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MILESTONE 1

M1 Concepts for prognosis and assessments of climate change related pressures on groundwater (WP1 - D.1.3.1)

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The evidence of the achievement of the 1st Milestone “Concepts for prognosis and assessments of climate change related pressures on groundwater” is the deliverable D.1.3.1. The document provides the necessary knowledge to develop climate change adaptation measures dealing with groundwater. The core of the document is presented in the following pages.

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Deliverable 1.3.1

D.1.3.1 - Concepts for prognosis and assessments of climate change related pressures on groundwater

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Concepts for prognosis and assessments of climate change related pressures on groundwater

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A. Introduction and scope of the report

Climate change is considered one of the key drivers of water availability in this century (IPCC, 2014). Primary implications are the rise of the mean global temperature and shifts in the precipitation distribution. The hydrological cycle can be highly impacted by these phenomena with serious consequences on water related human activities and ecosystems. Also, the socio-economic and demographic context is rapidly changing. The population is growing, and we are observing large migrations from rural areas to the cities, causing increases in water, energy, and food demand, especially in developing countries, where these changes are more emphasized and difficult to contain (UN, 2015). Under these fast-evolving conditions, water systems are expected to become increasingly vulnerable: designing flexible and robust adaptation options, performing well across multiple plausible futures, is key to mitigate degrading performance. In Alpine regions, climate change is expected to have a major impact on streamflow patterns, due to reductions in both the duration and extent of seasonal snow cover and increased glacier retreat in the medium and long term. This effect overlaps with the expected increase in temperature, which could increase the frequency of particularly dry years with important consequences on irrigation systems and therefore on agricultural production. Humanity has had a major role in shaping the climatic change we are facing and will have a great role in dealing with it. It is then important to include human activities into the water cycle context, to effectively understand the impacts and the adaptation strategies to implement (Abbott et al., 2019).

The scope of this report is to provide the necessary knowledge to be able to develop climate change adaptation measures dealing with groundwater. This is done through a comprehensive summary of the techniques used to obtain predictions on the future climate at regional and local scale, together with a review of the possible impacts groundwater and surface runoff will face.

B. State of the art in dealing with climate change scenarios and their downscaling

Traditionally, top-down approaches - describing the performance of water resource systems under a discrete set of global projections - have been used as the basis for developing adaptation strategies. Such projections are acquired using general and regional circulation models (GCMs / RCMs) (Arnell, 2004; Brekke et al., 2009), the outputs of which are fed into a water system model to determine the system performance with respect to each projection.

More recently, bottom-up approaches have been designed to identify performance thresholds independently from global projections. To implement a bottom-up approach, climate (and socio-economic) exposures are generated for a range of plausible futures, including those beyond the bounds of global projections, and system response is assessed against each generated exposure (Lempert et al., 2004; Prudhomme et al., 2010; Brown et al., 2012). This enables a more thorough understanding of how a system responds to changes in climate and society, for example, by identifying the changes in climate exposure that can cause unsatisfactory degradation in system performance (Whateley et al., 2014; Steinschneider et al., 2015).

In this project, we use the first approach. Still, we will draw inspiration from the second to consider the local territorial characteristics and the specific objectives in selecting the most significant scenarios and drivers.

1. Climate projections

Information about future climate is essential in order to assess future planning and management options, especially in the water resources management field, where uncertainties related to climate change are expected to impact severely on short- and long-term decisions (Mahmoud et al., 2009; Kwakkel et al., 2016).

The most consolidated method to assess the impacts of changing drivers on water resources systems is through the downscaling of global scenarios to the local scale. This approach is called "Scenario-based" or "Top-down" as it moves from global scenarios to local impact assessment (Vano et al., 2010; Wilby and Dessai, 2010; Anghileri et al., 2011).

The Top-Down strategy involves a downscaling of the climate variables from Global Climate Models (GCMs), under a range of possible emissions scenarios, to the local scale through the Regional Climate Models (RCMs). The resulting local scenarios are then used to estimate the impacts, as for example the probability of flood events, by using a rainfall-runoff model or the crop yield using an agricultural model.

1.1. Emission scenarios

The starting point of the Scenario-Based methods are the climate scenarios provided by the IPCC (Intergovernmental Panel on Climate Change). The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Program (UNEP) to assess scientific, technical and socio-economic information concerning climate change, its potential effects and options for adaptation and mitigation.

Before the Fifth Assessment Report (2014), future climate scenarios were developed by estimating greenhouse gas emissions and their atmospheric concentrations starting from socioeconomic factors, technological development, and energy production hypotheses. This process occurred through the carrying out of phases in succession, with a consequent accumulation of delays and a total time of approximately 10 years.

To reduce the time gaps and make the information more effective, climate and impact research communities have developed a parallel approach that starts from the identification of radiative forcing scenarios. The radiative forcing scenarios are more effective because they are not associated with unique storylines but can result from different combinations of economic, technological, demographic, political, and institutional futures (Moss et al., 2010; Change, 2014).

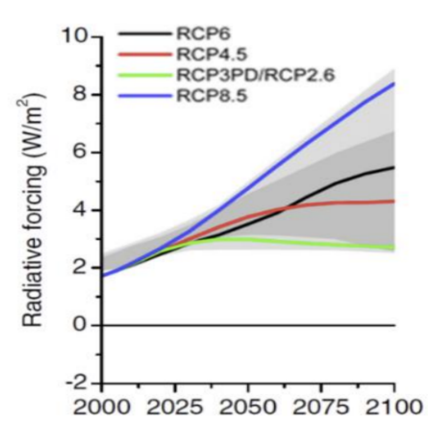


Figure 1 - Representative Concentration Pathways.

In the Fifth Assessment Report the scenarios described above are presented as 'Representative Concentration Pathways' (RCPs). To avoid the possibility of choosing an average scenario, the number of proposed RCPs is equal to four (see Figure 1) instead of an odd number. The numbers in the RCP's names refer to the radiative forcing, measured in watt per square meter, by the year 2100. The grey shaded area captures the 98% (light) and 90% (dark) of the range in the previous socio-economic scenarios.

More precisely, the Representative Concentration Pathways (RCP) consist of a set of four paths of radiative forcing developed as a basis for long-term and near-term modelling experiments relevant for the climate modelling community (Van Vuuren et al., 2011). They are the product of a collaboration between integrated assessment modelers, climate modelers, terrestrial ecosystem modelers and emission inventory experts. The resulting product forms a comprehensive dataset with high spatial and sectoral resolutions for the period extending to 2100. Therefore, RCPs describe possible climate futures based on radiative forcing values, measured in watt per square meter, by the year 2100. They can result from different combinations of demographic, economic, and technology futures, thus they are not associated with unique storylines. The four RCPs were selected to include one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6.0) and one very high baseline emission scenario (RCP8.5). The main differences among the four RCPs scenarios are here summarised:

- RCP2.6 known as peak-and-decline pathway, having maximum of radiative forcing (+3.1 W/m2) around mid-century and very low GHGs levels reaching 2.6 W/m2 in 2100. To achieve this target, ambitious greenhouse gas emissions reductions would be required over time.
- RCP4.5 is a stabilization pathway in which the radiative forcing is stabilized shortly after 2100 at 4.5 W/m2. It is consistent with a future with relatively ambitious emissions reductions.
- RCP6.0 another stabilization pathway in which the radiative forcing will stabilize shortly after 2100 at 6.0 W/m2, by applying some GHGs emission reductions. However, the GHGs concentration will be higher than in RCP4.5. It is consistent with the application of a range of technologies and strategies for reducing greenhouse gas emissions.
- RCP8.5 is a rising pathway in which GHGs emissions increase over time up to high concentrations. It will lead to 8.5 W/m2 in 2100.

1.2. Socio-economic pathways

The magnitude and extent of future climate change impacts is influenced by socio-economic developments, with differential consequences across regions, economic sectors, and time.

The climate change research community established, in the Sixth Assessment Report, a new scenario framework to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Kriegler et al., 2012). The Shared Socio-economic Pathways were already part of the Fifth Report, but they take a much more central position in this novel framework and have the intent to link Impact Adaptation Vulnerability (IAV) analysis and mitigation analysis more explicitly to socio-economic development. IAV research covers a very wide array of disciplines and domains, from modelers analysing the possible impacts of climate change on a particular system, such a yield of crops, to adaptation practitioners working at the community level to increase resilience to climate variability, such as reducing the impacts of coastal storm surges in a particular region. Mitigation analysis concentrates on the feasibility of actions to limit the magnitude or rate of long-term climate change (Fischer et al., 2007). Both IAV and mitigation analysis needs to assess socioeconomic contexts to evaluate the impacts of climate change (Wilbanks and Ebi, 2014).

Shared Socioeconomic Pathways (SSP) and their associated scenarios wants to "initiate open community process to build richer socio-economic data repository for climate change research" (Riahi et al., 2017). The framework would not only focus on quantifiable elements but also be relevant for social sciences, given their importance in the analysis of adaptation and mitigation strategies (Van Vuuren et al., 2011).

Figure 2 depicts the position of the five Shared Socioeconomic Pathways in the space of challenges to mitigation and to adaptation. The framing of SSPs in terms of challenges facilitates researchers to characterize a range of uncertainty in the mitigation policies required to achieve a given climate outcome or, on the other hand, the adaptation possibilities associated with that same outcome (O'Neill et al., 2017).

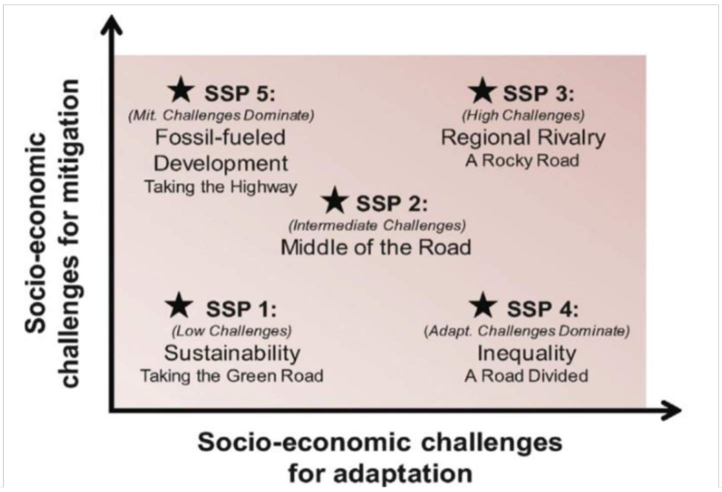


Figure 2 - Five shared socioeconomic pathways (SSPs) representing different combinations of challenges.

The SSPs are based on five qualitative narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development (for a detailed description of the narratives see O'Neill et al., 2017; Riahi et al., 2017; and Bauer et al., 2017). The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis generate the integrated scenarios of emissions and land use, as well as climate impact, adaptation, and vulnerability analysis. SSPs starting assumptions outline broad characteristics of the global future and country-level population, GDP and urbanisation projections. Thus, SSPs are not scenarios themselves but their building blocks (Riahi et al., 2016).

The role of Integrated Assessment Models (IAMs) is to bring multiple human and physical Earth systems together to shed light on system interactions, that are explored in a single computational platform. They take external SSP-based scenario assumptions as key drivers such as population, economic activity, technology costs, and policies, and produce a modelled scenario that illustrates the implications of scenarios assumptions, for example, on commodity prices, energy use, land use, water use, emissions, and concentrations (see Figure 3).

Integrated Assessment Models endeavour to represent all world region and all economic sectors in an economic framework to explore the interaction among these sectors and identify the potential ramification of climate mitigation actions.

The process of developing the SSPs scenarios involved four key steps:

1. Design of the narratives.
2. Translation of the narratives into a common set of "input tables", to enable quantitative interpretation of the key SSP elements and scenario assumptions.

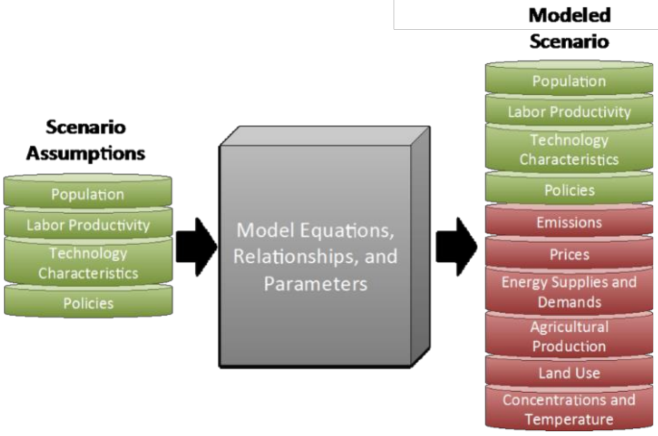


Figure 3 - Conceptual diagram of the way that Integrated Assessment Models (IAMs) use scenario.

3. Use of quantitative models to produce socio-economic driver projections (population, urbanization, and GDP) consistently with the related narrative (this phase was carried out by Samir and Lutz, 2017; Jiang and O'Neill, 2017; Dellink et al., 2017).
4. Narratives and associated projections of socio-economic drivers feed a range of IAMs, giving as output quantitative projections of energy, land use, and emissions associated with the SSP.

The results of this process are SSP baseline scenarios (without climate policies) and SSP mitigation scenarios (with climate policies).

Shared Socioeconomic Pathways baseline scenarios describe a future world in absence of new climate policies beyond those in place today, and should be considered as reference cases for mitigation, climate impacts and adaptation analyses (Riahi et al., 2017). Mitigation scenarios, instead, explore the implications of climate change mitigation policies applied on baseline scenarios. These policies are chosen considering RCPs' radiative forcing levels as a target. This is carried out applying different Shared Policy Assumption (SPA) to baseline scenarios consistently with the combination of the overall characteristic of the narratives and the RCP scenarios.

SPAs describe the climate mitigation policy environment for the different SSPs, focusing on critical issues for mitigation, such as the level of international cooperation in the short to the medium term (Riahi et al., 2017). This way of combining SSPs with RCPs constitutes an application of the Scenario Matrix architecture (Van Vuuren et al., 2014). In Scenario Matrix architecture RCPs and SSPs are respectively the rows and the columns of a matrix in which each cell represents a combination of the two pathways reached implementing a specific mitigation policy (see Figure 4). Thus, each cell defines a scenario, i.e. a combination of SSP, RCP and SPA. It is to be noticed that the SSP scenarios do not consider feedback from the climate system on its key drivers such as socio-economic impacts of climate change. This would be an issue evaluating land use changes, such as the ones in this work. On the other hand, the absence of a feedback on climate system makes these scenarios relevant for impact assessment purposes since it facilitates the superimposition of physical climate change on top of SSPs scenario.

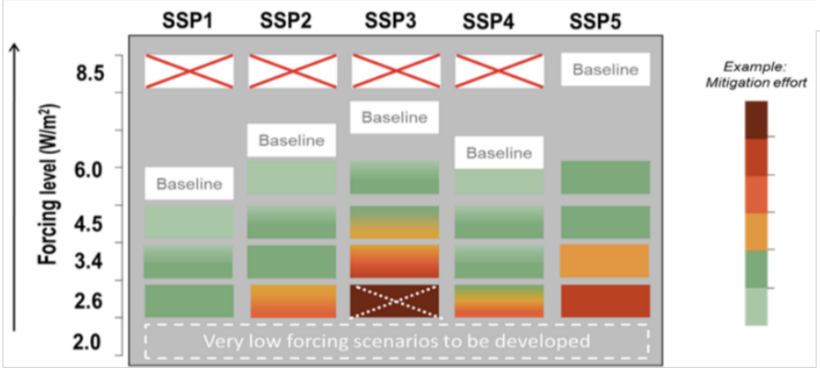


Figure 4 - An example of Scenario Matrix Architecture (Riahi et al. (2017)).

2. From global to local scale

2.1. Global and Regional Climate models

The climate scenarios provided by the IPCC are then used to force Global Climate Models. GCMs are mathematical models of the physical processes occurring in atmosphere, ocean, land, ice cover, and the interactions among them. These models rely on a discretization of the Earth in a three-dimensional grid, typically having a horizontal resolution between 250 and 600 km. Each cell contains all the interactions among natural and human components (IPCC, 2013).

It is to be noted that for the estimation of local impacts related, for example to small sub-catchments, GCMs spatial resolution is too coarse. In fact, many physical phenomena, such as the clouds or orography, cannot be accurately modelled at this scale (Anghileri et al., 2011). To carry out an impact assessment, global variables coming from GCMs must be downscaled to local scale (Gudmundsson et al., 2012).

A set of techniques is available to downscale the global models' variables to higher resolution (i.e. Regional Climate Models) allowing to capture regional and local climate forcing. Particularly used for their accuracy and availability of variables are the products obtained from EURO-CORDEX. EURO-CORDEX (Coordinated downscaling experiment - European Domain) is the European branch of the international CORDEX initiative, a program sponsored by the World Climate Research Program to organize an internationally coordinated framework to produce improved regional climate change projections for all land regions world-wide. EURO-CORDEX provides a high-resolution regional climate change ensemble over the European domain within the framework of the IPCC Fifth Assessment Report (Jacob et al., 2014).

2.2. Downscaling

More in general, we can divide downscaling techniques in dynamical downscaling (Fowler et al., 2007; Giorgi and Gutowski Jr, 2015), statistical downscaling (Fowler et al., 2007; Beheshti et al., 2019), and stochastic (Taner et al., 2017; Peleg et al., 2019). A combination of dynamical and statistical (or stochastic) downscaling is also often used (e.g. Mearns et al., 1999).

2.2.1. Dynamical downscaling

The dynamical method involves a RCM nested within a GCM. The Figure 5 shows the refinement that can be obtained from the use of an RCM. The squared area surrounding the RCM interior domain represents the lateral buffer zone (Giorgi and Gutowski Jr, 2015). Regional Climate Models, in fact, operate as global ones but with a higher resolution (50 - 25 km), so RCM boundary conditions are provided by a GCM. RCM adds regional forcing (i.e. orography and land use) and provides more accurate projections at the regional scale than a GCM. But, even if this approach allows for a better description of the climate at a regional scale, it is strongly dependent on GCM boundary forcing and it also may be still too coarse for estimating local impacts (Fowler et al., 2007).

The main shortcomings of this approach are the high computational time, the dependency of the quality of the regional model control run on the quality of the GCM boundary conditions, and the need of tuning the parameters when applied to new regions (Mearns et al., 1999). Additionally, it was proved that the outputs of the regional models are subject to varying levels of systematic biases, and they need to be post processed before being used for climate impact assessment (e.g. Christensen et al., 2008).

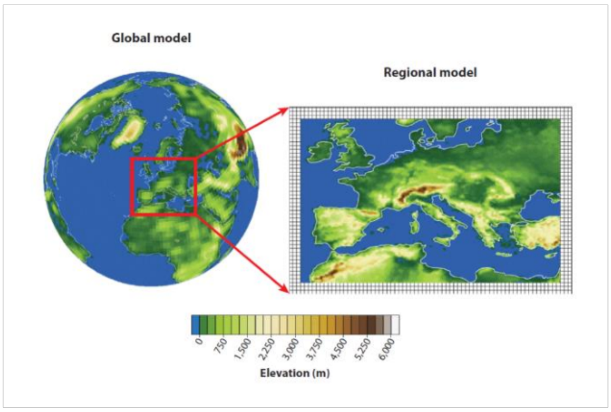


Figure 5 - Schematic depiction of the dynamical downscaling technique.

2.2.2. Statistical downscaling

Statistical downscaling, instead, is an empirical approach that uses relationships between the observed local and large-scale data to increase the resolution of the climatic variables. The relationship is a deterministic/stochastic function calibrated with observed data to map a large-scale predictor X produced by a GCM or RCM, into their corresponding local scale predictand Y. Normally the predictor X and the predictand Y are the same variable (e.g. Coulibaly et al., 2005). Once the function is estimated, it can be used for predictions of the future climate variables under the strong assumptions that this relationship will remain valid in the future and the predictor will remain within the range observed in the calibration period.

The statistical downscaling is based on a statistical link between large-scale and small-scale climate variables to translate large-scale GCM output onto a finer resolution (Wilby et al. (2002); Fowler et al. (2007)). The simplest method is to apply GCM-scale projections in the form of change factors. Differences between the control and future GCM simulations are applied to baseline observations by simply adding or scaling the mean climatic change factor to each day.

2.2.3. Stochastic downscaling

Finally, variant of statistical downscaling is stochastic downscaling, and its general concept is to randomize the relation between predictors and predictands to account for natural climate variability together with the climate change signal (Peleg et al., 2019). Considering this approach, a generating synthetic time series of climate variables with a Weather Generator (WG) is used. Weather Generators are numerical tools designed to simulate synthetic time series of various meteorological variables of theoretically infinite length for a given climate and location based only on historical observations (Peleg et al., 2017). Many Weather Generators exist, with different methods to compute the meteorological variables (i.e. stochastic-statistical or physical-dynamical approaches) for different spatial and temporal resolutions.

2.2.4. Combination of dynamical and statistical downscaling

Beside the dynamic and statistical methods, the downscaling procedure can be achieved with a third option called combined downscaling, which is a combination of the methods described above. The output of the dynamical downscaling, the RCM variables, are corrected using a statistical transformation calibrated as previously described (e.g. Piani et al., 2010), but instead of using the large scale observed data as the predictor, the RCM outputs are employed to eliminate any modelling bias that may still affect RCMs outputs when compared to local climate (Anghileri et al., 2011).

2.3. Final Remarks

Once the downscaling process provided all the input climatic variables at the desired resolution, they can be used for the calculation of the impacts at the local scale.

The most recognized limitation of this method is the expansion of the uncertainty at each step of the process. This happens because the information is cascaded from one step to the next and at each step there is a range of possible models and methods that can be chosen by the user. Firstly, one must select a global scenario between the RCPs provided by the IPCC, then select a GCM within a large variety of models developed by different climate institutes. The GCM's resolution must be increased with different methods of dynamical, statistical, or combined downscaling to get the corrected RCM variables, but also the choice of the RCM is subject to uncertainty. Lastly, the local impact model must be selected, within a large range of possible choices (Prudhomme et al., 2010). In short, every choice at each step implies different results on the impacts and consequently on the adaptation strategies. Depending on the selection of GCM, RCM or the downscaling technique, the impacts might be divergent, in one way minimal, in another way very dangerous for the system (Brown et al.,2011). This effect is known as envelope of the uncertainty and is illustrated in Figure 6.

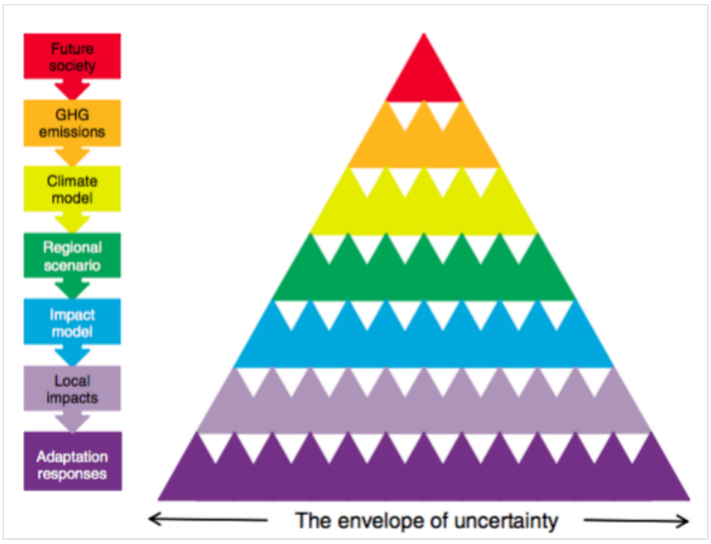


Figure 6 - The envelope of the uncertainty: the increasing number of triangles at each level symbolise.

The second shortcoming of the Scenario Based implementation is the discrete set of scenarios explored by the approach. If the researchers analyse exclusively the climate projections, the future variable space under climate change may not be fully explored, and consequently the model range would lead to a partial estimation of future impacts (Brown and Wilby, 2012). It thus represents the lower bound on the maximum range of uncertainty (Stainforth et al., 2007). Moreover, the limitation due to the discrete number of scenarios doesn't allow to identify the acceptance or refusal thresholds of the system performance under changes in climate. In other words, using the top-down approach, the degree of climate change to which the system is more sensitive are very difficult to find (Culley et al., 2016).

However, the bottom-up approach requires fine-tuned calibration of the individual case studies' specific characteristics and sources of vulnerability; therefore, it is very complex to adapt it to different cases. The main concern is to decide on a case-by-case basis which variables and which statistics to perturb, and in theory the most critical ones for the analysed system should be selected. For this reason, despite the limitations mentioned above, the project will make use of the consolidated top-down approach.

Finally, the results and approach of AR6 certainly constitute an interesting novelty and will certainly represent the new paradigm for studies on the effects of climate change in the coming years. There are also extemporaneous and uncoordinated experiments of high-resolution downscaling for urban applications (even at 3 km compared to EUROCORDEX's 12.5). Unfortunately, in most cases the corresponding simulations only exist globally. Despite a significant improvement in spatial resolution compared to the previous version, they are not available everywhere after dynamic downscaling (like EUROCORDEX) and not yet with the variety of different model combinations as in AR5. On the other hand, this section is dedicated to the state of the art and must therefore summarize consolidated knowledge and tools that can be used in most cases. It is therefore appropriate to carry out the analyses required by the project starting from AR5 - of which there are widely used scenarios with dynamic downscaling - before carrying out some exploratory simulations considering AR6 instead.

C. Climate change pressures on groundwater and surface run-off

Climate change poses and will pose in the future unprecedented challenges. It brings several modifications to the Earth's conditions which we have grew with and studied in the past centuries. While the scientific community is unanimous in confirming climate change is happening and humans have been contributing to it (Abbott et al., 2019), high uncertainties lie on the severity and extension of the impacts. The impacts of climate change will depend on the temperature increase and global circulations changes, plus a cascade of effects from global to regional to local scale. Thus, considering climate change impacts on groundwater and surface run off requires the consideration of many possible aspects, which will be treated in this chapter. The most visible and observed changes are on the temperature, precipitation and wind circulation spectrums. All converge towards a general hydrological cycle change as illustrated in Figure 7. Globally, the negative impacts of climate change on freshwater systems are very likely to outweigh their benefits (Kundzewicz et al., 2008). Both surface waters and groundwater will be affected, posing serious concerns over future water scarcity conditions and achievable quality of water.

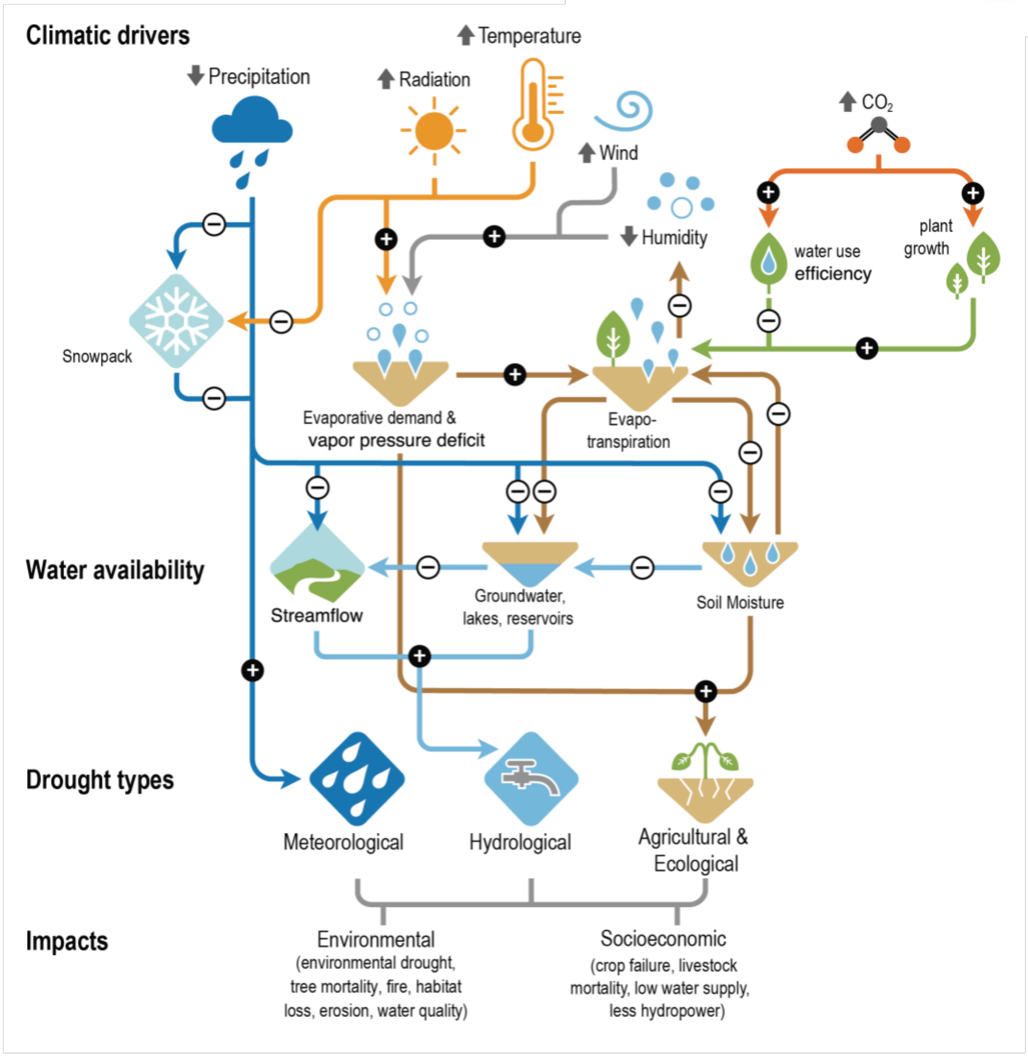
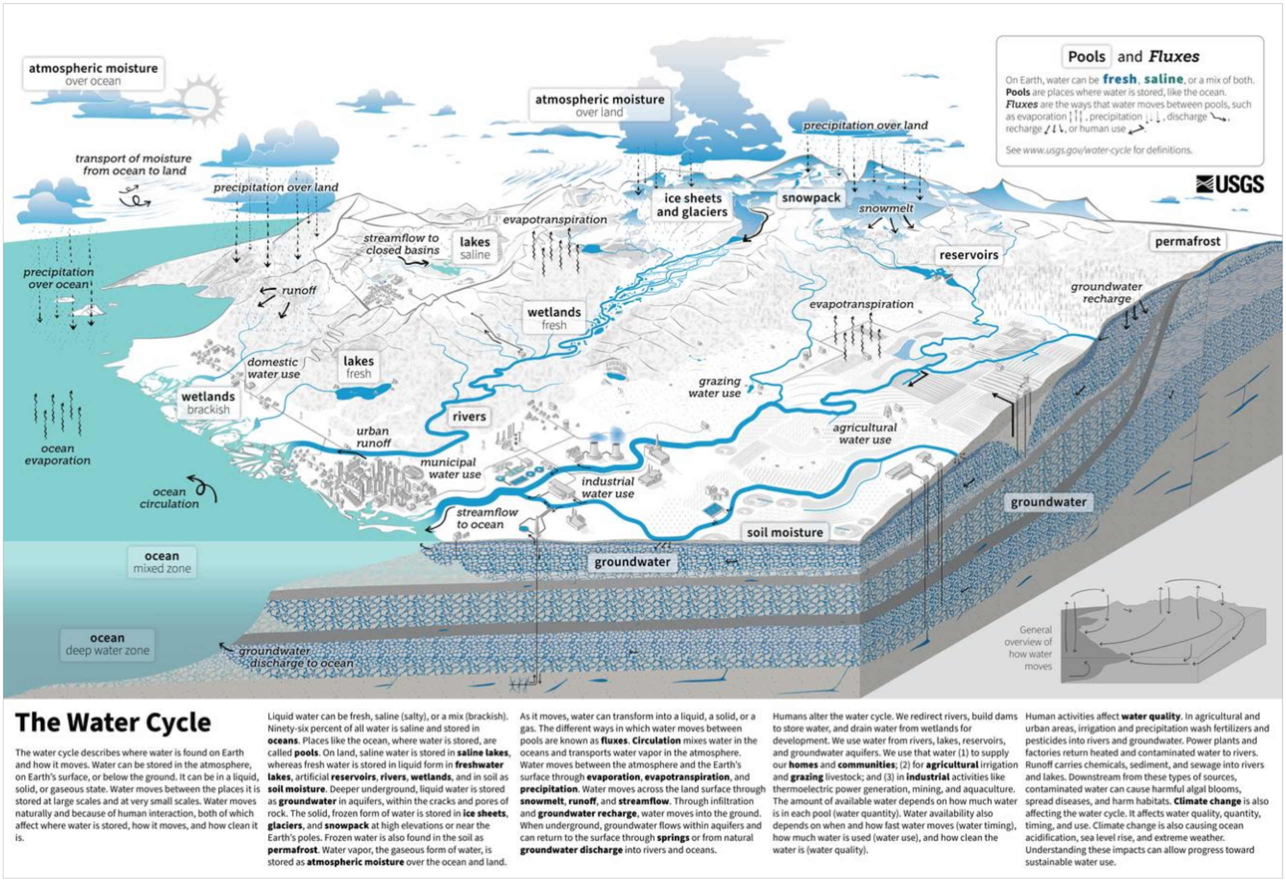


Figure 7 - Climatic drivers and impacts concerning water availability (IPCC, 2021)

3. Pressures on groundwater

Groundwater, as illustrated in Figure 8, is related to climatic drivers through multiples exchange processes happening at different times. When talking about climate change pressures on groundwater, the most self-evident one is the variation in aquifer's recharge. Recharge and exchanges with rivers are the only two natural inputs into aquifers aside from human contributions. Groundwater recharge depends on precipitation, both liquid and solid, which, once it reaches the soil, can infiltrate, pass through the soil's unsaturated zone, and reach the aquifers. Shallow aquifers with unconfined water table can be recharged in the same area where the precipitation has fallen, while deep, confined aquifers will have a so-called recharge zone, where the aquifer is free, and precipitation can infiltrate. For these aquifers, changes in the water content are thus related to precipitation occurring in the recharge zone, plus eventual exchanges with deeper or shallower aquifers and human extractions. It is thus evident how climate change can impact groundwater recharge: if, as an effect of climate change, precipitation regimes change in volumes or in periodicity it would propagate to a change in the total volume entering the aquifers or to a change in the water table levels periodicity. The type of precipitation influences recharge as well, since snowmelt is more efficient than rainfall in recharging groundwater, as it provides a steady source of water for infiltration for longer periods (Hughes et al., 2011). Since snowfall could be less frequent in some areas due to temperature increases and precipitation regimes change, this can also lead to a decrease in groundwater recharge.



On Earth, water can be **fresh**, **saline**, or a mix of both. **Pools** are places where water is stored, like the ocean. ***Fluxes*** are the ways that water moves between pools, such as evaporation, precipitation, discharge, recharge, or human use.

See *www.usgs.gov/water-cycle* for definitions.

The Water Cycle

The water cycle describes where water is found on Earth and how it moves. Water can be stored in the atmosphere, on Earth's surface, or below the ground. It can be in a liquid, solid, or gaseous state. Water moves between the places it is stored at large scales and at very small scales. Water moves naturally and because of human interaction, both of which affect where water is stored, how it moves, and how clean it is.

Liquid water can be fresh, saline (salty), or a mix (brackish). Ninety-six percent of all water is saline and stored in **oceans**. Places like the ocean, where water is stored, are called **pools**. On land, saline water is stored in **saline lakes**, whereas fresh water is stored in liquid form in **freshwater lakes**, artificial **reservoirs**, **rivers**, **wetlands**, and in soil as **soil moisture**. Deeper underground, liquid water is stored as **groundwater** in aquifers, within the cracks and pores of rock. The solid, frozen form of water is stored in **ice sheets**, **glaciers**, and **snowpack** at high elevations or near the Earth's poles. Frozen water is also found in the soil as **permafrost**. Water vapor, the gaseous form of water, is stored as **atmospheric moisture** over the ocean and land.

As it moves, water can transform into a liquid, a solid, or a gas. The different ways in which water moves between pools are known as **fluxes**. **Circulation** mixes water in the oceans and transports water vapor in the atmosphere. Water moves between the atmosphere and the Earth's surface through **evaporation**, **evapotranspiration**, and **precipitation**. Water moves across the land surface through **snowmelt**, **runoff**, and **streamflow**. Through infiltration and **groundwater recharge**, water moves into the ground. When underground, groundwater flows within aquifers and can return to the surface through **springs** or from natural **groundwater discharge** into rivers and oceans.

Humans alter the water cycle. We redirect rivers, build dams to store water, and drain water from wetlands for development. We use water from rivers, lakes, reservoirs, and groundwater aquifers. We use that water (1) to supply our **homes** and **communities**; (2) for **agricultural** irrigation and **grazing** livestock; and (3) in **industrial** activities like thermoelectric power generation, mining, and aquaculture. The amount of available water depends on how much water is in each pool (water quantity). Water availability also depends on when and how fast water moves (water timing), how much water is used (water use), and how clean the water is (water quality).

Human activities affect **water quality**. In agricultural and urban areas, irrigation and precipitation wash fertilizers and pesticides into rivers and groundwater. Power plants and factories return heated and contaminated water to rivers. Runoff carries chemicals, sediment, and sewage into rivers and lakes. Downstream from these types of sources, contaminated water can cause harmful algal blooms, spread diseases, and harm habitats. **Climate change** is also affecting the water cycle. It affects water quality, quantity, timing, and use. Climate change is also causing ocean acidification, sea level rise, and extreme weather. Understanding these impacts can allow progress toward sustainable water use.

Figure 8 - USGS water cycle including human influences (USGS, 2022)

Alongside with recharge, also discharge is easily impacted by climatic changes. Groundwater discharge is defined in Green et al. (2011) as the loss of water from an aquifer to a surface-water body, the atmosphere, or abstraction for human uses. Changes in recharge and in the storage can thus propagate to discharge, impacting spring flow, transpiration by local vegetation, in, subsurface outflow and the human withdrawal availability (Amanambu et al., 2020).

Groundwater levels are already decreasing in many aquifers globally (Jasechko et al., 2024). However, groundwater storage is relatively less sensitive to seasonal or multiyear climatic variability than other groundwater linked variables such as recharge and discharge, reacting slower to variation in precipitations events than surface water bodies (Amanambu et al., 2020). But groundwater storage depletion shouldn't be disregarded due to its resistance to sudden changes. As Amanambu et al., 2020 sums up, storage loss is in fact deleterious for livelihood and ecological sustainability, while reducing the possible discharge to surface waters as streams and lakes and enhancing the risks of land subsidence due to soil compaction and open spore spaces previously filled with water (Andaryani et al., 2019).

Both discharge and storage relate to another area interested by climate change: groundwater-surface water interactions. Pressures on groundwater can influence surface water bodies, but the contrary is also considered an indirect impact of climate change. As it is shown in Figure 9 (Banerjee & Ganguly, 2023), surface water can be in different relationships with groundwater. Decreasing river discharges or lake levels due to climate change could alter their equilibrium with surrounding aquifers, reclaiming more water from aquifers as in condition a. Decreasing groundwater levels could instead create the conditions for an increased inflow from streams (e.g. b condition in figure), which could exacerbate eventual pre-existing drought conditions.

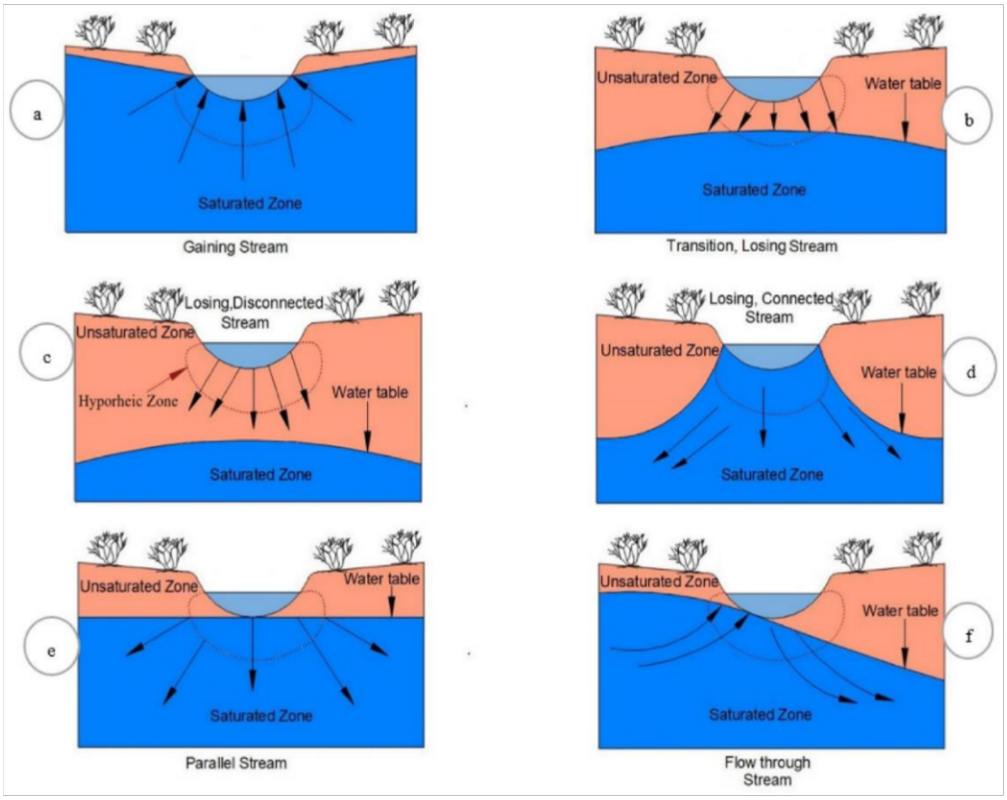


Figure 9 - Different stream-water and groundwater interaction scenarios (Banerjee & Ganguly, 2023)

The influence of climate change on groundwater quality can be related to an increased leaching of contaminants from pesticides due to warmer climates, but predictions and observations retain numerous uncertainties as the impacts could be related to land use changes or increases pest pressures (Amanambu et al., 2020; Kløve et al., 2014). However, significant changes in the frequency and regime of groundwater recharge as a variable in climate change projections may also have a significant impact on groundwater quality (Barbieri et al., 2023). When contaminants are present in the aquifer, recharge from sources such as surface water, mountain fronts or precipitation can contribute to the mixing of freshwater with contaminated water, the so-called dilution effect (Mas-Pla et al., 2017). The potential decline in freshwater recharge due to climate change threatens to impair the dilution (Mas-Pla et al., 2017; Ortmeyer, 2021). However, it is important to note that while dilution may reduce the contaminant concentrations in groundwater, it does not reduce the total contaminant load (Altman et al., 1995). The altered interaction between groundwater and surface water has also been reported to change the direction of groundwater flow (Akpan et al., 2016). This can be important if the main flow of pollutants is diverted towards the pumping stations for drinking water supply.

An indirect impact can come from overexploitation of coastal aquifers in response to droughts, which can then lead groundwater to be contaminated via saltwater intrusion. Temperature could also be considered a quality parameter. Recent studies show how the increase in air temperature is also found in groundwater temperatures (Egidio et al., 2022). Temperature increase may also lead to indirect impacts on groundwater quality as it may alter the hydrogeochemical processes of contaminants mobility and dissolution or could help the proliferation of microbial activity in aquifers or connected water bodies (Riedel, 2019).

The human response to climate change is considered the major indirect impact as it can have an important role in stressing pressures on groundwater recharge, storage, quality, interactions with surface water bodies. Land use and irrigation practices changes have a high impact on groundwater recharge (Kundu et al., 2017). For example, groundwater human usage may increase due to meteorological or surface water scarcity. If the human water demand remains constant while temperatures increase and precipitations decrease, surface water can become scarcer, shifting water utilization from surface water towards groundwater, increasing pumped volumes (Amanambu et al., 2020). This feedback loop is a menace to groundwater resources, since it enhances the decreased recharge adding an increase in usage output, leading to faster depletion and low water table levels.

4. Pressures on surface runoff

Surface runoff is usually related to groundwater infiltration when talking about the soil-water balance during and after a rainfall event or the complete water cycle as the one shown in Figure 8. Precipitation on land can in fact be distributed across different elements: interception from plants and buildings, evapotranspiration from soil and plant, infiltration, surface runoff. These components' shares depend on soil composition and its compaction, on land cover and degree of impermeabilization, on the amount of vegetation present and other factors as the type of precipitation and atmospheric conditions. Surface runoff is thus a fundamental component of the water cycle, as it will go on to form different magnitudes of streams and rivers and contribute to the environmental cycles and human utilizations. Since it is related to the water cycle, and the water cycle is highly impacted by climate change, runoff also has repercussions coming from climate change. Quality variations due to climate change have also been observed in surface water both in nutrients content (Bouraoui et al., 2004) and in temperature (van Vliet et al., 2023).

During intense precipitation events, infiltration capacity of the soil is rapidly reached, meaning that any excess water will result in surface run off with the possibility of floods generation, generally referred as flash floods. With increased frequency of extreme rainfalls due to climate change, this phenomenon will also become more frequent. In the past few years, many events like this happened across Europe, as in Slovenia in August 2023, with different floodings throughout the country (Bezak et al., 2023). Hydrological drought is another impact of climate change on surface runoff, in this case targeting streams and rivers. Low precipitation volumes or concentrated in a short period of time result in stream discharges which may have high peaks but have a low average discharge and longer periods of low or absent discharge, depending on the size of the hydrographical basin of the stream. Europe experienced this phenomenon as well in recent years, with the example of river Po in Northern Italy being one of the most impactful one (Toreti et al., 2022). Droughts and floods can also result in a joint phenomenon, since periods of meteorological droughts can lead to conditions (dry soils, lack of vegetation) which will make the areas more incline to floodings after intense precipitation events (Ward et al., 2020). In 2023, in Emilia Romagna, Italy, a combination of a long dry period and a severe precipitation event led to an unprecedented flooding with multiple casualties and enormous damages to the environment and buildings (Weisbrod, 2023; World Weather Attribution, 2023).

Moreover, an increase in runoff caused by greater precipitation intensity result in an increase in pollutants mobilisation and transport. The increase of the nitrogen and phosphorous concentration due to the leaching of fertilizer from the soil by excessive run-off was previously reported (Delpa et al., 2009).

Excessive outflow of surface water caused by climate change also results in local flooding. This phenomenon is particularly intense in highly urbanized areas and other areas subject to anthropogenic pressure, for example post-mining areas. The progressing urbanization of cities and increasing density of the development causes the decrease in water retention capacity of these areas. For these areas, the effective precipitation (the fraction of the total precipitation lowered by terrain wetting, filling of land depressions, infiltration, and evaporation) is almost equal to the actual precipitation. The exposition to the local flooding and greater surface runoff often results in the destruction of property, buildings, and communication routes. Additionally, these negative effects could be also observed in other urban sectors. The water and wastewater sector are the most exposed to the effects of climate change. Heavy rains cause inefficiency of the drainage system and limit the possibilities of producing and distributing treated water (Walczykiewicz et al., 2020) In cities, where storm water and sewage is transported via combined sewer system, more intense and more frequent storms due to climate change also increase the frequency of CSO events, which contributes to increased receiving waters pollution and ecosystem impairment (Radinja et al.,2022).

Very significant negative impacts on surface water quality with climate change are related to urban agglomerations, in which built-up areas (preventing rainwater retention) represent the dominant area of the agglomeration. Rainfall in urban agglomerations is most often drained from covered areas into sewage systems, which are unable to hold such a large amount of water during intense rainfall, and it is necessary to drain excess water away from wastewater treatment plants. Since in the vast majority of urban agglomerations there are no separate sewage networks for municipal wastewater and separately for rainwater, the discharge of water from the sewage system without sufficient cleaning directly into the recipient causes serious surface water pollution (microbiological, chemical, micropollutant pollution, etc.). Such pollution of surface water can be the cause of a serious threat to human health and the quality of the environment.

D. References

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