complexes in these surroundings (Diputación de Málaga: Málaga's River Basins. (Diputación de Málaga: Málaga's River Basins) built to generate electricity, water crops or supply the cities, such as the reservoirs Conde de

Guadalhorce, Gaitanejos, Guadalteba, Guadalhorce, Encantada Superior, Encantada Inferior and Casasola. Further, the watercourse crosses the lands of Archidona, where it carves the Garganta del Guadalhorce gorge through limestone, clay and gypsum. It then runs from west to east through the Depresión de Antequera. Downstream it supplies weirs, irrigation streams and irrigation canals distributed mainly in the Hoya de Málaga to support the agricultural and livestock industries. This area produces potatoes, onions, asparagus, and different types of grains. It subsequently crosses the Sierra de Huma and the vast alluvial plains of a group of villages belonging to the Valle del Guadalhorce region, known for its fertile farmland, mainly used for irrigated crops and citrus trees.

The area where the reservoirs Conde de Guadalhorce, Guadalteba and Guadalhorce meet is a recognized leisure location, with tourist centres and facilities for water sports and climbing.

The agricultural uses and tourism development decide the location of the pressures within and around the Guadalhorce Demonstration site (**Figure 12**), mostly upstream of the Conde de Guadalhorce Reservoir and Guadalteba. The river Guadalhorce, El Caminho del Rey, and the landscape park of the Paraje Natural Desfiladero de los Gaitanes are also subject of pressures but of less intensity.

The area with the highest index of potential ecosystem service bundles is located between three reservoirs: Guadalhorce, Guadalteba and Conde del Guadalhorce (**Figure**). It covers the area of the El Mirador de los Tres Embalses: located at the confluence between the reservoirs of the rivers Turón, Guadalteba and Guadalhorce, and the Mirador des Embalses. They make up the hydrological network of El Chorro. Further, the area extends towards the walkway El Caminito del Rey and the Los Gaitanes gorge. The area of realized ecosystem services exceeds the one indicated as a hotspot of natural capital. It develops much further east, southeast and south towards the Valle de Abdalajís, Bermejo and Ardales (**Figure**). The weight of services in the bundles also differs between potential and realized ones.

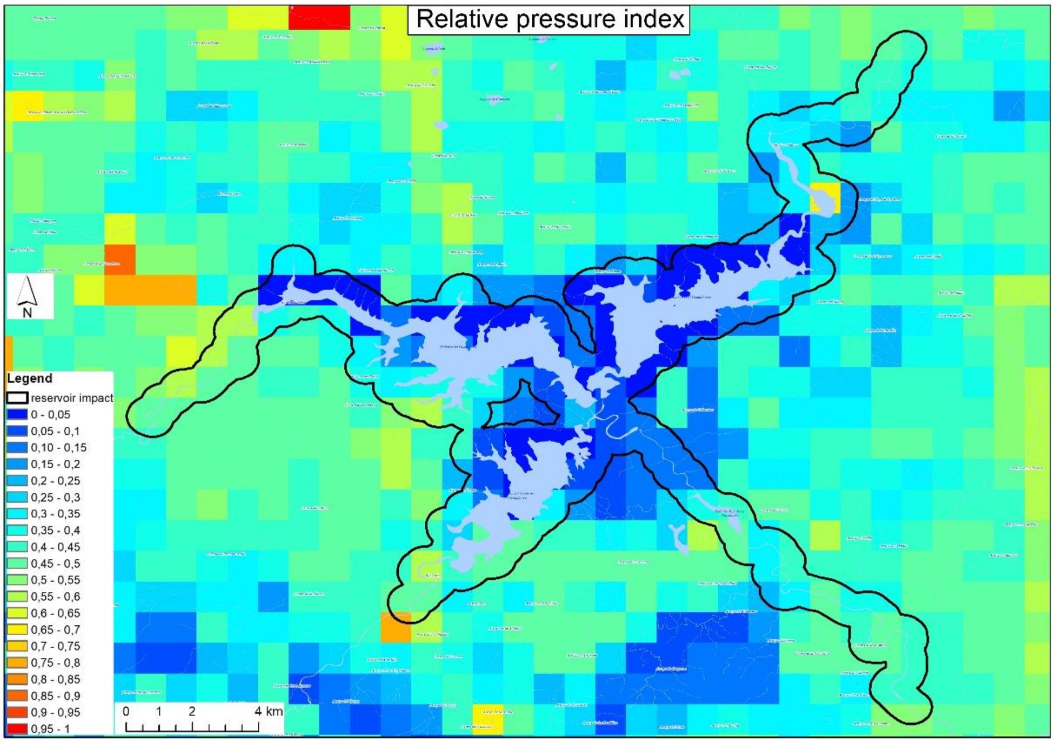

Figure 12. Current pressures in the Guadalhorce Demo site (marked with black line) according to population, wildfire frequency, grazing intensity, agricultural intensity, dam density, and infrastructure (dams, mines, oil and gas, urban) density.

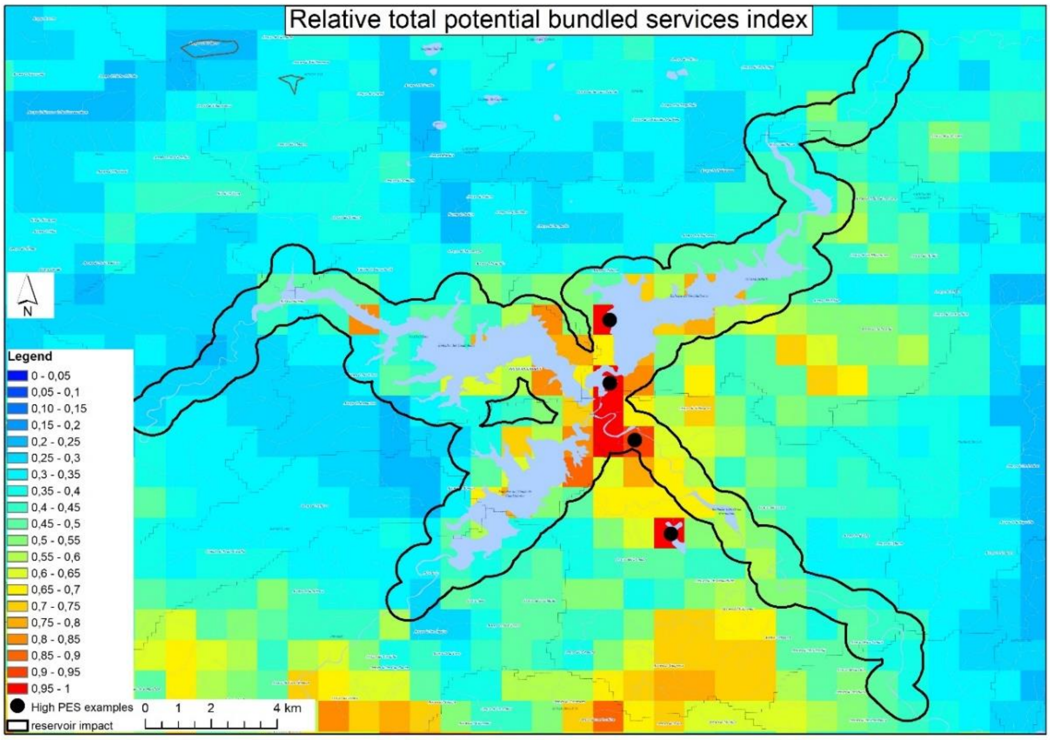

Figure 13. The allocation of potential ecosystem service bundles within the Guadalhorce demo area marked with black line (natural capital hotspots).

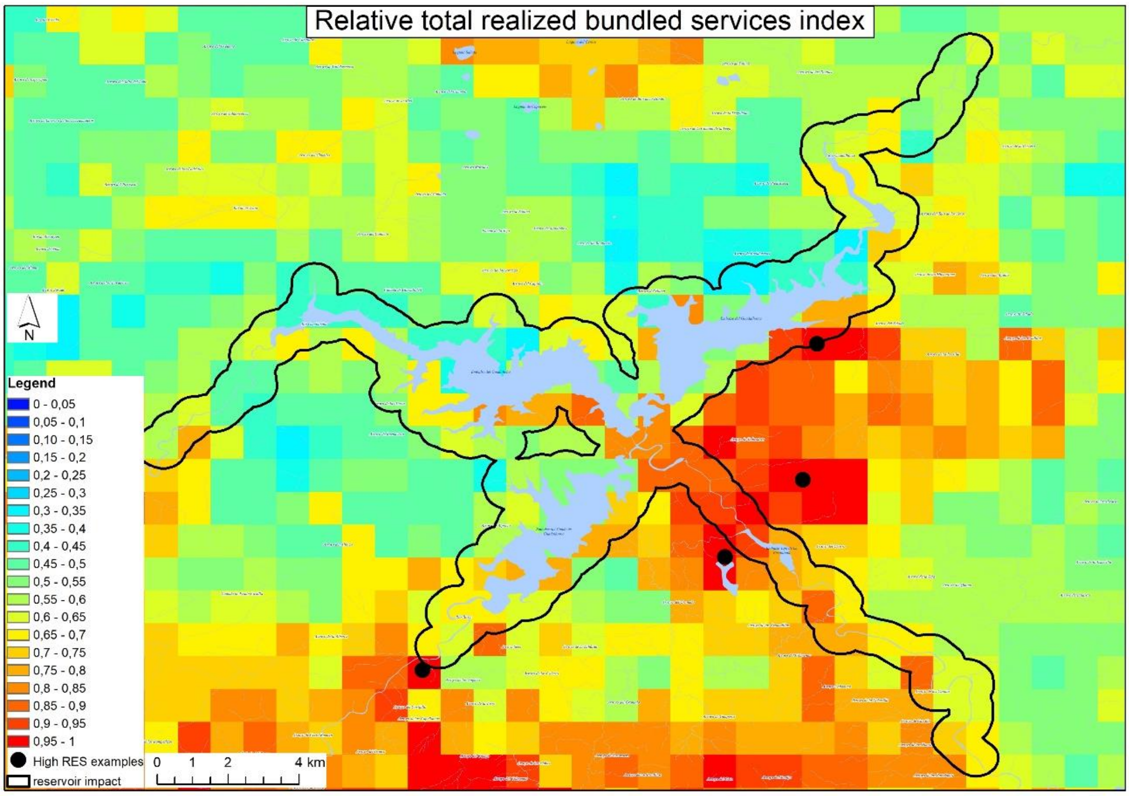

Figure 14. The allocation of realized ecosystem service bundles within the Guadalhorce demo area marked with black line (ecosystem service hotspots).

Among potential services not realized within the reservoirs' hotspots, there are non-wood forest products, fuelwood and timber production (points 1and 4, **Figure 15**), water provision (points 1, 2, 3 and 4, **Figure 15**), hazard mitigation (points 2 and 4, **Figure 15**) and carbon sequestration (points 3 and 4,**Error! Reference source not found.**). Also commercial and artisanal fisheries appear as significant components of natural capital but not significant ecosystem services (points 2 and 3, **Figure 15** to be compared withError! Reference source not found.**)**. Wildlife disservices appear to be important aspects in the area of the El Mirador de los Tres Embalses, among disservices forest fires, lack of water and erosion have been pointed out as the most important problems (IMA, 2006).

Among realized services, in all four hotspots, nature-based tourism and environmental aesthetics play a key role (Error! Reference source not found.) and dominate the ecosystem service bundles. The third important service is grazing, but only on the left side impact zone of the Guadalhorce reservoir and along the river Guadalhorce (point 2, Error! Reference source not found.), and hazard mitigation upstream of the Conde del Guadalhorce (point 4,Error! Reference source not found.).

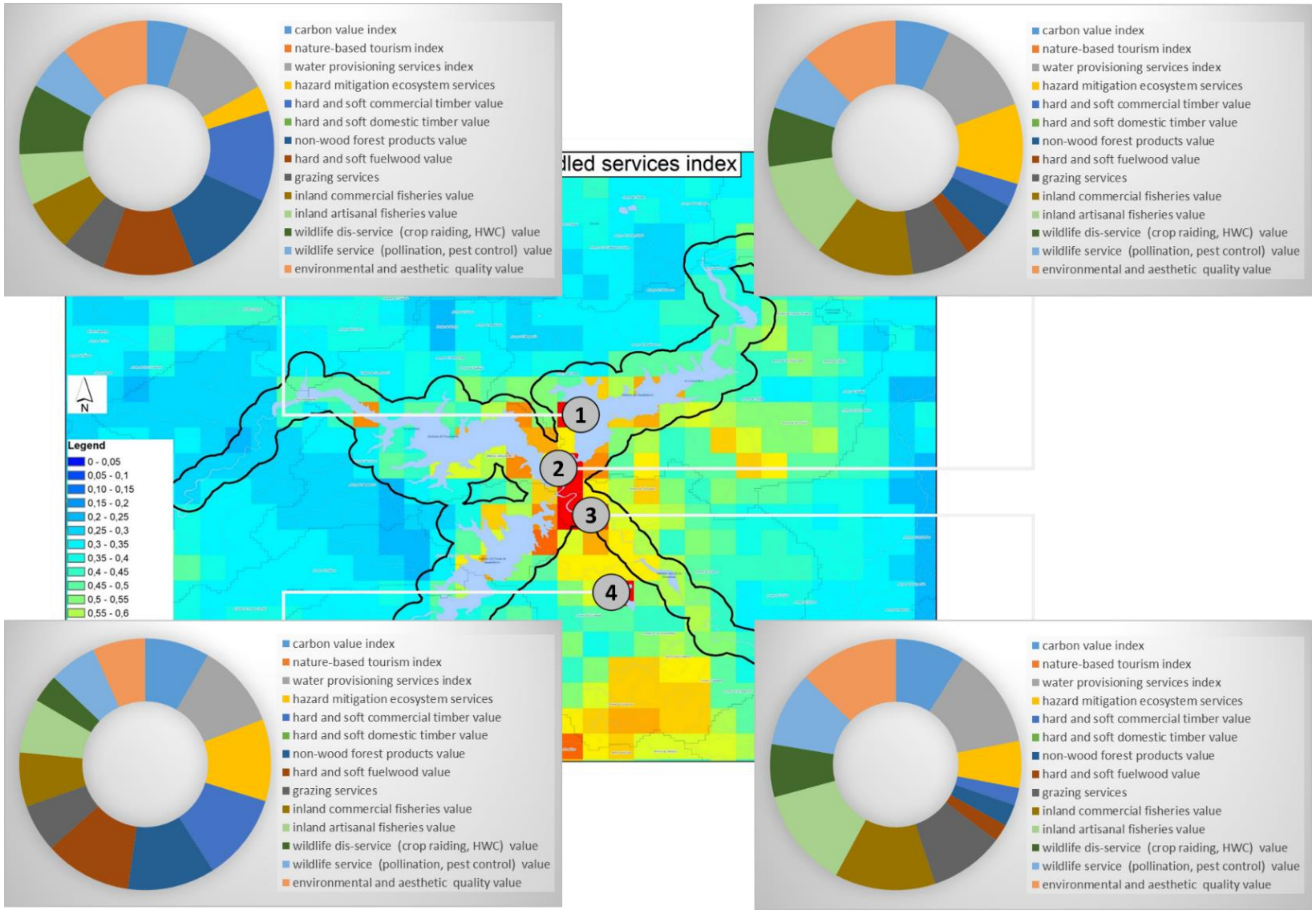

Figure 15. Ecosystem service bundles of the Guadalhorce demo site hotspot areas. Relative contribution of 14 ecosystem services to the weight of the hotspot area according to the potential ecosystem service bundle index

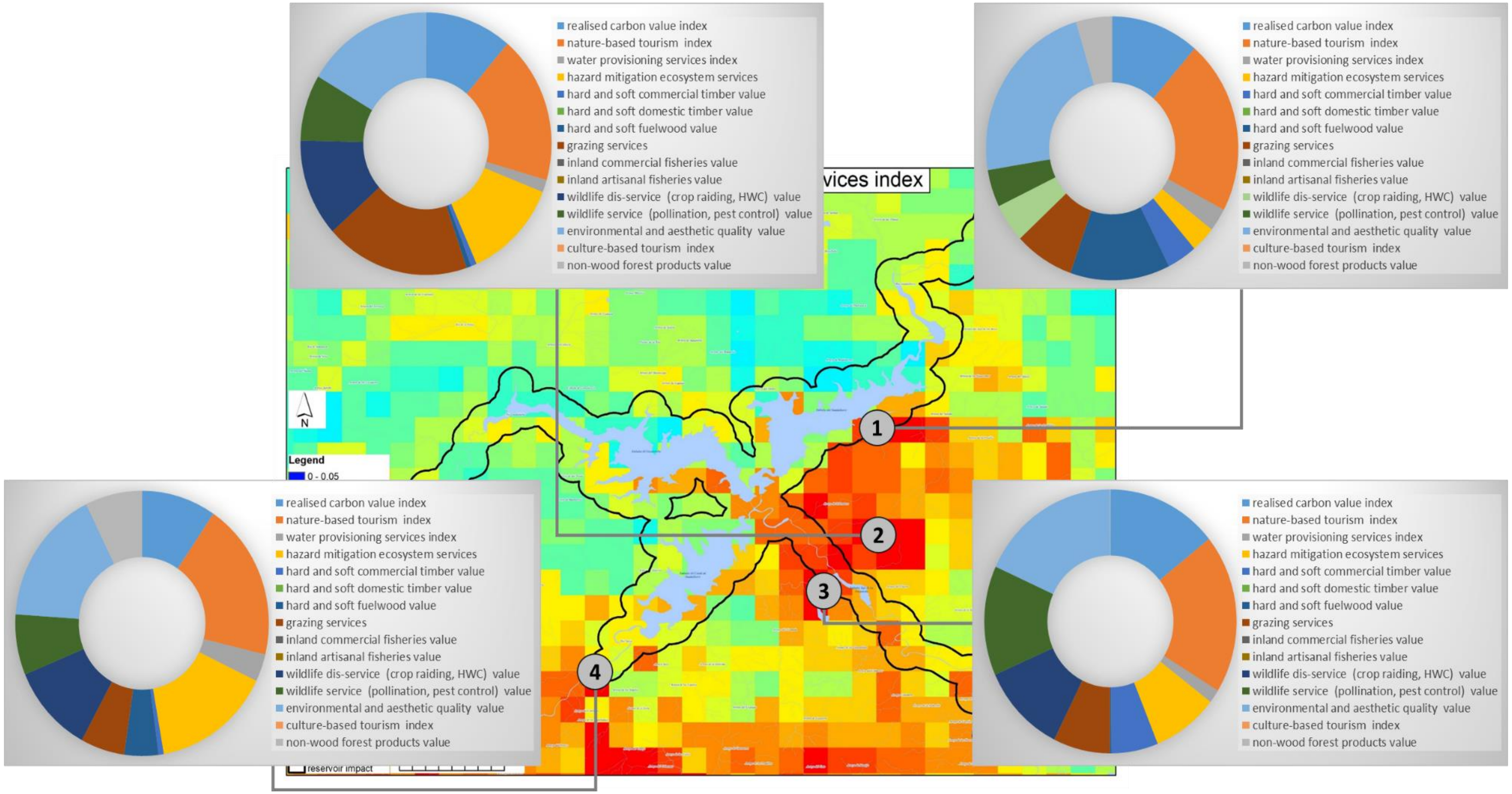

Figure 16. Ecosystem service bundles of the Guadalhorce demo site hot-spot areas. Relative contribution of 14 ecosystem services to the weight of the hotspot area according to the realized ecosystem service bundle index.

3.2.2 Impact of climate change

Spain lies in an area of special climate-change vulnerability. In Spain, annual average temperatures, especially minimum temperature, have increased over the last century by around 1.5°C (Fernández-González, 2005). The data shows a continuous warming and a 20% decrease in summer precipitation with high uncertainty of winter precipitation (IPCC, 2007). A general decreasing trend is detected in the spring. Similar decreasing trends have been found in other areas of southern Europe, in rough agreement with the most general GCM estimations for the Mediterranean area.

The thermal evolution of the seasonal maximum temperatures shows an outstanding warming in spring, about 2°C, but the amplitude of the changes is smaller in autumn and winter (about 1°C). Minimum temperature shows similar, but less pronounced fluctuations; the total warming amplitude in the 20th century is around 1°C. The mean temperatures in Andalusia have changed in agreement with those of the Iberian Peninsula, characterized by a warming in the 20th century in two periods, one in the first half of the 20th century and the second one starting in the 1970s (Castro-Diez, 2007).

Downscaled results of Co$tingNature for an A2 scenario forecast shows a decline of spring precipitation on the edges of Guadalhorce demosite of approximately 40%, with around a 50% decrease in the central area for the 2041-2100 horizon (**Figure 17**). For summer, the forecast changes reached 1.7-2mm of rainfall monthly, and appeared to be uniformly distributed across the area. Autumn precipitation is to increase by up to 8% at the edges of the demosite area, but decrease in its centre.

The temperature is projected to increase evenly throughout the whole area. The change is estimatedto be around 23% in springtime, 40% in summer and 12-25% in autumn compared to the baseline (**Figure 18**).

Considering the overlap of location of hotspots of natural capital and ecosystem services and the most severe climate change impact, potential services are more exposed to changes in water balance than realized services. Additionally, natural capital is more linked with availability of water, for example, carbon sequestration, water provision or wood and non-wood forest production. Dominating ecosystem services – nature-based tourism and aesthetic value - are mostly dependent on landscape features and infrastructure, which are less vulnerable to climate variability (**Figure 19**).

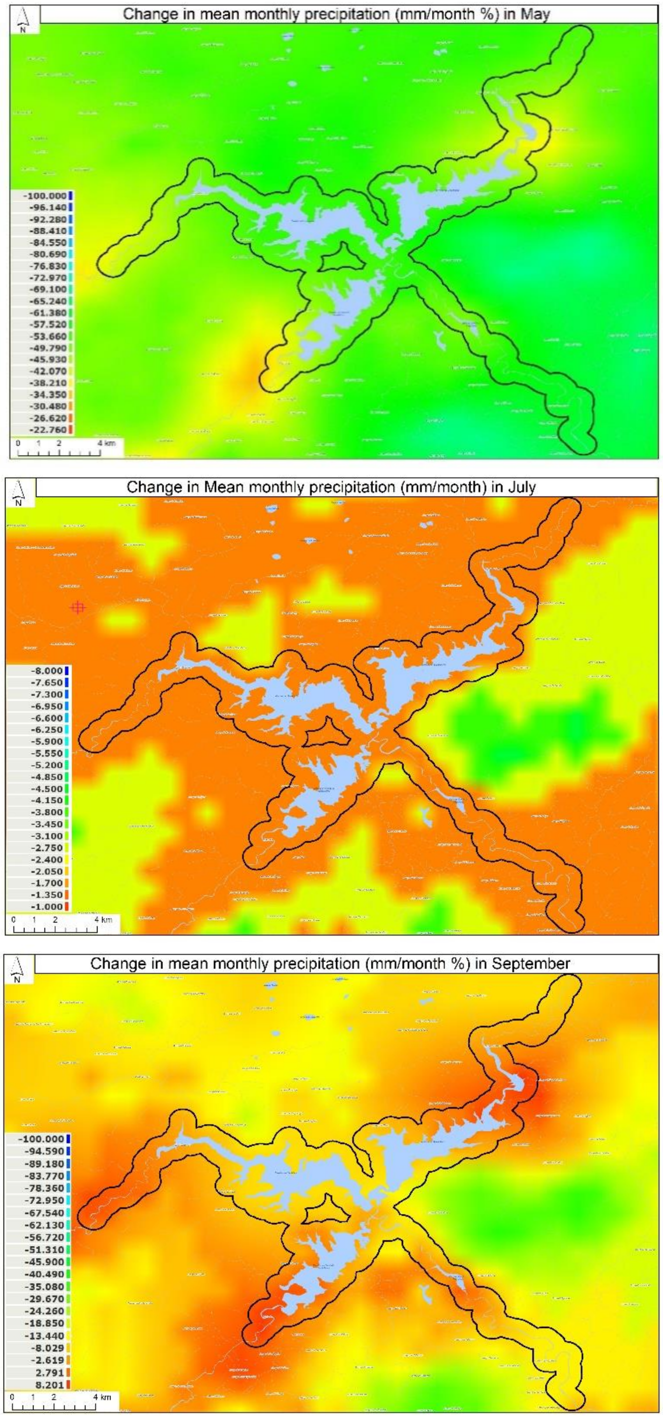

Figure 17. The change in mean monthly precipitation for May, July and September respectively in the Guadalhorce demo (in mm/month % for May and September and mm/month for July due to lack of other information).

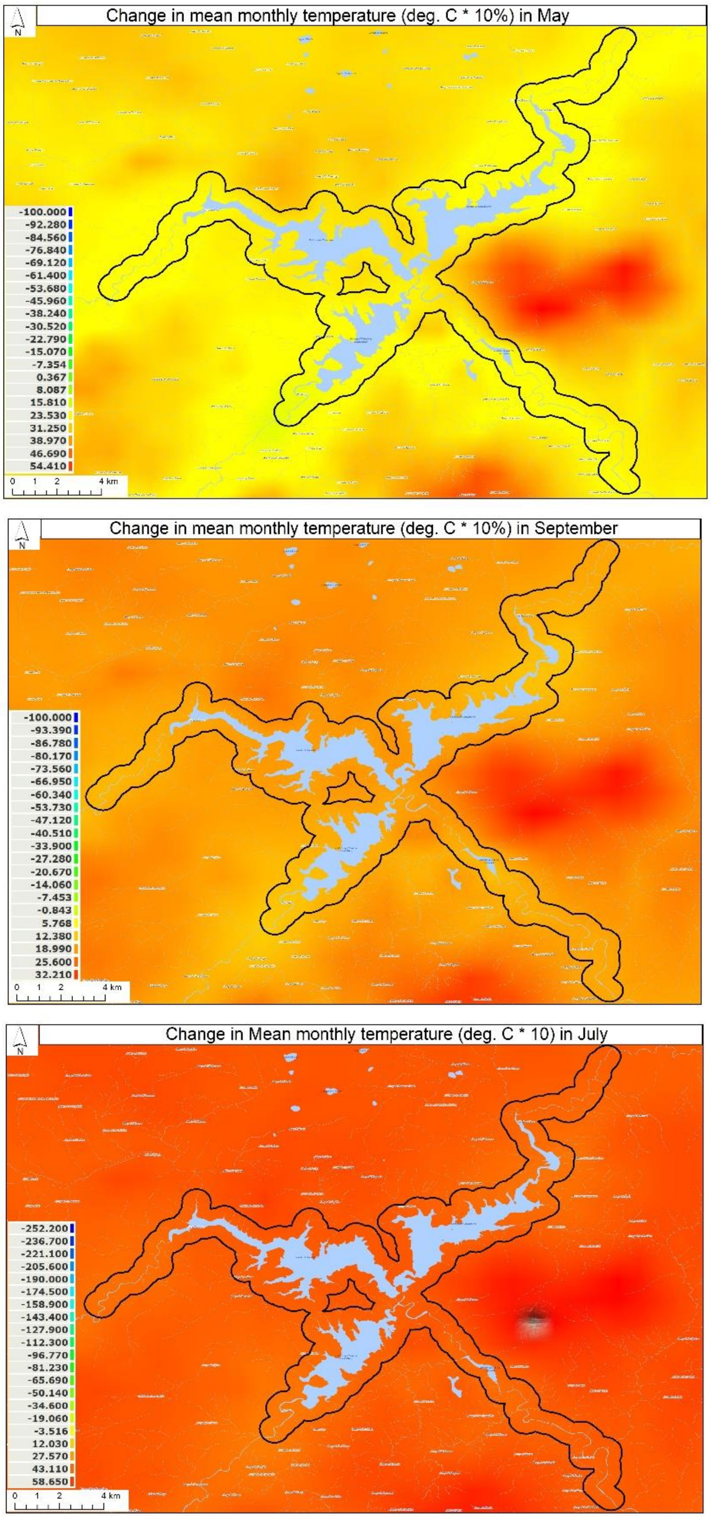

Figure 18. The change in mean monthly precipitation for May, July and September respectively in the Guadalhorce demo (in mm/month % for May and September and mm/month for July due to lack of other information).

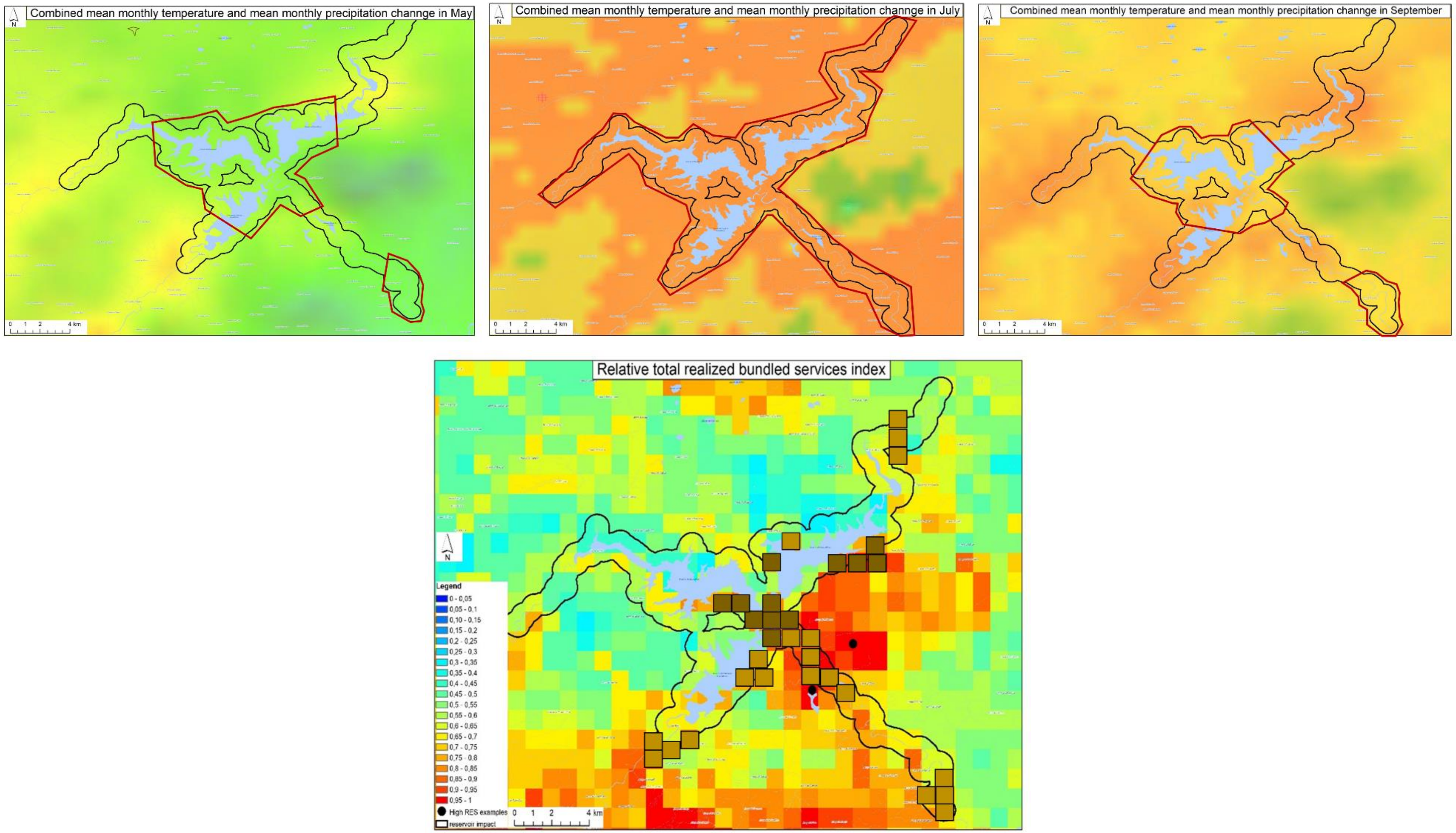

Figure 19. Areas within the Guadalhorce demo most affected by effects of climate change - May, July and September respectively vs hotspots of ecosystem services delivery.

3.3 The Neckar River, Germany

The Neckar River Basin (area, 14 000km^2) is located in the southwest part of Germany and is a tributary of the Upper Rhine. The elevation in the Neckar catchment ranges from 1020 m a.s.l. in the Black Forest to 78 m a.s.l. at Mannheim; the mean value is 435 m a.s.l. The precipitation in the region is strongly modified by the local orography. The Neckar is the principal tributary of the Upper Rhine, rises in the eastern Black Forest and is 367km long. It is the river with the largest catchment in the Federal State of Baden-Württemberg, southwest Germany. The Neckar River Valley is an example of the utilization of one of the smaller rivers for a variety of purposes in providing the needs of the resident population. In earlier times these needs were water transport, potable water supply, hydro-electric energy, agricultural water supply, dilution and disposal of waste water, cooling of thermal power plants, as well as providing zones of retreat for relaxation and leisure activities along the river banks Giesecke, 2009). Currently, the Neckar is still navigable from Plochingen at the inflow of the Fils (km 202.5) to Mannheim (at the river mouth) and beside the rivers Rhine and Main, it is one of the three main waterways in Baden-Württemberg. Several industrial centres are situated in the Neckar Basin around Stuttgart and Mannheim (Sudhaus et al., 2008). The River is used by more than 8,000 barges a year, transporting coal, gravel, scrap and scheduled transport, for example, high quality automotive products in more than 20,000 Containers.

The federal government is responsible for the Neckar as a waterway. The adjoining areas such as the bank area belong to the municipalities. Both have different and often conflicting tasks (https://www.my-favourite-river.de). For example, the use of brooks and rivers to generate electricity from hydropower has been the subject of bitter dispute for years. Fishermen and nature conservationists emphasise the considerable impairments associated with the use of hydropower in natural water systems. For those in favour of hydropower, the advantages of electricity generated without CO_2 emissions far outweigh the ecological disadvantages against the background of incipient climate change.

Those in favour of hydropower are also calling for the largest possible expansion of hydropower on the watercourse, as it is still the most important renewable energy source in the Baden-Württemberg region. At the present time, since climate change has increasingly gained media attention, the question of the future use of our waters for power generation has been raised in sharp focus. In fact, ideas have recently been developed to use unused transverse structures on the Neckar and its tributaries for hydropower, and to dam up free-flowing stretches of water and realise new locations for hydropower plants. Up to now, new constructions of transverse structures have generally been rejected by the Water Management Administration with reference to the ecological damage and the objectives of the WFD, even when the political pressure on the administration increases. As great as the need for action to mitigate climate change is, the potential of hydropower in Baden-Württemberg must be viewed with considerable scepticism. There is no doubt that there are a large number of artificial transverse structures on the state's water network that could theoretically be used to build small hydropower plants. Due to their height of fall and water availability, these plants could probably only make a minor contribution to avoiding CO_2. In a pilot project funded by the Federal Environment Agency and supported by the water management administration of the state of Baden-Württemberg, the office on the river in Plochingen is developing and testing an alternative funding model for a network of several operators of small hydropower plants together with Deutsche Umwelthilfe. The aim is to enable several operators to benefit from increased feed-in tariffs under the EEG, even if the measures are not carried out at all plants but concentrate on ecologically priority locations and waterways (Wotke et al., 2008).

3.3.1 Natural Capital and Ecosystem services

The Neckar catchment has a size of 14000km^2 and covers 39% of the total area of Baden-Wűrttemberg, inhabited by half of the state population. The numerous intense uses of the river and its catchment led to current challenges including: high demographic and industrial density, water demand and supply, water quality issues, and groundwater shortages related to the geological structure of the area, i.e. karstified shell limestone. Additional pressure is caused by a need for flood control which should be mitigated through securing water quality improvement and restructuring of river banks (over 40% of the river length is considered as artificial) (Giesecke, 2009).

Co$tingNature modelling confirmed high pressure originating from urban development, thus occurring mostly in the Mannheim - Heidelberg region, Ludwigsburg, Bad Cannstatt and Stuttgart, but also from cities associated with agricultural areas (**Figure 20**).

The natural capital hotspots are located mostly in the forested mountains of the northern part of Baden- Württemberg and the southmost part of the Hessen region, and along the Neckar River from Heidelberg to Mosbach. The other hotspot is a forested region east from the City of Esslingen am Neckar (**Figure 19**).

The realized services bundle index reaches the highest value in the Neckar floodplain between Mannheim and Heilbronn and along the river Kocher. It is also high in the southernmost edge of the Demo site East of the Neckar and South from the Fils (**Figure 20**).

The natural capital is related to hazard mitigation, water provision, fishieries potential and non wood forest products (points 1-6, **Figure 23**). Hazard mitigation is the most important component of the potential ecosystem service bundles in the Mannheim region. Water provision took first place in all the other hot spot locations.

The key contributors to hotspots of realized services are commercial fisheries (points 1 and 2, **Figure 24**), nature (point 1, **Figure 24**) and culture-based tourism (points 3 and 5, **Figure 24**). Hazard mitigation potential service is realized in point 5 (**Figure 24**), while fuel wood and non-wood forest products are key services of the bundle in hotspot 4 (**Figure 24**).

The distribution of natural capital and ecosystem service hotspots coincides partially with the areas of high environmental pressure. That refers to hotspot areas around points 1-3 and 5 and 6 of the natural capital distribution map (**Figure 23**) and 1 and 6 on the ecosystem service map (**Figure 24**).

The services demanded by society but not delivered by the river (neither present as potential service) are water related recreation and habitat creation (Giesecke, 2009).

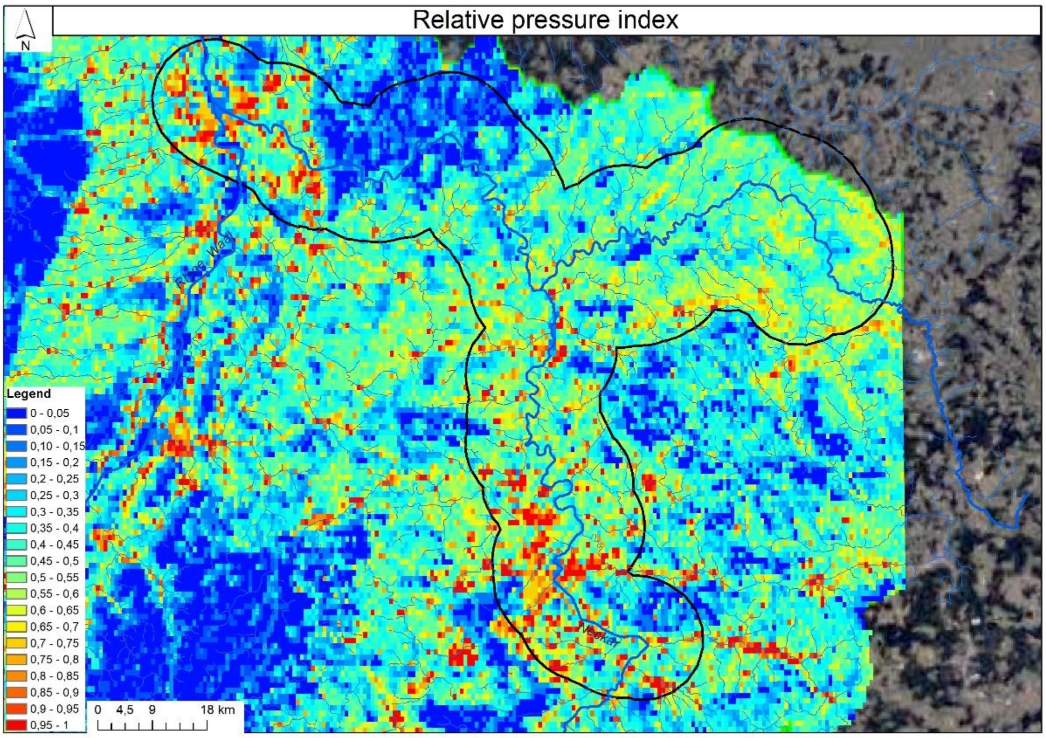

Figure 20. Current pressures in the Neckar demo site (marked with black line) according to population, wildfire frequency, grazing intensity, agricultural intensity, dam density, and infrastructure (dams, mines, oil and gas, urban) density.

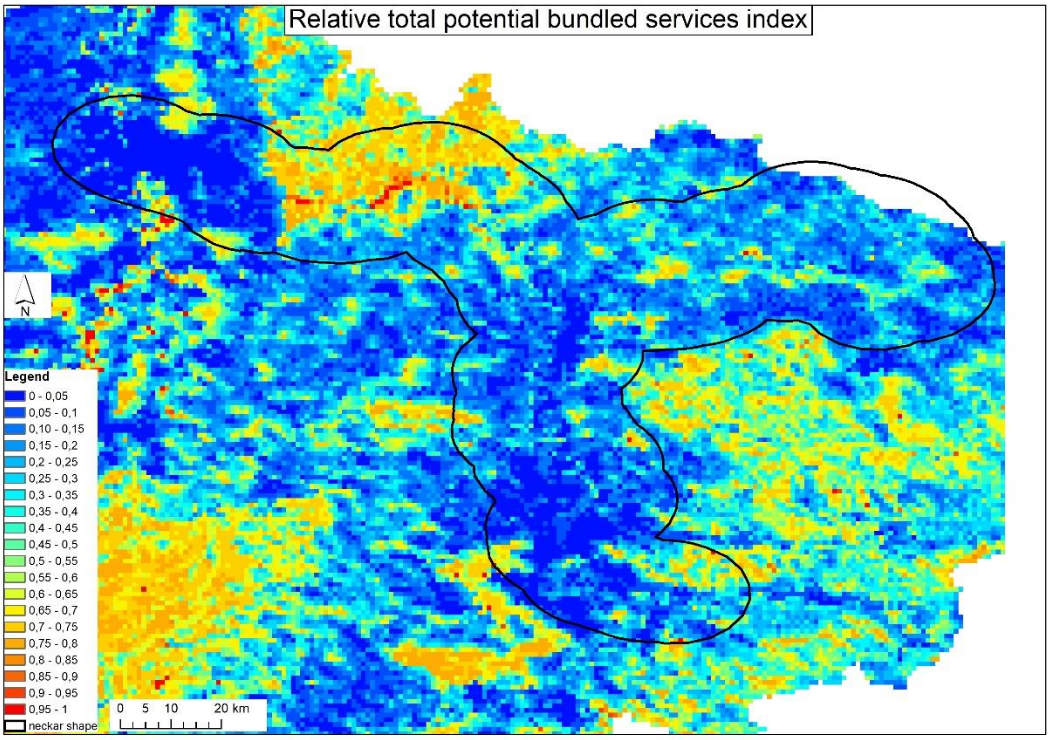

Figure 21. The allocation of potential ecosystem service bundles within Neckar demo area (natural capital hotspots).

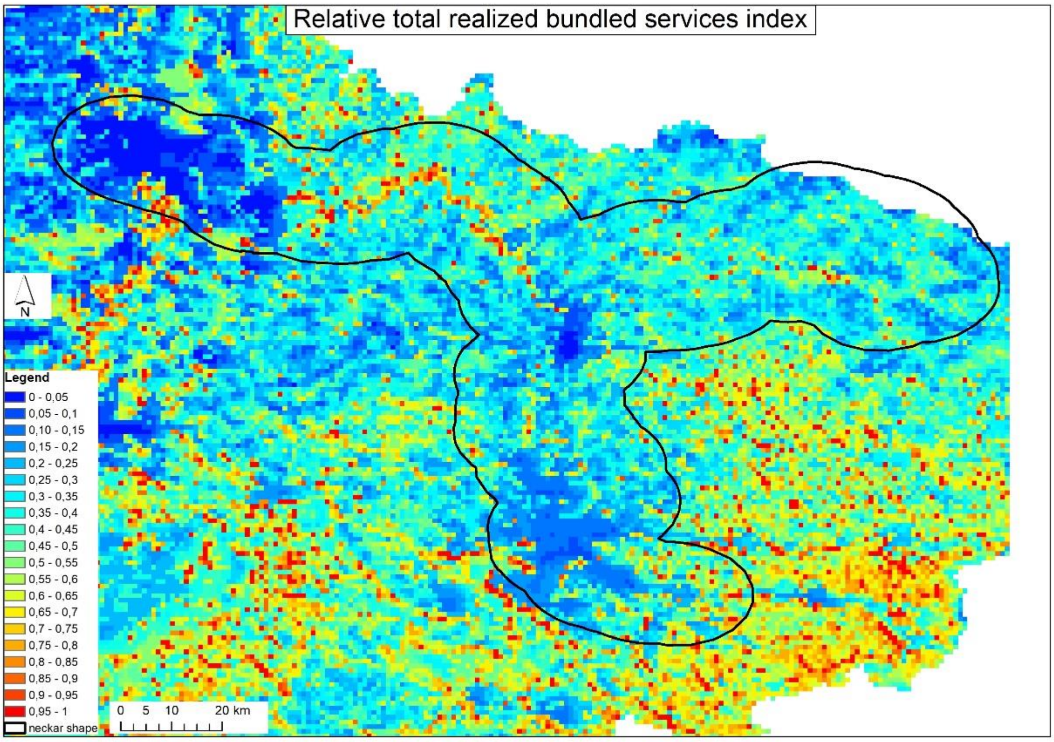

Figure 22. The allocation of realized ecosystem service bundles within Neckar demo area (ecosystem service hotspots).

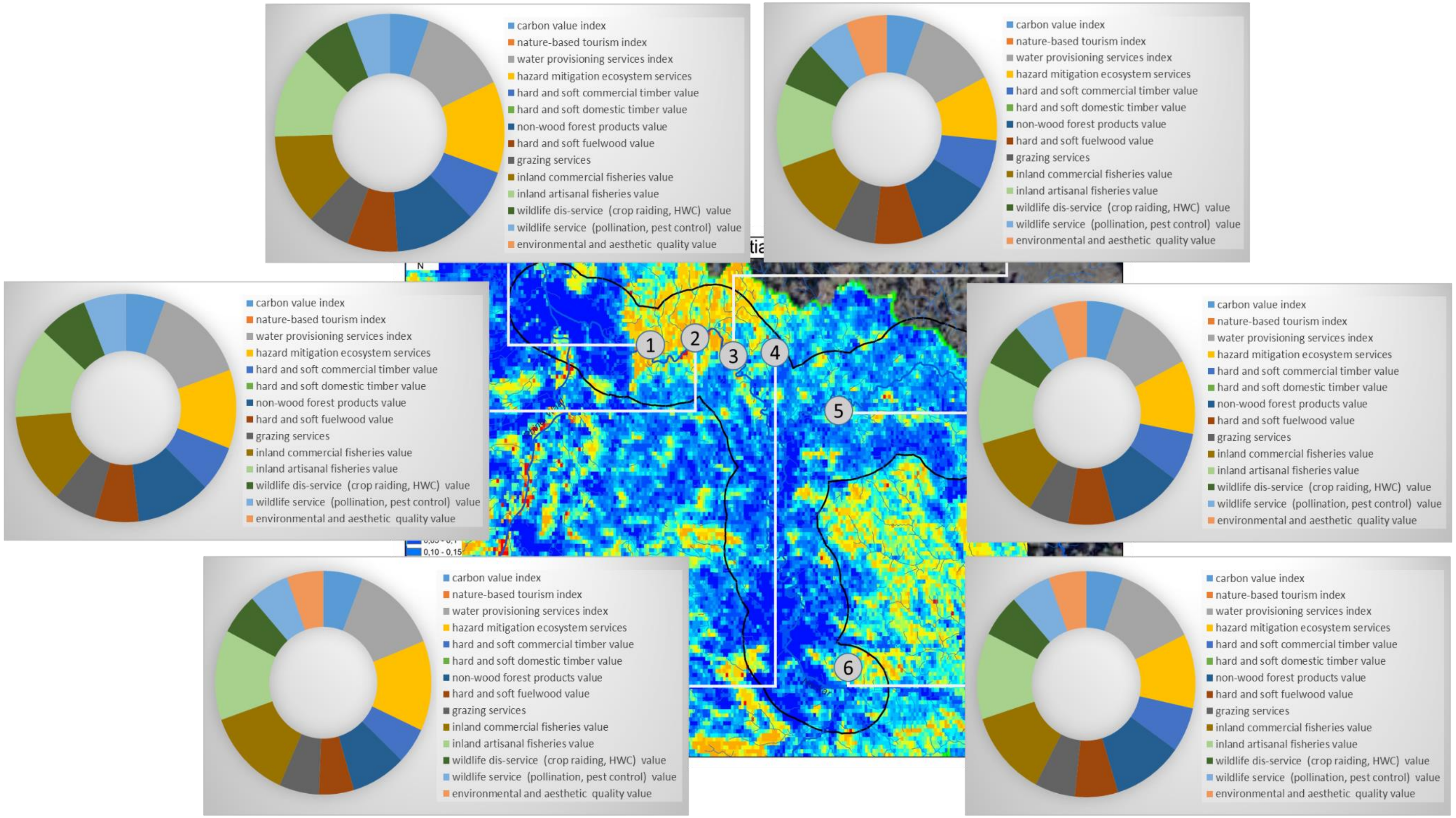

Figure 23. Ecosystem service bundles of the Neckar demo site hotspot areas. Relative contribution of 14 ecosystem services to the weight of the hotspot area according to the potential ecosystem service bundle index.

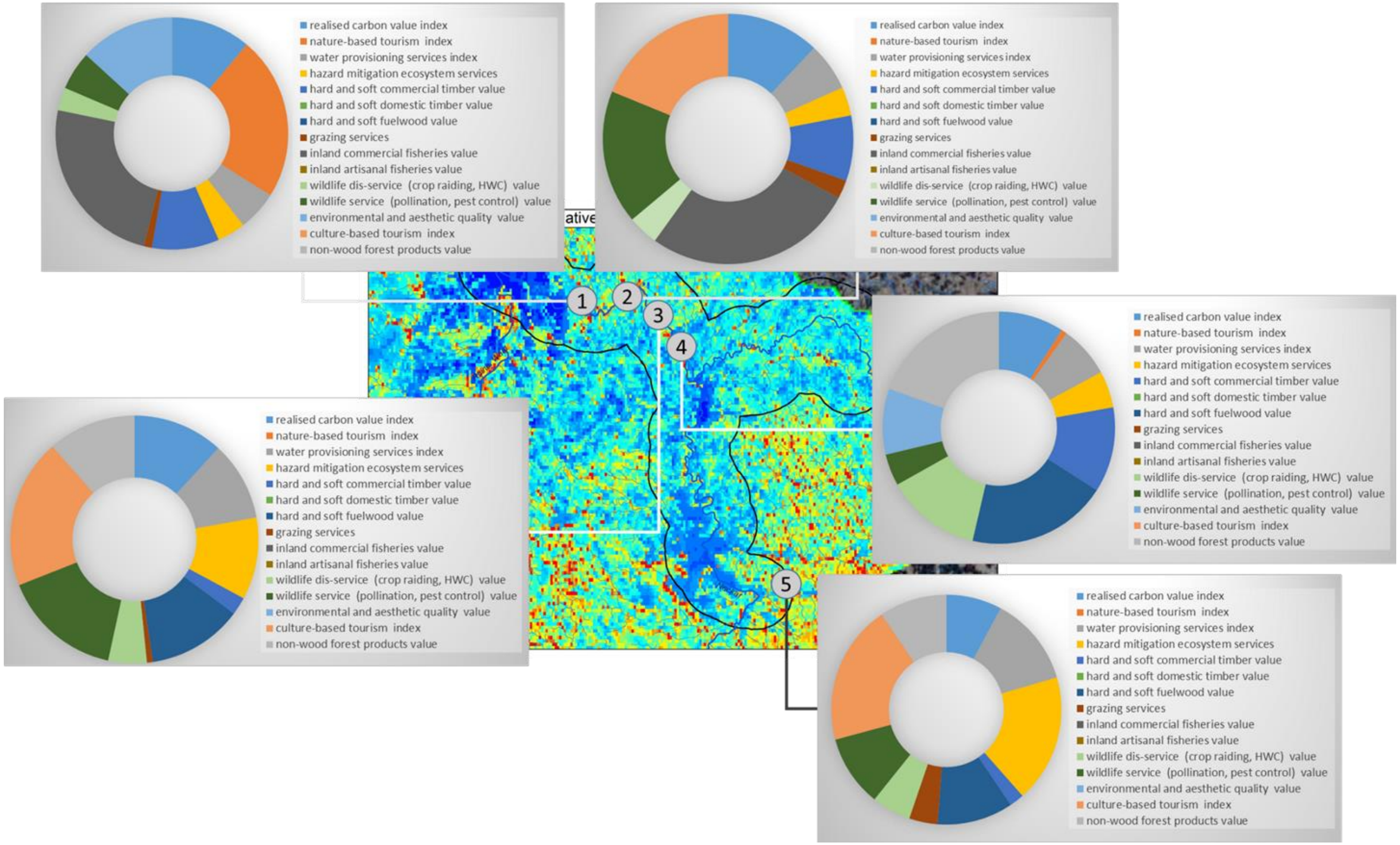

Figure 24. Ecosystem service bundles of the Neckar demo site hot-spot areas. Relative contribution of 14 ecosystem services to the weight of the hotspot area according to the realized ecosystem service bundle index.

3.3.2 Impact of climate change

The State of Baden-Württemberg is already experiencing the impact of climate changes which will very likely accelerate even further in the future. The analysis of historical data shows that the mean temperature in Baden-Württemberg has risen from 1901 to the present day from around 8°C to over 9°C. The biggest increase has taken place over the last 30 years. Since the 1980s, maximum winter precipitation levels have risen by 35%, as have the number of flood events. On the other hand, summers tend to be drier than in the past. The number of days on which lower-lying areas are covered in snow has decreased by an average of 30 to 40%. By 2009, the number of summer days in Stuttgart had risen to 45, while the number of ice days had fallen to just 15 (Ministry of the Environment, Climate Protection and the Energy Sector, 2012).

The forcast until 2040 foresees an increase in the number of summer days (maximum temperatures of at least 25°C) at different rates according to region. The number of summer days in the Rhine and Neckar Valleys, as well as Lake Constance, will increase by 15 - 20 days a year; in higher-lying areas by just under 10 days. While this means an increase of "just" 40 % for the Rhine Valley, these figures imply twice as many summer days in parts of the Black Forest and the Swabian Alb. What is more, the KLARA research programme shows that some of the lower-lying areas of Baden-Württemberg in particular, such as the Upper Rhine Valley, will have up to 15 more hot days (maximum temperatures of at least 30°C) in the period 2046 to 2055 than they did between 1951 and 2000.

The Karlsruhe Institute of Technology (KIT) has also studied the probability of an increase in heavy rainfall in Baden-Württemberg in the future. The findings reveal that flooding following heavy rainfall, landslides or erosion poses a real danger in low mountain ranges in particular. The climate simulations suggest that while the total amount of precipitation will remain much the same throughout the course of the year, the incidence of rainfall will be distributed differently. Overall there will be an increase in extreme weather events in Baden-Württemberg (Ministry of the Environment, Climate Protection and the Energy Sector, 2012).

According to the WaterWorld simulation of A2 scenario for 2041-2100, spring monthly precipitation is to remain almost the same - from a 3% increase to 2% decrease across the Neckar Demo site area. Summer precipitation is likely to decrease in the whole area by around 6-11.5%. The autumn precipitation is foreseen to increase from 2 to 11% on average, however the increase is to be higher – up to 20% - in the Hirschhorn-Heidelberg area (**Figure 25**). The temperatures are projected to rise, with the smallest change modelled for spring – 2-20% increase, except Mannheim – Neckargerach area with increase up to 32%. In summer the right side of the catchment is to experience a temperature rise of around 15-20% and the left-side 10-15%. Finally, in autumn the upper part of the demo site (above Kocher inflow) is to experience a 19-25% increase in temperature and lower around 13-19% (**Figure 26**).

Comparison of ecosystem service and climate change hotspots indicate both temperature and precipitation increase in critical service donor/stock areas. The smallest changes appear in the spring-summer period, although temperatures will increase more than precipitation and imposes a risk to water resources in vegetative periods. The biggest changes are forecast for autumn (**Figure 27**).

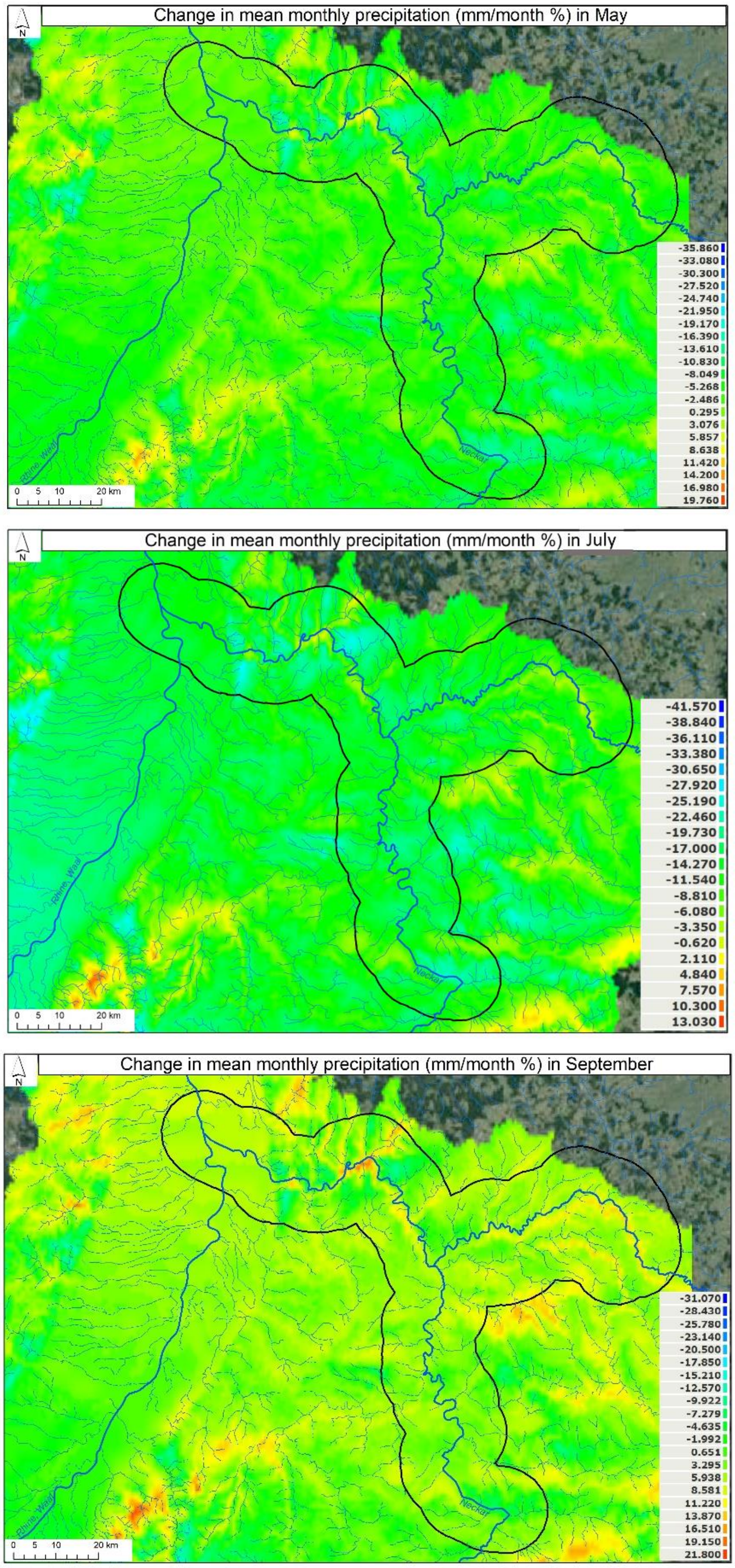

Figure 25. The change in mean monthly precipitation for May, July and September respectively in the Neckar demo (in mm/month %).

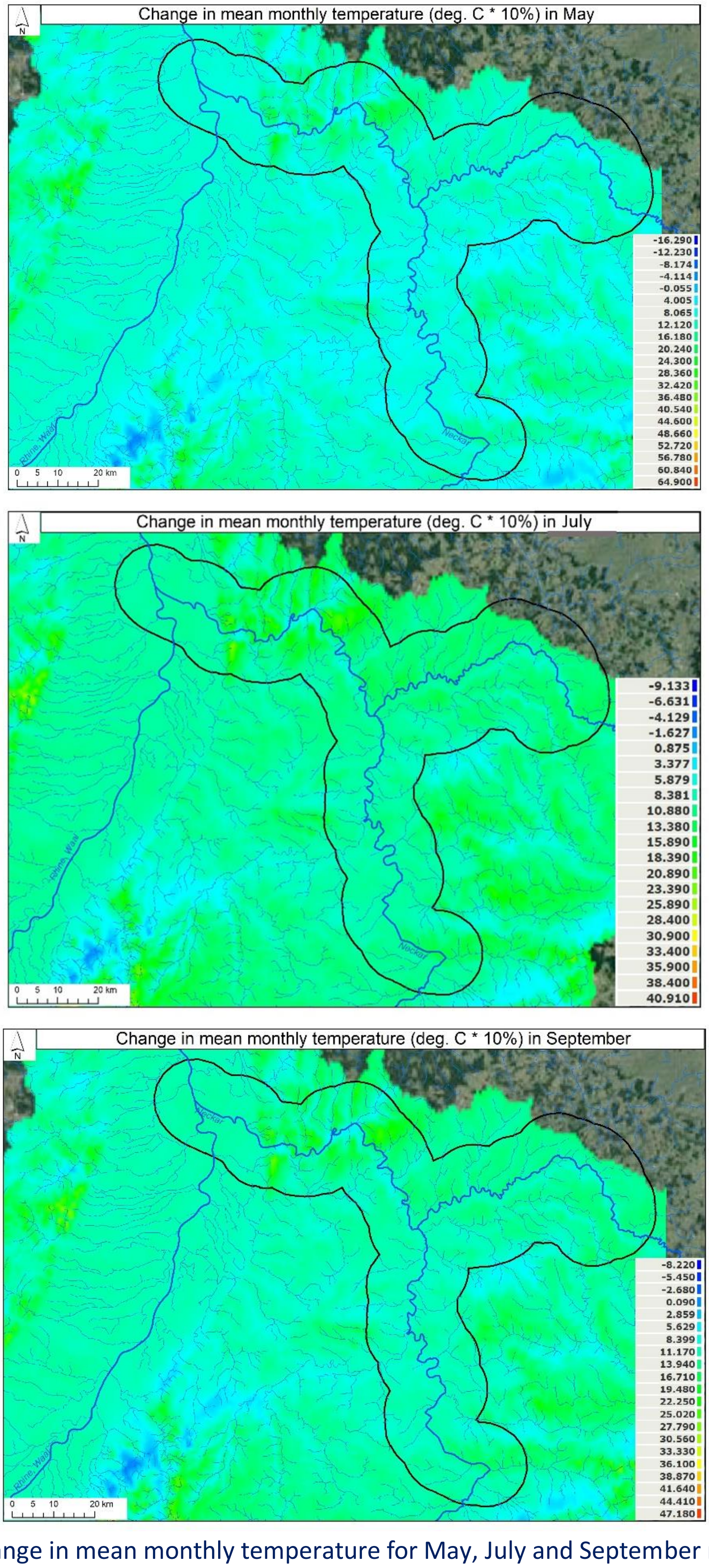

Figure 26. The change in mean monthly temperature for May, July and September respectively in the Neckar demo (in deg. C *10 %).

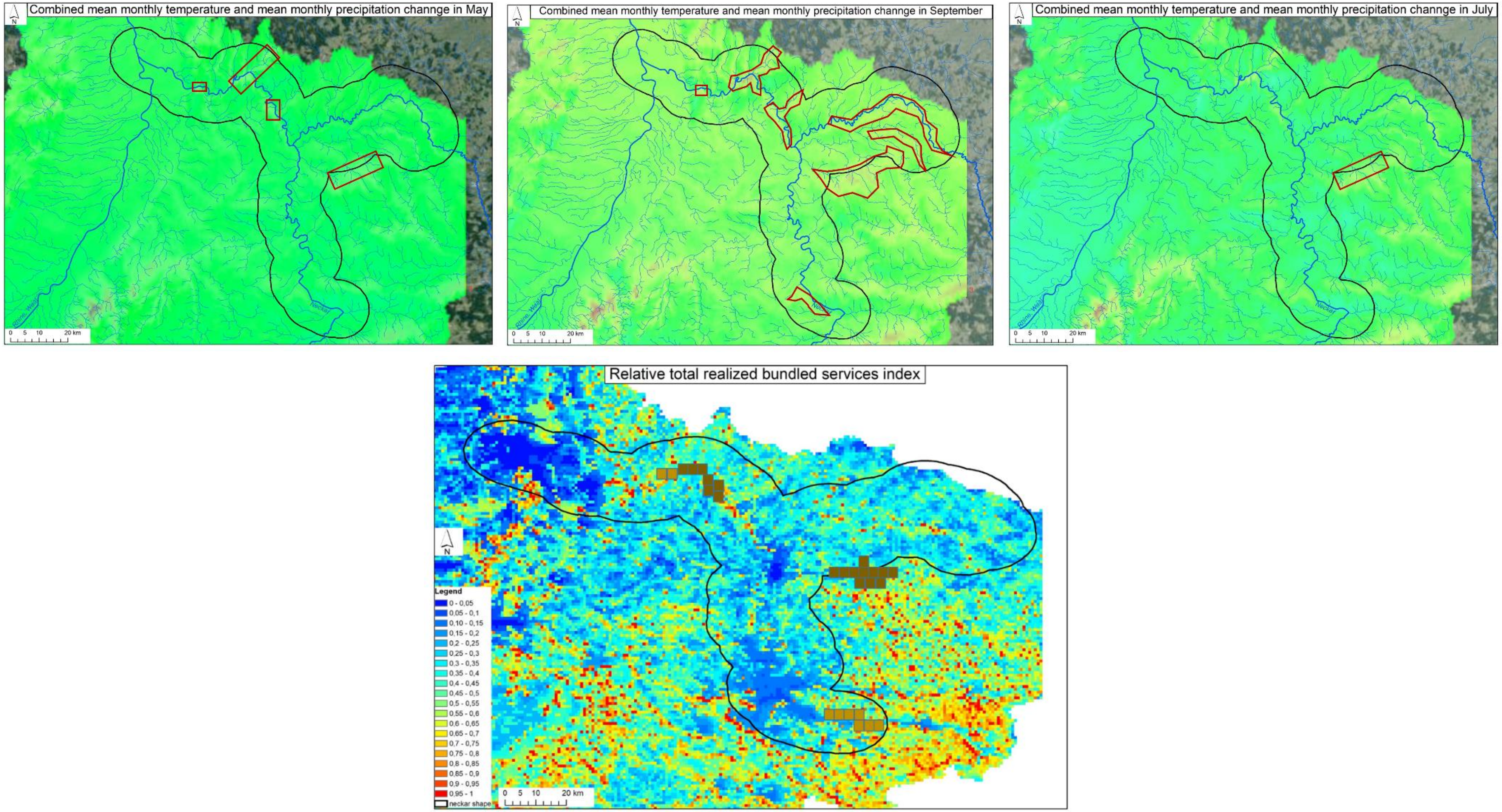

Figure 27. Areas within the Neckar demo the most affected by adverse effects of climate change - May, July and September respectively vs hotspots of ecosystem services delivery.

4 CLIMATE CHANGE AND WATER MANAGEMENT FOR ECOSYSTEM SERVICES

The provision of ecosystem services is projected to decline across all categories in response to climate change in the Mediterranean region and mountain areas. Both gains and losses in the provision of ecosystem services are projected for the other European regions, and the provision of cultural services such as recreation and tourism are projected to decline in the Continental, Northern and Southern regions (IPCC, 2014).

The first reason is to be a change in water cycle affecting runoffs. Smakhtin et al. (2004) made an attempt to estimate the volume of water required for the maintenance of freshwater-dependent ecosystems at the global scale. This total environmental water requirement (EWR) consists of ecologically relevant low-flow and high-flow components. The relationship between water availability, total use and the EWR is described by the water stress indicator (WSI). If WSI exceeds 1.0, the basin is classified as "environmentally water scarce". In such a basin, the discharge has already been reduced by total withdrawals to such levels that the amount of water left in the basin is less than EWR. Smaller index values indicate progressively lower water resources exploitation and lower risk of "environmental water scarcity."

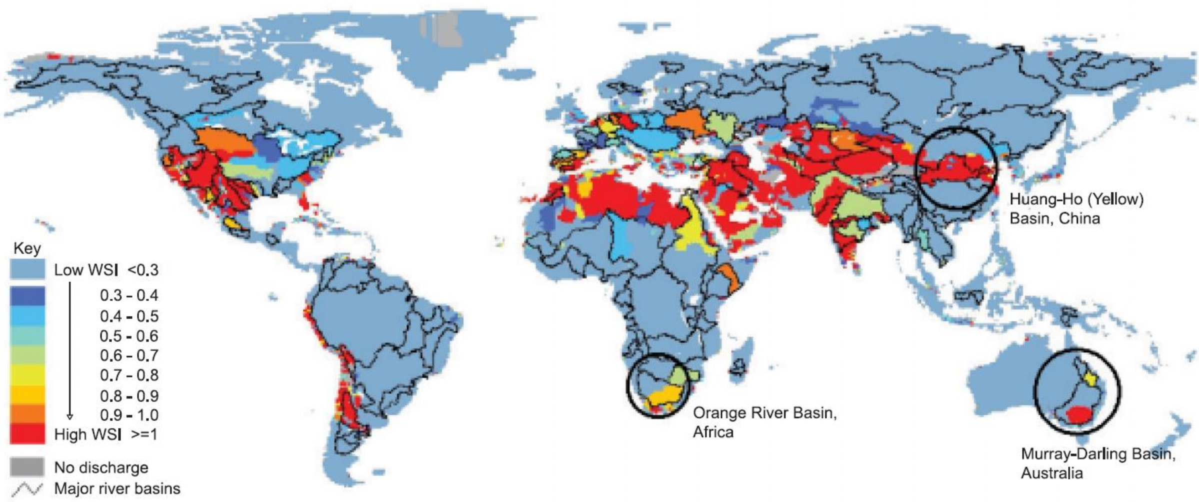

Figure 28. A map of a water stress indicator that takes into account EWR. Areas shown in red are those where EWR may not be satisfied under current water use. The circles include example river basins which can move into a higher category of human water scacrity if EWR are to be satisfied. The risk of not meeting EWR will remain high in these basins, particularly as water withdrawals grow (Smakhtin et al., 2004).

The study indicated that the basins considered in this report have already been experiencing water stress: much of Spain presents a high WSI, similarly Germany, while Poland falls into the 0.4-0.5 category, thus basins moderately exploited (**Figure 28**).

The second cause of the change in ecosystem service delivery is the complex interaction among water users and water-energy-land nexus. Rockstrom et al. (2009) assessed green-blue water (irrigation and infiltrated water) availability and requirements by applying the LPJml vegetation and water balance model (Gerten, 2004). They applied climate data for a present-day simulation, and climate change projections from the HadCM2 GCM under the SRES A2 scenario to represent the climate change scenario for the year 2050. When water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency.

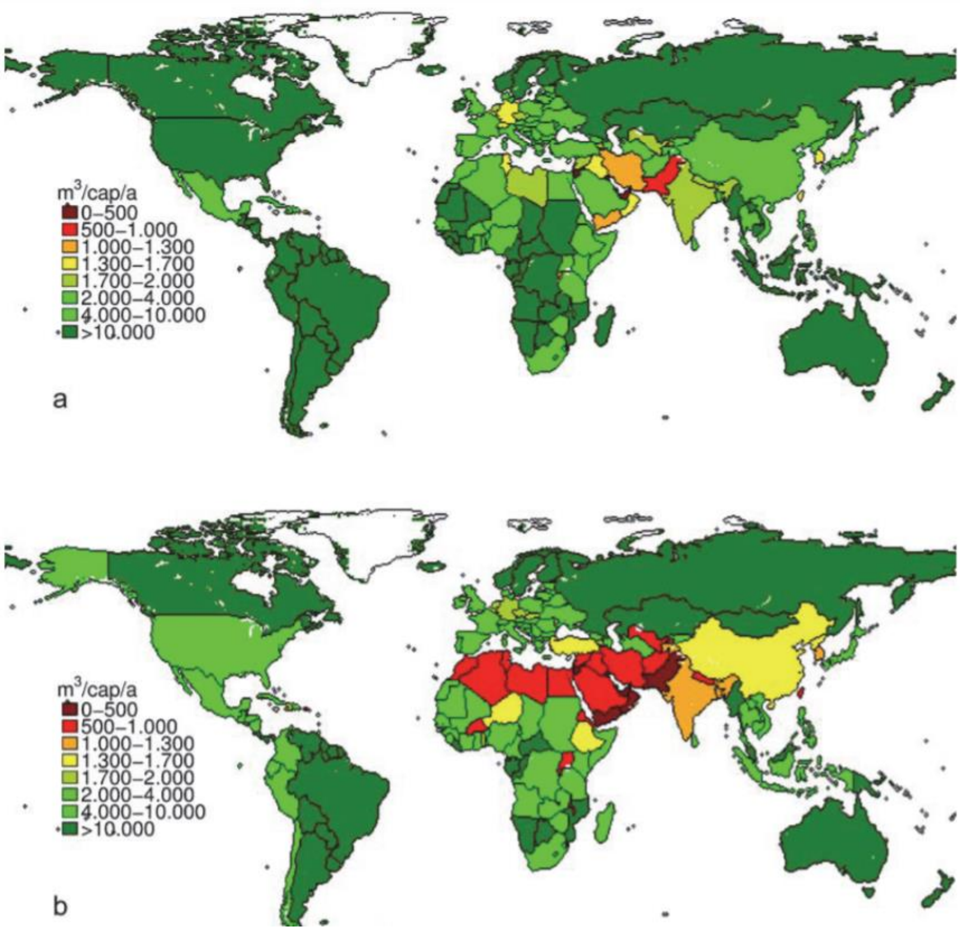

Figure 29. Simulated blue-green water availability (m^3/capita/year) for present climate (top panel) and including both demographic and climate change under the SRES A2 scenario in 2050 (bottom panel) (Rockstrom et al., 2009).

The results showed that globally in 2050 and under the SRES A2 scenario (the same as applied by this report), around 59% of the world's population could be exposed to "blue water shortage" (i.e. irrigation water shortage), and 36% exposed to "green water shortages" (i.e. infiltrated rain shortage). For all the studied areas, blue-green water availability is far above the threshold in current, and projected, conditions (**Figure 29**). This indicates that demos' water resource requirements should be met without major disruption of water balance by 2050. However WaterWorld and Co$tingNature simulations warn of significant regional and temporal differences that may change the global picture locally. There may be also an issue of uncertainty of projections. For example, the reaction of the Rhine basin to climate change may significantly vary spatially. Following the HIGH scenarios, the estimated temperature change, resulting in increased evapotranspiration, cannot compensate for increased precipitation, and results in an increase in water availability and stream flow in all seasons.

Whereas according to the LOW scenarios, temperature increase amplified the effects of precipitation decrease, resulting in lower discharges at the basin ouflet (Kwadijk, 1995).

Land use is the third major factor influencing the distribution and functioning of ecosystems and thus the delivery of ecosystem services. Urbanization, increase of irrigated agricultural land, intensification of agriculture and forest management is jeopardising the provision of several key ecosystem services, threatening biodiversity, and increasing Europe's vulnerability to climate change and natural disasters. The increasing impacts from climate change are already affecting species and habitats, exacerbating other threats, like soil degradation and desertification (EEA, 2012). More than 25% of the EU's territory is affected by soil erosion by water, which compromises soil functions and freshwater quality. Soil contamination and soil sealing are also persistent problems (EC, 2013). These impacts are projected to become progressively more significant in the coming decades, i.e. an atmospheric nitrogen deposition (EEA 2015), or increased sediment load to reservoirs and rivers.

Up to now, ecosystem disservices played a relatively small role in all three demo sites, although their presence has already been noted in the cases of the Włocławek Reservoir and the Guadalhorce demosite. However fires, erosion, nutrient leakage, sediment load and flooding are becoming disservices increasing the risk to local and regional economies. The latter two have already been projected as affecting future ecological and economic sustainability of the Neckar demo site (Middelkoop, 2000).

Taking this into account, the EEA (2017) formulated a number of challenges related to land use across Europe **(Figure 30**). Considering the three analysed AMBER demo sites, each falls into three different priorities of action. The Włocławek demo site represents an area challenged with maintaining on-field biodiversity, establishing good practices in planning and land use and increasing land profitability without intensification of use. As of now the goals are met, the area is delivering important ecosystem services, and securing natural capital is more or less free from significant pressures. However, there are plans for development of infrastucture, namely a number of barriers downstream with development of transportation network along the Vistula. This may, together with climate change, threaten or even shorten delivery of services now and in the future. The Guadalhorce demo is located in the area which, on top of maintaining on-field biodiversity and increasing land profitability without intensification of resourec use, is challenged with the need to reduce water stress caused by irrigation. Considering temperature increases and decreases in precipitation, thus an increase of evapotranspiration, demand for water supply for agriculture may significantly increase in the coming decades. Finally, the Neckar demo is challenged with reduction of pressure on air, soil and waters caused by urbanization and industrial agriculture. The Co$tingNature model proved high dispersion of pressures, which intensify around metropolitan areas and coincide with natural capital and ecosystem service hot spots.

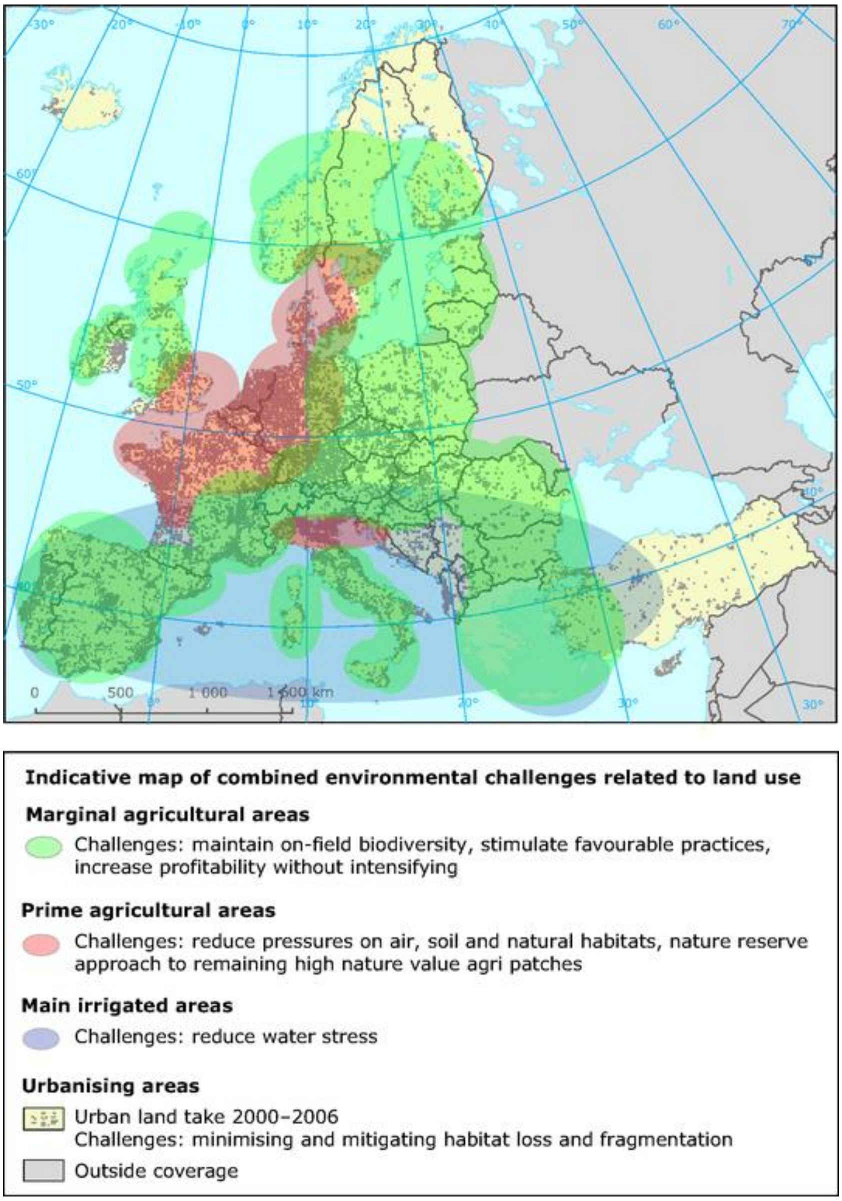

Figure 30. The indicative map of combined environmental challenges captures some of the complexity of the multiple demands on land resources, with urban sprawl, agricultural intensification and land abandonment exerting pressures on biodiversity and water resources (source EEA https://www.eea.europa.eu/data-and-maps/figures/indicative-map-of-combined-environmental).

5 SUMMARY

The question of possible climatic change effects on nature and human society is presently a major topic of public discussion. The observed weather phenomena of recent years, in particular precipitation events, make clear that water management must also adapt to changes occurring in runoff behaviour. It is necessary even if greenhouse gas emissions were to stop today, because the climate changes are projected to continue for many decades as a result of past emissions and the inertia of the climate system (IPCC, 2013). While mitigation of climate change is crucial, it is also necessary to adapt to already experienced changes in climate and to plausible future climate scenarios. Adaptation focuses on ensuring that even under changing conditions socio-ecological systems maintain the functionality of the different assets, like built infrastructure, the natural environment, culture, society and economy (EEA, 2017).

UN Water (https://sustainabledevelopment.un.org/content/documents/UNWclimatechange_EN.pdf) considers the following main steps in adaptation of water management to climate change:

1. Mainstreaming adaptation within the broader development context;
2. Strengthening governance of water resources management and improving integration of land and water management;
3. Improving and sharing knowledge and information on climate, water and adaptation measures, and investing in comprehensive and sustainable data collection and monitoring systems;
4. Building long-term resilience through stronger institutions and water infrastructure, including well-functioning ecosystems;
5. Investing in cost-effective adaptive water management and technology transfer;
6. Releasing additional funds through increased national budgetary allocations and innovative funding mechanisms for adaptation through improved water management.

Furthermore, the scale, as well as the spatial and temporal concurrence of supply and consumption of ecosystem services, determines the scale at which policy must be effective (Foley et al., 2005). Brauman et al. (2007) suggest that “if a lower bound exists for the area of an ecosystem necessary to produce a service, markets might need to bundle services at the beneficiary end, provide adjacency bonuses to suppliers, or develop existing institutions into structures such as ecosystem service districts”.

From this perspective, barrier (de)construction and management, ecosystem-service based adaptation to climate change, and sustaining delivery of important services, requires extensive understanding of the sensitivity of local systems. The key operational issues seem to be:

- Re-evaluation of stream flow changes and annual water availability for aquatic and water dependent systems, as well as key stakeholders in the area of barrier impact, considering that for most of sites the adherence of high and low flows will probably increase; consequently -

- Protection of areas prone to flooding with binding local land-use plans and no zoning/buildings allowed in high risk areas, but also areas offering drought/flood protection through accumulated natural capital; through -
- Establishing ecological design of river/reservoir banks and floodplains and ecosystem hotspot areas, being not necessary in physical proximity of the barrier/reservoir/river but bound functionally; and also through -
- Expansion of retention potential, restoration of systems increasing adaptive potential of barrier affected areas, for example, extensive forests, extensive agricultural lands, wetlands, multi-functional urban and peri-urban spaces; and
- Well controlled upgrading of certain areas for recreational activities to decrease ecosystem disservices.

6 ACKNOWLEDGMENTS

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7 REFERENCES

Bagstad, K.J., Semmens, D., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. *Ecosystem Services* **5**: 27-39

Baró, F., Gómez-Baggethun, E., & Haase, D. 2017. Ecosystem service bundles along the urban-rural gradient: Insights for landscape planning and management. *Ecosystem Services,* **24**: 147–159.

Bennett EM, Peterson GD, Gordon LJ. Understanding relationships among multiple ecosystem services. *Ecol Lett*, **12**:1394–1404.

Brauman, K. A., Daily, G. C., Duarte, T. K., & Mooney, H. A., 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. *Annual Review of Environment and Resources*, **32**(1), 67–98.

Bruijnzeel, L. Mulligan, M. Scatena F.N., 2011. Hydrometeorology of tropical montane cloud forests: emerging patterns *Hydrol. Process*., **25** (3): 465-498

Canadell, J. G., Ciais, P., Cox, P., & Heimann, M. 2004. Quantifying, Understanding and Managing the Carbon Cycle in the Next Decades. *Climatic Change*, **67**(2-3): 147-160

Castro-Díez,Y.,Jesús Esteban-Parra, M., Staudt, M., Gámiz-Fortis, S., 2007. Temperature and Precipitation Changes in Andalusia in the Iberian Peninsula and Northern Hemisphere context. El cambio climático en Andalucía: evolución y consecuencias medioambientales Consejería de Medio Ambiente (Junta de Andalucía): 57-77

de Groot R.S., Wilson M.A., Boumans R., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol Econ* **41**:393–408.

Sudhaus, D., Seidel, J. Burger, K., Dostal, P., Imbery, F., Mayer, H., Glaser, R. and W. Konold, 2008. Discharges of past flood events based on hydrological river profiles. *Hydrol. Earth Syst. Sci.*, **12:** 1201–1209

EC 2013. Mapping and assessment of ecosystems and their services — An analytical framework for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020, European Commission

EC, 2014. Attitudes of European citizens towards the environment. *Special Eurobarometer* 416.

EC, 2015. Attitudes of europeans towards biodiversity. *Special Eurobarometer* 436. DOI 10.2779/832333.

EEA 2012. Climate change, impacts and vulnerability in Europe 2012 — an indicator-based report, EEA ReportNo 12/2012, European Environment Agency

EEA 2017. Climate change, impacts and vulnerability in Europe 2016. An indicator-based report. EEA Report No 1/2017

EEA, 2009. Water resources across Europe — confronting water scarcity and drought. EEA Report No 2/2009.

EEA, 2011. Annual report 2010 and Environmental statement 2011. EEA, Copenhagen

EEA, 2012. Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions. A Blueprint to Safeguard Europe's Water Resources. COM(2012) 673 final

EEA, 2015. SOER 2015: The European environment — state and outlook 2015 with the European briefings on Soil (Published 18 Feb 2015)

EEA, 2015. The European environment — state and outlook 2015: synthesis report, European. Environment Agency, Copenhagen.

1FAO, 2011. the State of the World's Land and Water Resources for Food and Agriculture (SOLAW)-Managing Systems at Risk, Earthscan, London.

Fernández-González, F., Loidi, J., Moreno, J.C., del Arco, M., Férnández-Cancio, A., Galán, C., García-Mozo, H., Muñoz, J. Pérez-Badia, R., Sardinero, S. & Tellería, M., 2005. Impact on Plant Biodiversity. In: Impacts on Climatic Change in Spain. OCCE. Moreno, J.M. ed. Ministerio de Medio Ambiente. Madrid, Spain. 183-248pp.

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, et al. 2005. Global consequences of land use. *Science* **309**: 570–74

Gerten D., Schaphoff S., Haberlandt U., Lucht W., Sitch S. 2004 . Terrestrial vegetation and water balance: hydrological evaluation of a dynamic global vegetation model. *International Journal Water Resource Development*, **286:** 249–270.

Giesecke, J., 2009. Sustainable industrial water use in Southern Germany. Fresh Surface Water 3: 167-195. EOLSS Publications

Giesecke, J., 2009. Sustainable Industrial Water Use in Southern Germany. In: Dooge, J. (Ed.), Fresh Surface Water - Volume III. Eolss Publications, 338pp

Howe C, Suich H, Vira B, Mace GM, 2014. Creating winwins from trade-offs? Ecosystem services for human well-being: a meta-analysis of ecosystem service trade-offs and synergies in the real world. *Glob Environ Change* **28**:263–275.

IMA, 2006. Environment in Andalusia through environmental indicators. http://www.juntadeandalucia.es/

IPCC 2013. Climate Change 2013. The Physical Science Basis Summary for Policymakers, Technical Summary and Frequently Asked Questions. Working Group I Contribution To The Fifth Assessment Report Of The Intergovernmental Panel On Climate Change.

IPCC AR4 SYR, 2007. Core Writing Team; Pachauri, R.K; Reisinger, A. (eds.), Climate Change 2007: Synthesis Report, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, ISBN 92-9169-122-4

IPCC SRES, 2000. Nakićenović, N.; Swart, R. (eds.), Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change (book), Cambridge University Press, ISBN 0-521-80081-1

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge,United Kingdom and New York, NY, USA, 996 pp

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Keeler, B. L., Polasky, S., Brauman, K. A., Johnson, K. A., Finlay, J. C., O'Neill, A., … Dalzell, B., 2012. Linking water quality and well-being for improved assessment and valuation of ecosystem services. *Proceedings of the National Academy of Sciences*, **109**(45), 18619–18624.

Kong, L., Zheng, H., Xiao, Y., Ouyang, Z., Li, C., Zhang, J., & Huang, B., 2018. Mapping Ecosystem Service Bundles to Detect Distinct Types of Multifunctionality within the Diverse Landscape of the Yangtze River Basin, China. *Sustainability*, **10**(3): 857.

Kwadijk, J., & Rotmans, J., 1995. The impact of climate change on the river R hine: A scenario study. *Climatic Change*, **30**(4), 397–425.

Locatelli B., Kanninen M., Brockhaus M., Colfer C.J.P., Murdiyarso D., Santoso H., 2008. Facing an uncertain future: how forests and people can adapt to climate change. Centre for International Forestry Research. Bogor

Locatelli, B., 2016. Ecosystem Services and Climate Change. In: Potschin, M., Haines-Young, R., Fish, R., Turner, K. (eds.). Routledge Handbook of Ecosystem Services. Routledge :481-490. ISBN: 978-1-13-802508-0

Maes J, Teller A, Erhard M, Grizzetti B, Barredo JI, Paracchini ML, Condé S, Somma F, Orgiazzi A, Jones A, Zulian A, Vallecilo S, Petersen JE, Marquardt D, Kovacevic V, Abdul Malak D, Marin AI, Czúcz B, Mauri A, Loffler P, BastrupBirk A, Biala K, Christiansen T, Werner B, 2018. Mapping and Assessment of Ecosystems and their Services: An analytical framework for ecosystem condition. Publications office of the European Union, Luxembourg.

Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M. L., Barredo, J. I., … Lavalle, C., 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosystem Services*, **17:** 14–23.

Maes, J., Paracchini, M.L., Zulian, G., Dunbar, M.B., Alkemade, R., 2012. Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. *Biol. Conserv*. **155**: 1–12.

Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Amo, D. G. D., … Montes, C. 2012. Uncovering Ecosystem Service Bundles through Social Preferences. *PLoS ONE*, **7**(6), e38970.

Mezghani, A., Dobler, A., Benestad, R., Haugen, J. E., Parding, K. M., Piniewski, M., & Kundzewicz, Z. W., 2019. Sub-sampling impact on the climate change signal over Poland based on simulations from statistical and dynamical downscaling. *Journal of Applied Meteorology and Climatology*.

Middelkoop, H., 2000. The impact of climate change on the river Rhine and the implications for water management in the Netherlands. Summary report of the NRP project 952210

Ministry of the Environment, Climate Protection and the Energy Sector, 2012. Climate Change in Baden-Württemberg. Facts – Impacts – Perspectives. http://www.um.baden-wuerttemberg.de/

Mulligan, M. A. Guerry, K. Arkema, K. Bagstad, Villa F. 2010. Capturing and quantifying the flow of ecosystem services in Silvestri S., Kershaw F., (eds.). Framing the flow: Innovative Approaches to Understand, Protect and Value Ecosystem Services Across Linked Habitats. UNEP World Conservation Monitoring Centre, Cambridge, UK. ISBN 978-92-807-3065-4.

Mulligan, M. Burke, S.M. Sanz-Cruz, van Soesbergen L. A., 2010. A review of methods and tools for modelling freshwater services flows Rep. Conserv. Int.

Mulligan, M. Saenz-Cruz , L., van Soesbergen, A., Smith, V.T. and Zurita, L., 2009. Global dams database and geowiki. Version 1. http://www.ambiotek.com/dams. Version 1. http://geodata.policysupport.org/dams

Mulligan, M., 2010. Fire-burn frequency dataset based on MODIS burnt area product. http://geodata.policysupport.org/fire-burn-frequency

Mulligan, M., 2018. Documentation for the Co$tingNature Model V3. www.policysupport.org/waterworld

Mulligan, M., Burke, S., 2005. Global cloud forests and environmental change in a hydrological context, Final Report DFID FRP Project ZF0216.

OECD, 2017. The Land-Water-Energy Nexus: Biophysical and Economic Consequences, OECD Publishing, Paris.

Pedrono, M., Locatelli, B., Ezzine-de-Blas, D., Pesche, D., Morand, S., & Binot, A. (2015). Impact of Climate Change on Ecosystem Services. *Climate Change and Agriculture Worldwide*, 251–261

Raudsepp-Hearne C, Peterson GD, Bennett EM, 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc Natl Acad Sci USA*, **107**:5242–5247.

Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc. Natl. Acad. Sci.* **107:** 5242-5247.

Renard, D., Rhemtulla, J.M., Bennett, E.M., 2015. Historical dynamics in ecosystem service bundles. *Proc. Natl. Acad. Sci.* **112**: 13411–13416.

Rockstrom, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S. & Gerten, D. 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research*, **45**.

Scholes, R. J. 2016. Climate change and ecosystem services. Wiley Interdisciplinary Reviews: *Climate Change*, **7**(4): 537–550.

Scholes, R., and Settele, J. 2014. Terrestrial and Inland Water Systems. Working Group 2 Contribution to the Fifth Assessment Report. IPCC, International Panel on Climate Change, Geneva

Shaw, M. R., Pendleton, L., Cameron, D. R., Morris, B., Bachelet, D., Klausmeyer, K., … Roehrdanz, P. R. 2011. The impact of climate change on California's ecosystem services. *Climatic Change*, **109**(S1): 465–484

Smakhtin, V.; Revenga, C.; and Döll, P. 2004. Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive Assessment Research Report 2. Colombo, Sri Lanka: Comprehensive Assessment Secretariat.

Trojanowska, A., Kurasiewicz, M., Pleśniak, Ł., Orion Jędrysek, M., 2009. Emission of methane from sediments of selected Polish dam reservoirs. „Teka Komisji Ochrony i Kształtowania Środowiska Przyrodniczego – OL PAN", 6: 368–373.

WEC, 2007. Deciding the future: Energy Policy Scenarios to 2050, Executive Summary, World energy Council, London, UK.

Wint,G.R.W. and T.P. Robinson. (2007). Gridded livestock of the world 2007. FAO, Rome, 131 pp.

World Bank, 2009. Convenient Solutions to an Inconvenient Truth: Ecosystem-Based Approaches to Climate Change. The World Bank, Washington DC.

Wotke, A. Appl R., Hellgardt, J. Reiss, J. Knödler M. 2008. Zukunft der Wasserkraft im Zeitalter des Klimaschutzes - ein alter Konflikt mit neuer Aktualität.1st Neckar Newsletter. Büro am Fluss, Plochingen

8 ANNEX 1

Workspace data used by the Co$ting nature model for calculations of i.e. ecosystem service bundles, pressures and threats, and water footprint.

17 model mean precipitation change to 2050s (IPCC)
17 model mean temperature change to 2050s (IPCC SR)
Accessibility (minutes to nearest town of 50K pop)
Rainfall accumulated down flow lines (Hydro1k) (Mm3)
Presence of mines (unique id)
Endemism richness for (IUCN red list) amphibians
Species richness for (IUCN red list) amphibians
Mean slope upstream (>10 deg) (degrees)
Endemism richness for (IUCN red list) birds
Species richness for (IUCN red list) birds (species)
Carbon stock (tonnes C/km2)
Cell area (fraction*100000)
Cereal crop fraction (fraction)
Underweight population under 5 years old
Study area (Hydrosheds) (mask)
Coal bearing areas (unique ID)
Coastline (SWBD) (Unique ID)
Coral presence (Boolean)
Croplands (2005) (%)
Upstream cropland (km^2)
Upstream relative cyclone hazard frequency index
Dams (unique id)
Number of dams downstream (number)
Number of dams upstream (GOOD) (scalar)
All mineral deposits (unique ID)
Distance from urban area (pixels)
Dry matter productivity (Dg/ha/day)
DMSP Night-time lights (2013)
Total economic activity (2006) (millions US$/km^2)
Endemic bird areas (Birdlife International)
Ecoregions (WWF) (unique ID)
Endemism richness for ferns (v2) (dimensionless)
Species richness for ferns (v2) (species)

Fibre crop fraction (fraction)
Frequency of fire burn events (% of observations)
Floodplain area upstream (%)
Forage crop fraction (fraction)
Forest loss since pre-human times (%)
LUCC: Forma forest loss (2000-2012) (%)
Fruit crop fraction (fraction)
Relative cyclone hazard frequency index (CHRR)
Forest gain (2000-2015, Hansen/UMD/Google/USGS/NAS)
LUCC: Forest loss (2000-2012, Hansen/UMD/Google/US)
Global 200 ecoregions (WWF) (unique ID)
Globcover land use classes (unique id)
Water occurrence (1984-2015, EC JRC/Google) frequency
Mean rainfed crop suitability (high inputs) (index)
Biodiversity hotspots (Conservation International)
Elevation (Hydrosheds) (metres (a.s.l)
Important bird areas (Birdlife International, 2016)
Downstream irrigated area (km^2)
FAO irrigation percentage (%)
Upstream irrigated area (km^2)
Key biodiversity areas (2016) (dimensionless)
Downstream land area (km^2)
Upstream land area (km^2)
Local drainage direction (Hydrosheds) (directions)
Mean rainfed crop suitability (low inputs) (index)
Last of the Wild (unique ID)
Mining concessions (Unique ID)
Endemism richness for (IUCN red list) mammals
Species richness for (IUCN red list) mammals
Managed grazers (2006) (headcount/km2)
Mangroves (1997, UNEP-WCMC/ISME) (unique id)
Urban Areas (Unique ID)
Oil and gas concessions (Unique ID)
Presence of oil and gas wells (unique id)
Oil crop fraction (fraction)
Other crops fraction (fraction)
Number of panoramic photos (November 2010) (number)
Pastures (2005) (%)
Protected floodplain area upstream (%)
Planned transportation routes (Unique ID)
Population (2007, Landscan) (persons/km cell)

Downstream population (sum p/km^2)
Upstream population (sum p/km^2)
Percentage of population considered poor (<$2)
Upstream population considered poor (<$2 per day)
Protected areas upstream (WDPA) (km^2)
Pulses crop fraction (fraction)
Endemism richness for reptiles (dimensionless)
Species richness for reptiles (species)
Roads (GAUL) (type)
Root and tuber crop fraction (fraction)
Rural populated places (Unique ID)
Soil carbon (t/km2)
GDP projection (SRES B2 scenario) 1990
GDP projection (SRES B2 scenario) 2025
Population projection (SRES B2 scenario) 1990
Population projection (SRES B2 scenario, world pop)
Sugar crop fraction (fraction)
Total annual precipitation (mm/year)
Water bodies (SWBD lakes) (Unique ID)
Area of water bodies upstream (km^2)
LUCC: Terra-i forest loss (2000-) (%)
Touristiness (photos by different users per unit area)
Trees and nuts crop fraction (fraction)
Total tree cover upstream (%)
Number of observed tsunami since 2000BC(NGDC) (frequency)
Cover of bare ground (MODIS 2010) (Percentage)
Cover of herb-covered ground (MODIS 2010) (Percentage)
Cover of tree-covered ground (MODIS 2010) (Percentage)
Vegetables and melons crop fraction (fraction)
Water balance (WorldClim rainfall - CPWF AET)
Landsat water mask (Hansen/UMD/Google/USGS/NASA)
Protected areas (UNEP-WCMC WCPA) 2016 (unique ID)
Wetlands including lakes, rivers and reservoirs
Area of wetlands upstream (km^2)
Wildland grazers headcount (2006) (headcount/km2)

9 ANNEX 2

Components calculated for the indexes used in the report:

Relative **pressure** index	Current pressure according to population, wildfire frequency, grazing intensity, agricultural intensity, dam density, infrastructure (dams, mines, oil and gas, urban) density
Relative total **potential** bundled services index	Total potential services including water, carbon, nature based tourism, hazard mitigation services, timber (commercial and domestic), fuelwood, grazing, wildlife services, Non-wood forest products, wildlife dis-services, aquatic fisheries (commercial and artisanal) and environmental quality
Relative total **realised** bundled services index	Total realised services including water, carbon, nature based tourism, hazard mitigation services, timber (commercial and domestic), fuelwood, grazing, wildlife services, Non-wood forest products, wildlife dis-services, aquatic fisheries (commercial and artisanal) and environmental quality

10 ANNEX 3

Workspace data of WaterWorld model used i.e. for climate change projections (https://docs.google.com/document/d/1B-pyk6PK1ND58RUuzeJlhng38xp1eT8IMAygZB670kk/edit#id.ffee2014f42b)

Presence of mines (unique id)
Boundary layer wind direction January (degrees)
Boundary layer wind direction February (degrees)
Boundary layer wind direction March (degrees)
Boundary layer wind direction April (degrees)
Boundary layer wind direction May (degrees)
Boundary layer wind direction June (degrees)
Boundary layer wind direction July (degrees)
Boundary layer wind direction August (degrees)
Boundary layer wind direction September (degrees)
Boundary layer wind direction October (degrees)
Boundary layer wind direction November (degrees)
Boundary layer wind direction December (degrees)
Cell area (fraction*100000)
Study area (Hydrosheds)
Croplands (2005) (%)
Dams (unique id)
Forest gain (2000-2015, Hansen/UMD/Google/USGS/NAS)
LUCC: Forest loss (2000-2012, Hansen/UMD/Google/US)
Glacier water equivalent (mm)
Mean sea level pressure January (mb)
Mean sea level pressure February (mb)
Mean sea level pressure March (mb)
Mean sea level pressure April (mb)

Mean sea level pressure May (mb)
Mean sea level pressure June (mb)
Mean sea level pressure July (mb)
Mean sea level pressure August (mb)
Mean sea level pressure September (mb)
Mean sea level pressure October (mb)
Mean sea level pressure November (mb)
Mean sea level pressure December (mb)
Elevation (Hydrosheds) (metres (a.s.l))
Mean snow water equivalent (mm)
Lakes (unique ID)
Local drainage direction (Hydrosheds) (directions)
Managed grazers (2005) (headcount/km2?)
Cloud frequency 00:00-06:00 hrs (MOD35) (fraction)
Cloud frequency January (MOD35) (fraction)
Cloud frequency February (MOD35) (fraction)
Cloud frequency March (MOD35) (fraction)
Cloud frequency April (MOD35) (fraction)
Cloud frequency May (MOD35) (fraction)
Cloud frequency 06:00-12:00 hrs (MOD35) (fraction)
Cloud frequency June (MOD35) (fraction)
Cloud frequency July (MOD35) (fraction)
Cloud frequency August (MOD35) (fraction)
Cloud frequency September (MOD35) (fraction)
Cloud frequency October (MOD35) (fraction)
Cloud frequency November (MOD35) (fraction)
Cloud frequency 12:00-18:00 hrs (MOD35) (fraction)
Cloud frequency December (MOD35) (fraction)
Cloud frequency 18:00-24:00 hrs (MOD35) (fraction)
Mean annual cloud frequency (MOD35) (fraction)
Cloud frequency (DJF) (MOD35) (fraction)
Cloud frequency (JJA) (MOD35) (fraction)
Cloud frequency (MAM) (MOD35) (fraction)
Cloud frequency (SON) (MOD35) (fraction)
Urban Areas (Unique ID)
Presence of oil and gas wells (unique id)
Pastures (2005) (%)
Population (2007, Landscan) (persons/km cell)
Percentage of population considered poor (<$2)
Roads (GAUL) (type)
Relative Humidity January (UEA) (%)

Relative Humidity February (UEA) (%)
Relative Humidity March (UEA) (%)
Relative Humidity April (UEA) (%)
Relative Humidity May (UEA) (%)
Relative Humidity June (UEA) (%)
Relative Humidity July (UEA) (%)
Relative Humidity August (UEA) (%)
Relative Humidity September (UEA) (%)
Relative Humidity October (UEA) (%)
Relative Humidity November (UEA) (%)
Relative Humidity December (UEA) (%)
Air temperature January (UEA) (deg. C)
Air temperature February (UEA) (deg. C)
Air temperature March (UEA) (deg. C)
Air temperature April (UEA) (deg. C)
Air temperature May (UEA) (deg. C)
Air temperature June (UEA) (deg. C)
Air temperature July (UEA) (deg. C)
Air temperature August (UEA) (deg. C)
Air temperature September (UEA) (deg. C
Air temperature October (UEA) (deg. C)
Air temperature November (UEA) (deg. C)
Air temperature December (UEA) (deg. C)
Wind speed January (UEA) (m/s *10)
Wind speed February (UEA) (m/s *10)
Wind speed March (UEA) (m/s *10)
Wind speed April (UEA) (m/s *10)
Wind speed May (UEA) (m/s *10)
Wind speed June (UEA) (m/s *10)
Wind speed July (UEA) (m/s *10)
Wind speed August (UEA) (m/s *10)
Wind speed September (UEA) (m/s *10)
Wind speed October (UEA) (m/s *10)
Wind speed November (UEA) (m/s *10)
Wind speed December (UEA) (m/s *10)
Cover of bare ground (MODIS 2010) (percentage)
Cover of herb-covered ground (MODIS 2010) (percent)
Cover of tree-covered ground (MODIS 2010) (percent)
Landsat water mask (Hansen/UMD/Google/USGS/NASA)
Daily temperature range January (WC) (deg C * 10)
Daily temperature range February (WC) (deg C * 10)

Daily temperature range March (WC) (deg C * 10)
Daily temperature range April (WC) (deg C * 10)
Daily temperature range May (WC) (deg C * 10)
Daily temperature range June (WC) (deg C * 10)
Daily temperature range July (WC) (deg C * 10)
Daily temperature range August (WC) (deg C * 10)
Daily temperature range September (WC) (deg C * 10)
Daily temperature range October (WC) (deg C * 10)
Daily temperature range November (WC) (deg C * 10)
Daily temperature range December (WC) (deg C * 10)
Mean monthly precipitation January (WC) (mm/month)
Mean monthly precipitation February (WC) (mm/month)
Mean monthly precipitation March (WC) (mm/month)
Mean monthly precipitation April (WC) (mm/month)
Mean monthly precipitation May (WC) (mm/month)
Mean monthly precipitation June (WC) (mm/month)
Mean monthly precipitation July (WC) (mm/month)
Mean monthly precipitation August (WC) (mm/month)
Mean monthly precipitation September (WC) (mm/month)
Mean monthly precipitation October (WC) (mm/month)
Mean monthly precipitation November (WC) (mm/month)
Mean monthly precipitation December (WC) (mm/month)
Mean monthly temperature January (WC) (deg. C *10)
Mean monthly temperature February (WC) (deg. C *10)
Mean monthly temperature March (WC) (deg. C *10)
Mean monthly temperature April (WC) (deg. C *10)
Mean monthly temperature May (WC) (deg. C *10)
Mean monthly temperature June (WC) (deg. C *10)
Mean monthly temperature July (WC) (deg. C *10)
Mean monthly temperature August (WC) (deg. C *10)
Mean monthly temperature September (WC) (deg. C *10)
Mean monthly temperature October (WC) (deg. C *10)
Mean monthly temperature November (WC) (deg. C *10)
Mean monthly temperature December (WC) (deg. C *10)
Protected areas (UNEP-WCMC WCPA) 2016 (unique ID)
Wetlands including lakes, rivers and reservoirs
Wildland grazers headcount (2005) (headcount/km2)