STUDY OF THE IMPACTS OF PRESSURES ON GROUNDWATER IN EUROPE

SERVICE CONTRACT No 3415/B2020/EEA.58185

Overview of groundwater-surface water interdependencies

Sub-study 3 - Final draft report

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1.0	First draft report	20.04.2021
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3.0	Approved consolidated final report	23.06.2021

Contents

List of abbreviations

This document uses a series of abbreviations, which are provided below for the sake of clarity to the reader.

DWD	Drinking Water Directive
EU-27_2020	27 EU Member States by 2020, after exit of UK
GWAAE	Groundwater Associated Aquatic Ecosystems
GWB	Groundwater Body
GWDTE	Groundwater Dependent Terrestrial Ecosystems
HD	Habitats Directive
IED	Industrial Emissions Directive
JRC	Joint Research Centre
PFAS	Per- and polyfluoroalkyl substances
SWB	Surface Water Body
UWWTD	Urban Waste Water Treatment Directive
WFD	Water Framework Directive, Directive 2000/60/EC
WISE	Water Information System for Europe

Key findings

- The strategic importance of groundwater bodies (GWBs) is increasingly recognised, because they can store water with negligible evaporation, they buffer the impacts of climate variability, and they provide better protection against pollution, compared to surface waters.
- Groundwater associated aquatic ecosystems (GWAAEs) and groundwater dependent terrestrial ecosystems (GWDTE) are an important part of Europe's natural capital and heritage, and they provide numerous ecosystems services, including carbon sequestration, climate change mitigation and adaptation, purification of surface and groundwater, natural water retention, biodiversity conservation, and provision of cultural services.
- However, GWBs in the EU 27 are under significant pollution and abstraction pressures, both of which are likely to intensify in the future, due to population growth, land use change and climate change. According to the 2nd River Basin Management Plans, 27% of the total GWB area in the EU 27 had either poor quantitative or chemical status, with the area having poor chemical status being significantly larger.
- Approximately one third of the GWB area, which is linked with GWAAEs or GWDTEs, was in poor quantitative or chemical status in the 2nd RBMPs. Furthermore, around 5% of the total GWB area in the EU 27 had poor quantitative or chemical status, and it was also linked with GWAAEs having less than good ecological or chemical status and less than favourable habitat conservation status. Similarly, 7% of the total GWB area had poor quantitative or chemical status, and it was also linked with GWDTEs having less than favourable habitat conservation status.
- Porous, fissured and karstic aquifers are more likely to be in less than good status, compared to fractured and insignificant aquifers, as they are the most widespread and exposed to pressures from socio-economic development and climate change. The aquifer size, thickness, composition, and mechanisms for groundwater flow and pollutant transport also affect the vulnerability of aquifers. Furthermore, shallow aquifers, linked with surface water bodies, are more likely to be polluted or over-exploited, based on the analysis of this study.
- Agriculture is a key driver of pressures that lead to less than good groundwater status, with 20% of the EU 27 GWB area being affected by agricultural diffuse source pollution and 7% by agricultural abstraction. Other significant pressures include the supply of water to the public (7%), discharges from scattered dwellings non-connected to sewerage networks (5%), point source pollution from abandoned industrial or contaminated sites (4%), point source pollution from industrial plants regulated under the Industrial Emissions Directive (4%). The same pressures also significant for those GWBs linked with GWAAEs and GWDTEs.
- Many GWBs are affected simultaneously by multiple drivers and pressures, which can be related both to water quantity and quality. GWBs in less than good status are also associated with multiple impacts, such as chemical and nutrient pollution, water imbalances, and impacts on GWAAEs and GWDTEs. Managing the trade-offs between different types of drivers and pressures, and their combined impacts on groundwater status, will be key for restoring GWBs in less than good status and reversing negative impacts.
- The quantitative and chemical status of GWBs can be strongly interdependent. Tackling over-abstraction may prevent salinisation of groundwater in coastal or inland areas, while

reducing agricultural pollution can support the delivery of safe and affordable drinking water. This is particularly relevant for southern EU 27 Member States, where GWBs were twice more likely to have both poor quantitative and chemical status (8%), compared to the EU 27 average (4%), according to the 2nd River Basin Management Plans.

- Adaptation to the impacts of climate change will be a major challenge, as groundwater recharge is expected to decrease further in southern Europe, and parts of western and central Europe, where many aquifers are already over-exploited. In northern and north-eastern Europe, earlier snow melting is expected to change groundwater infiltration patterns, decreasing summer baseflow further, and making shallow aquifers more vulnerable to pollution. Saline intrusion will be more likely to affect coastal aquifers, where droughts lead to increased abstraction and the average sea level rises. Maintaining and achieving good groundwater status can increase the climate resilience of European society and economy.

- The EU has established an elaborate environmental policy framework that contributes to sustainable management of groundwater and its linkages to GWAAEs and GWDTEs. Key policies include the Water Framework Directive, the Groundwater Directive, the Biodiversity Strategy, the EU Climate Change Adaptation Strategy, and the Zero Pollution Action Plan. Through the European Green Deal, the European Union is establishing new ambitious environmental targets in the field of biodiversity and nature restoration, agriculture and food, chemicals and the circular economy, as well as adaptation to and mitigation of climate change. Meeting these targets will contribute to more sustainable management of groundwater resources, and ensure sufficient, good quality water for the environment and for people.

- However, effective implementation of policy provisions faces major operational challenges, due to challenges in monitoring and measuring groundwater balance and quality, understanding dynamics, and raising awareness of the risks related to groundwater pollution and over-abstraction. The link between GWBs and GWAAEs or GWDTEs is not always made. Furthermore, there are significant data and knowledge gaps for providing a comprehensive European overview on this topic.

- The precautionary principle should be more widely applied to groundwater management, given the long time and the high costs usually required for groundwater restoration. Further action is also needed to regulate land uses and activities that pose significant risks to groundwater quality. In addition, it is important to control groundwater abstraction, especially by agriculture and public water supply, and prevent emerging pollutants and new pressures to irreversibly damage good groundwater status, as well as GWAAEs and GWDTEs.

1 Introduction

1.1 Groundwater in Europe: a resource to protect

Groundwater is a finite resource which needs protection from over-exploitation and pollution to ensure the long-term sustainability of its use for human activities. Groundwater is the main source of good quality drinking water for a significant part of the European population, covering more than 65% of water supply to the public in the EU Member States abstracting high volumes for this purpose, such as France, Germany, Hungary, Italy and Poland. Groundwater serves as a reliable buffer source against climate variability, because of its relatively greater storage capacity, reduced evaporation, and higher protection against pollution compared to surface waters. In Europe, 32% of the water abstraction for supply to the public, agriculture and industry comes from groundwater, including springs (EEA, 2018a). Sustaining sufficient and clean water in aquifers can also enhance societal resilience to the negative impacts of climate change and human development. Groundwater, thus, plays a strategic role in the overall river basin management, provided that surface water and groundwater resources are managed in an integrated way (see Chapters 2 and 3 of this sub-study).

Once a GWB is over-exploited or polluted, the natural processes of recharge and attenuation, as well as the artificial efforts to recharge groundwater and treat pollution, can take years or decades before groundwater levels and/or quality recover (see Box 1.1). Understanding the impacts of pressures on groundwater and their consequences for GWAAEs and GWDTEs, as well as how to manage those impacts, is crucial for achieving the objectives of flagship EU environmental legislation, such as the EU Water Framework Directive (WFD) and the ambitious goals of the EU Green Deal (see Chapter 3 of this sub-study).

Box 1.1 Overview of groundwater management challenges per aquifer type

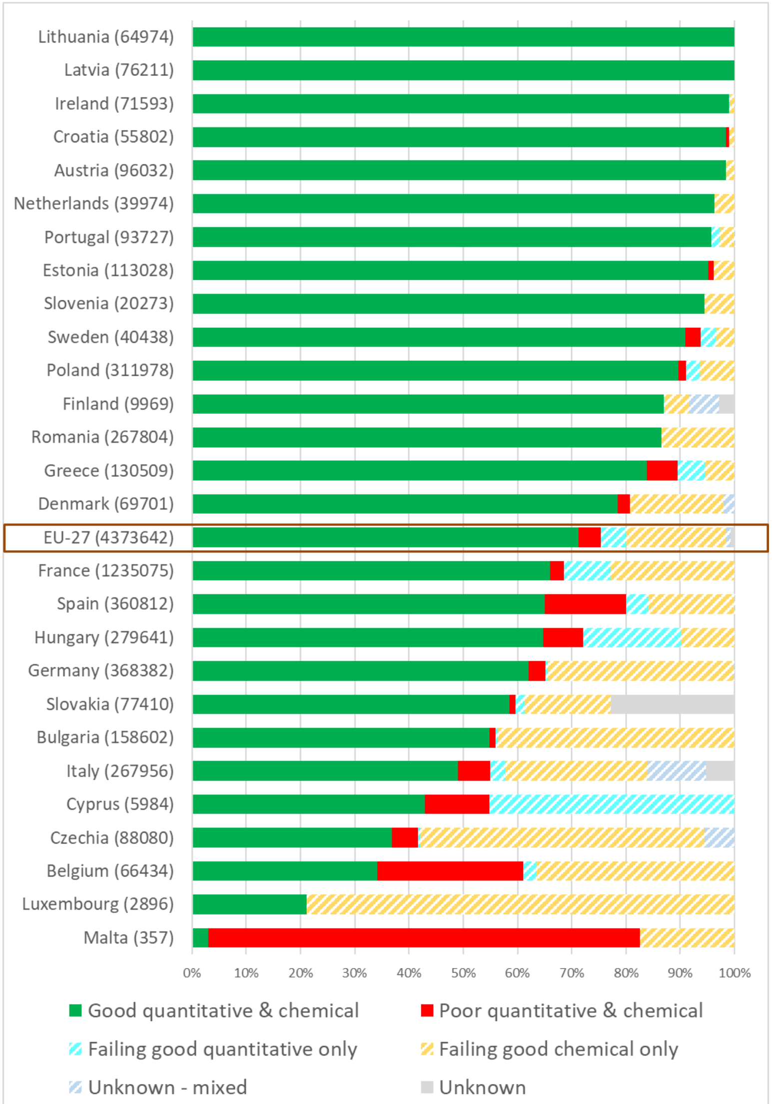
A wide range of porous aquifers can be found across Europe, including river flood plain deposits (e.g. sands, silts and gravels), glacial drift (e.g. sands and gravels in thick continuous aquifers or isolated eskers), and consolidated sedimentary rocks (e.g. sandstones, conglomerates, siltstones). Unconsolidated sand and gravel porous aquifers are the most vulnerable to pollution and over-abstraction, because they are located closer to the ground surface, they are frequently linked to SWBs and they are typically small with shallow thickness, leading to low storage capacity. In contract, porous sandstones and conglomerates have a large storage capacity and, therefore, tend to respond slowly to over-abstraction and pollution. Once over-exploited or polluted, though, they recover very slowly also (e.g. over time scales of decades / centuries). Porous aquifers are the most common type of GWBs for which environmental objectives have been set under the WFD. They are typically exploited in river flood plain areas where water demand is often higher due to multiple water users (e.g. urban centres, agriculture, industries). Therefore, they are more likely to be exposed to significant pressures from human development.

Fissured aquifers of high productivity (e.g. limestone, chalk and other carbonate rocks having dual porosity or karsts) are vulnerable to pollution, because they allow rapid flow-paths through their mass, which spread the pollutants rapidly. Although rapid fissure transport allows groundwater levels to recover quickly (e.g. over the time scale of weeks / months), the existing matrix of pore spaces can trap particles of pollutants through diffusion, and they can be released slowly over a longer period of time (e.g. over the time scale of decades). When the aquifer is also over-exploited, because the long-term abstraction rate exceeds the recharge rate, then the aquifer is likely be in both poor quantitative and chemical status.

Crystalline basement rocks, volcanic rocks, schists and shales have limited matrix porosity. Thus, they have very low storage capacity of pore water and insignificant flow-paths through their mass, compared to fissured rocks with dual porosity or karsts. In this case, they form low-yield aquifers. Their storage capacity and productivity increases, though, where the degree of their fracturing is higher. However, unlike fissured aquifers with dual porosity and karsts, increased productivity of fractured aquifers facilitates rapid flushing out of pollutants. Therefore, they are also less vulnerable to pollution. Furthermore, clays, marls and mudstones form low permeability layers or aquitards, which retard water flow. Localised bands of coarser sediments such as sandstone or gravel lenses within such layers can form small pockets of groundwater. Although these are unsuitable for large scale abstraction, they can provide small potable sources for isolated dwellings. In general, they are also less vulnerable to pollution from the surface. However, retarded water flow conditions can significantly slow down their recovery from over-exploitation or pollution, where such incidents occur.

Nevertheless, European groundwater is currently under significant pollution and abstraction pressure, both of which are likely to intensify in the future, due to population growth and climate change. Under the WFD, EU Member States (MS) characterise, monitor and assess GWBs, and implement measures, where required. Their aim is to maintain and achieve good groundwater status. In the 2nd River Basin Management Plans (RBMPs), which were reported in 2016, 27% of the total GWB area in EU 27[1] had either poor quantitative or chemical status, while 4% actually had both poor quantitative and chemical status (Figure 1.1) (see sub-study 1, Psomas et al., 2021b).

Figure 1.1 Distribution of groundwater status per EU 27 Member State in the 2nd RBMPs (in % of total national GWB area).



Note: The reported total national GWB area is given in brackets next to country name (in km^2)

[1] EU 27_2020, or EU 27 in short, is used in this report for the 27 EU Member States as of 1 February 2020; thus, accounting for the withdrawal of the United Kingdom from the European Union

Source: Author's compilation based on data from WISE Water Framework Directive Database – 2nd RBMPs (EEA, 2020b)

The problems affecting groundwater quantity are commonly triggered by water abstraction and alteration of groundwater level/volume. However, these quantitative issues often co-exist with groundwater quality issues, because pollution pressures are also present. For instance, it is estimated that 47% of the GWB area in both poor quantitative and chemical status is affected by chemical pollution and water imbalances/lowering water tables, while 26% is affected by chemical pollution, nutrient pollution, saline intrusion and water imbalances/lowering water tables. Therefore, less than good overall status of GWBs can be related to combinations of multiple pressures, causing a wide range of impact types (see sub-study 1, Psomas et al., 2021b).

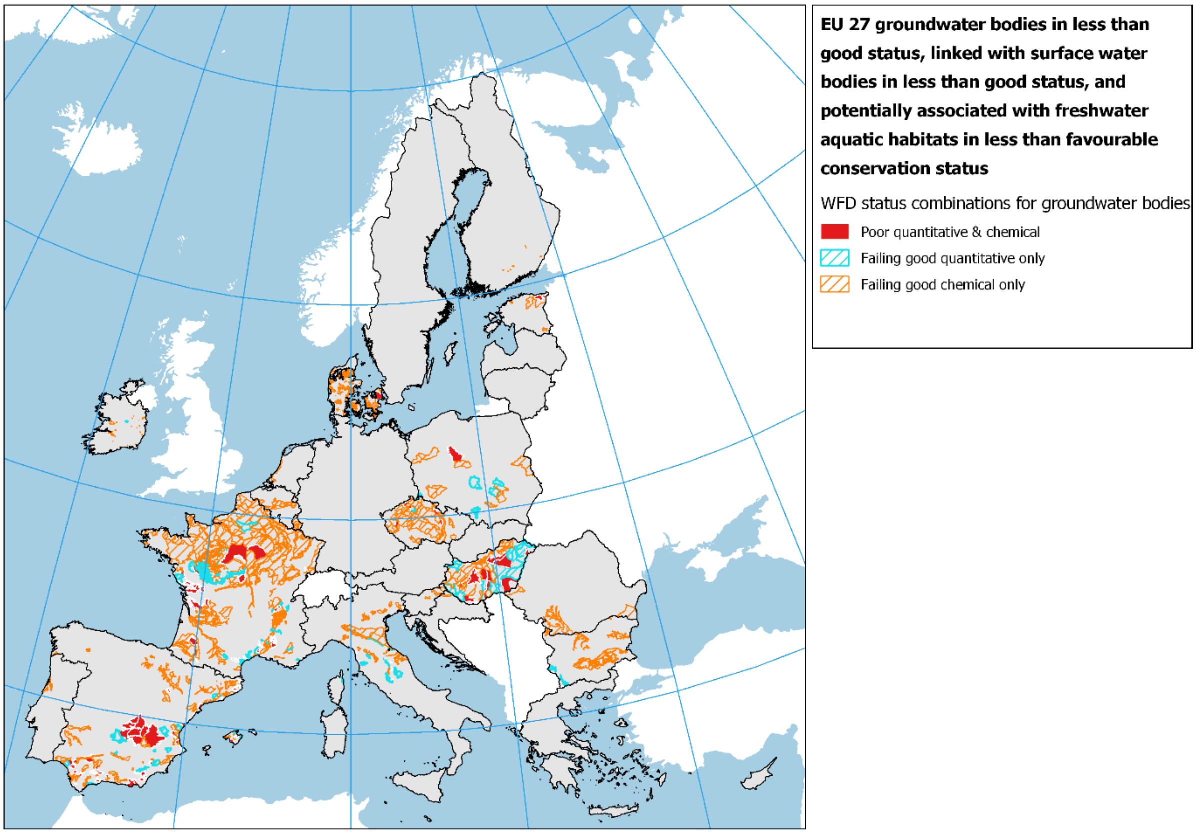
Furthermore, interdependencies of poor quantitative and chemical status are observed in various cases, including: increased concentrations of pollutants due to lower dilution capacity of over-exploited groundwater; human-induced influx of impaired waters, deeper brines from “ancient seas”, dissolved evaporites, connate waters and mixture with clean groundwater; sea water intrusion in coastal aquifers due to over-abstraction and climate-driven seas-level rise and storm surges; relocation of abstraction points due to deterioration of groundwater quality; increased groundwater abstraction due to deterioration of surface water quality; acid mine drainage after phasing-out dewatering operations at mining sites and other pollution sources for groundwater (see sub-study 1, Psomas et al., 2021b).

Groundwater plays a key role in the ecological functioning of freshwater and coastal ecosystems and provides essential services to society. Groundwater is part of the larger hydrological cycle and interacts with surface water systems, including rivers, lakes and estuaries. Aquatic species (e.g. macrophytes, phytoplankton-algae, fish, benthic invertebrates) and their ecosystems rely on a stable supply of water with specific properties to their aquatic habitats. The input groundwater quantity (e.g. volumes, stages, flows) and quality (e.g. temperature, oxygen level, salinity, acidity/alkalinity, nutrient load, etc.) can be critical to their condition (see sub-study 2, Psomas et al., 2021b). Some terrestrial ecosystems are also dependent on groundwater fluxes, including marshes, meadows, swamps, wet slacks, wet heaths and scrubs, wet forests/woodlands, mangroves, wetlands and peatlands (e.g. fens, bogs and mires). Certain freshwater and terrestrial habitats, and their species, depend to a varying degree on the good chemical and quantitative status of groundwater bodies (GWBs), as well as on the good ecological and chemical status of associated surface water bodies (SWBs) (see sub-study 2, Psomas et al., 2021b).

Such groundwater associated aquatic ecosystems (GWAAEs) and groundwater dependent terrestrial ecosystems (GWDTEs) are an important part of Europe’s natural capital and heritage. Furthermore, they provide important ecosystems services, including: intensive sequestration of carbon dioxide; contribution to climate change mitigation and adaptation; purification of surface and groundwaters from pollutants; facilitation of water storage, infiltration and deep percolation; flood mitigation; biodiversity enhancement; provision of unique habitats and breeding areas; freshwater supply to water-dependent sectors of the economy; supply of exploitable fish, animal and plant resources (see sub-study 2, Psomas et al., 2021b).

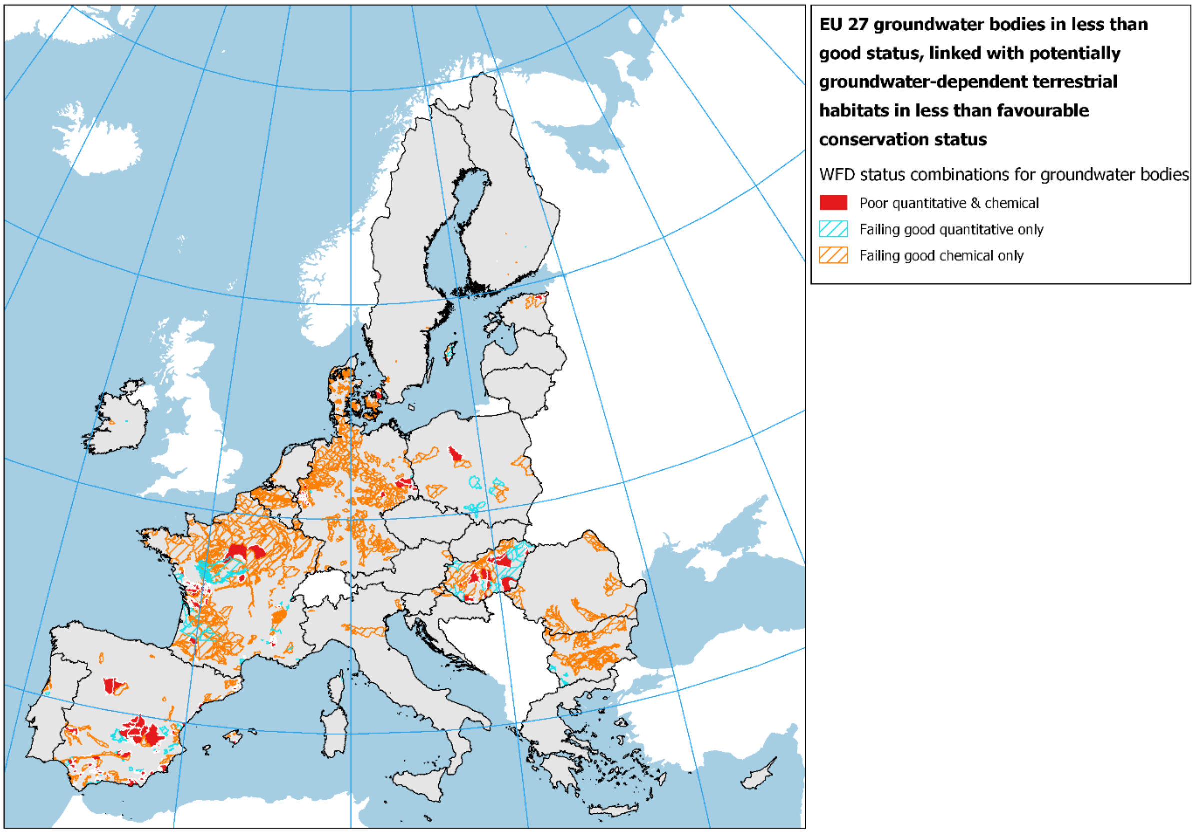
Pressures on groundwater threaten the supply of sufficient water of appropriate quality to GWAAEs and GWDTEs. Approximately 44% of the total GWB area in the EU 27 is potentially linked with GWAAEs and 53% with GWDTEs. Therefore, these ecosystems represent very large areas across Europe, and they are severely exposed to climate and human-induced pressures and impacts. In GWBs linked with GWAAEs and GWDTEs, the most significant pressure is agricultural diffuse source pollution, followed by abstraction for public water supply and abstraction for agriculture. The share of the total GWB area in the EU 27, which has less than good groundwater status, and it is also linked with GWAAEs and GWDTEs having less than favourable habitat conservation status, is estimated at 5% and 7%, respectively (Maps 1.1 and 1.2). The vast majority of these linked GWBs are made up of porous aquifers and they are found in the uppermost groundwater horizons (see sub-study 2, Psomas et al., 2021b).

Map 1.1 EU 27 areas where less than good status of GWBs and less than favourable conservation status of GWAAEs could be interdependent.



Note: EU 27 GWBs in poor quantitative or chemical status, linked with GWAAEs in poor chemical or ecological status and less than favourable conservation status;
Germany is blank because no links between GWBs and SWBs are reported. Lithuania and Slovakia are blank because there is no reporting on links between GWBs and SWBs. The maps do not include linked GWBs and SWBs from the whole territory of Sweden and from part of the territory of Italy, although such linkages are reported to exist, because the specific codes of the SWBs, which are linked with GWBs, are not provided.
Source: Authors' compilation based on data from WISE Water Framework Directive Database – 2nd RBMPs (EEA, 2020b) and from Habitats Directive – HD Art. 17 reporting (2007-2013) (EEA, 2020c); see sub-study 2, Psomas et al. (2021b)

Map 1.2 EU 27 areas where less than good status of GWBs and less than favourable conservation status of GWDTEs could be interdependent.



Note: EU 27 GWBs in poor quantitative or chemical status, linked with GWDTEs in less than favourable conservation status;
Czechia is blank because no links between GWBs and GWDTEs are reported. Lithuania and Slovakia are blank because there is no reporting on links between GWBs and SWBs.
Source: Authors' compilation based on data from WISE Water Framework Directive Database – 2nd RBMPs (EEA, 2020b) and from Habitats Directive – HD Art. 17 reporting (2007-2013) (EEA, 2020c); see sub-study 2, Psomas et al. (2021b)

1.2 Scope and outline of this report

This report presents an **overview of interdependencies between groundwater and surface water**, taking into account a series of five challenges to sustainable groundwater management in the EU 27. The five challenges are related to:

- Agricultural production;
- The supply of good quality and sufficient water to the public;
- Urban and industrial development pressures, and emerging pollutants;
- Mining activities; and
- The over-arching consequences of climate change.

For each challenge, there is an overview of the driver, and a description of associated pressures and impacts, as well as relevant management measures. Examples of relevant cases across the EU 27 are provided throughout the text. Separate sections highlight indicative cases with reported impacts on GWAAEs and GWDTEs. The concluding section provides an overview of EU policy action to protect groundwater resources, as well as challenges and recommendations.

The report draws upon key results from two parent “sub-studies” related to this contract (Psomas et al., 2021a; Psomas et al., 2021b), as well as on additional literature and evaluations. Links to the other two sub-studies are provided throughout the text, especially for the analysis of key pressures and impacts on GWBs, and their interdependencies with SWBs and linked GWAAEs and GWDTEs.

2 Pressures and responses for sustainable groundwater management

2.1 Agricultural production

2.1.1 Agriculture and groundwater

Over the past 70 years, the European agricultural sector has increased its production of food, animal feed and textiles to meet the rising demands of the population and markets in Europe and worldwide. EU is a global leader of agri-food exports, which reached 138 billion € in 2018 (DG AGRI, 2019).

However, the demand for agricultural products is associated with significant pressures on groundwater. For instance, the agricultural sector is using increasing quantities and types of fertilizers and pesticides to secure higher yields in cropland, orchards and grasslands. Furthermore, the agricultural sector is frequently responsible for cases of over-abstraction of groundwater for irrigation purposes (EEA, 2020f). The extent of land area which is intensively managed for food production has grown. Fertilisers are mostly consumed by the crops, whilst most permitted pesticides are designed to degrade in ultra-violate light and soils. However, excess use of both fertilisers and pesticides causes leaches of nutrients and chemicals into groundwater. Agricultural activities are also responsible for the pollution of groundwater with microbial pathogen pollutants (e.g. from poor manure use and slurry storage) and pharmaceuticals (e.g. from veterinary medicines and spreading of biosolids to land) (EEA, 2020f).

In addition, aquifers typically provide a buffer against seasonal variations of climate, due to their storage capacity and their relatively slow response to decreases of recharge (e.g. during spring and summer). However, excessive abstraction of groundwater can result in artificially low water tables, which reduce the groundwater discharge to GWAAEs and GWDTEs.

2.1.2 Agricultural pollution pressures on groundwater

Diffuse source agricultural pollution from fertilisers, pesticides, and other chemicals used in agricultural production is the most widespread pressure contributing to less than good status of GWBs in EU 27. In the 2^{nd} RBMPs, this pressure affected significantly 20% of the total GWB area in EU27, and it was reported as the most common pressure for all types of aquifers. Fissured (including karstic) and porous aquifers were affected proportionately more by this pressure (around 21% of their total area), compared to fractured or insignificant aquifers, which were still affected to a significant degree (13% of their total area) (see sub-study 1, Psomas et al., 2021a). Furthermore, 11% and 15% of the total GWB area in the EU 27, linked with GWAAEs and GWDTEs respectively, has less than good groundwater status due to diffuse source agricultural pollution. Agricultural pollution most commonly affects porous and fissured aquifers linked with GWAAEs/GWDTEs (see sub-study 2, Psomas et al., 2021b).

In Europe, the Nitrates Directive 91/676/EEC aims to control nitrogen pollution of GWBs where concentrations exceed 50 mg/L. In addition, the Drinking Water Directive (DWD) sets maximum permissible nitrate levels at the same concentration for tap water. In the period 2016-2018, the average nitrate concentration in untreated groundwater in 16 EU Member States was above that standard (EEA, 2020a). Belgium, Bulgaria, Cyprus, Czechia, Germany, Malta, and Spain had the highest proportion (more than 10 %) of GWBs with an average concentration above the standard. There were also GWBs with nitrate concentrations above the standard in Austria, Denmark, Estonia, France, Italy, the Netherlands, Poland, Portugal, and Slovakia (EEA, 2020a).

No reduction in average nitrate concentration in groundwater has been observed at European level for the last 30 years, with a slight increase in recent years (EEA, 2020a). Above average nitrogen surpluses in agricultural soils, which provide an ongoing source of nitrate to groundwater, are still identified in Germany, the Netherlands, Denmark, Czechia, Ireland, and large parts of France, Spain, Italy and Hungary (EEA, 2020f).

Agricultural pollution of groundwater by pesticides results from the diffuse leaching of pesticides following spraying onto fields or point sources of pollution following the clean-up of equipment and accidental spillages in handling areas. In accordance with the Groundwater Directive 2006/118/EC, the Groundwater Quality Standard for each active substance in pesticides is 0.1 µg/l and 0.5 µg/l for the total sum of pesticides and their relevant metabolites. It is estimated that 6.5% of the total GWB area is in less than good status in the 2nd RBMPs, due to pesticide pollution (Mohaupt et al., 2020). Furthermore, herbicide and insecticide concentrations exceeded the groundwater quality standard at 7 % and 1% of the total groundwater monitoring sites, respectively (Mohaupt et al., 2020).

In some cases, pollution with chemical products used in agriculture may not be a contemporary, but rather a legacy issue. For instance, atrazine is a banned herbicide due to its persistence in groundwater. According to the 2nd RBMPs, atrazine is reported to cause failure of good status in a significant proportion of the total GWB area linked with SWBs, as well as in a small proportion of the total length of SWBs linked with GWBs (without simultaneous failures of good status being reported, though) (see sub-study 2, Psomas et al., 2021b). Due to the official ban of atrazine, it is assumed that such cases represent a legacy pressure, with GWBs having been polluted in the past and still discharging this chemical substance. It is noted that the metabolites of pesticides are increasingly under scrutiny and those with the same properties as the parent substance (relevant metabolites) are already included in the Groundwater Quality Standard.

Impacts on GWAAEs and GWDTEs

Since groundwaters may provide baseflow to surface waters, pollutants may find a potential pathway to GWAAEs and GWDTEs, which can be damaged. This is typically more of an issue for nutrients compared to pesticides, due to the conservative nature of nitrate (see sub-study 2, Psomas et al., 2021b). Some examples include: the discharge of nutrient-rich groundwater to Turloughs, which is a unique groundwater-fed lake ecosystems linked to karstic areas in Ireland (Skeffington et al., 2006); and the risk for significant growth of filamentous algae and reduced sea-grass population, due to nitrate loading from groundwater into surface water discharging to the Horsens Estuary, Denmark (Hinsby et al., 2012).

2.1.3 Agricultural abstraction pressures on groundwater

The EU 27 Member States have abstracted annually around 51-61 billion m^3 of water for agricultural purposes between 2010-2017. The annual fluctuation suggests that the annual climatic conditions affect crop water needs and water abstraction follows up such patterns.

However, agricultural water abstraction is unevenly distributed. Almost 90% takes place in southern Member States, and only 10% in the rest. In southern Member States, agricultural water is abstracted mainly for crop irrigation, which takes up to 80% of the total water abstraction in some river basins

(EEA, 2018a). In southern Europe, the climate is warmer and drier, compared to other parts of Europe. Therefore, irrigation is essential to enable crop cultivation and improve crop yields. Irrigation is needed especially in spring and summer when the rainfall is at its lowest levels and the crop needs reach their peak.

Southern European Member States, such as Cyprus, Greece, Malta and Portugal apply the highest volume of irrigation water per hectare of irrigated land (> 6 000 m^3/hectare) (EEA, 2021b - forthcoming). In parallel, the same countries also rely heavily on groundwater to cover their irrigation needs (>40%), whereas the rest water is abstracted from surface waters (e.g. rivers, lakes, reservoirs) (Zal et al., 2017). Bulgaria, France and Spain also apply high volumes of irrigation water per hectare (EEA, 2021b - forthcoming). Although their main source of agricultural water at the national level is surface water (Zal et al., 2017), groundwater is also a key source regionally, such as the Spanish aquifers in lower Guadalquivir irrigating strawberry fields (De Stefano, 2004), and the French aquifers in Beauce region irrigating maize fields (Maréchal and Rouillard, 2020). Furthermore, other Member States which rely heavily on groundwater for agricultural abstraction are Denmark, Germany, and the Netherlands. However, they apply a much lower volume of irrigation per hectare compared to the above-mentioned countries, because their production is more rainfed. Irrigation is mainly applied when the cultivated crop types require more water than the rain can provide, and the water retention capacity of the soils is poor. For example, irrigation is applied across Denmark mostly on sandy soils where potatoes, maize and cereals are commonly grown (Ten Damme and Neumann Andersen, 2018), as well as on drought-sensitive sandy soils of Noord-Brabant, which is a major agricultural area in the Netherlands (Witte et al., 2019).

Agricultural water abstraction is a significant pressure causing less than good status of GWBs in various islandic areas. This happens especially when it coincides with additional groundwater abstraction pressures by households, tourism, and the industry, and surface water supplies on the island are limited (see Box 2.1).

Box 2.1 Groundwater abstraction for irrigation in the Canary Islands

The Canary Islands are a volcanic archipelago with a highly permeable geology. As a result, there are limited surface water resources and groundwater has historically been the most important source of freshwater, exploited through galleries draining productive aquifers, wells and boreholes. Some islands of the archipelago have substantial quantities of brackish groundwater, which have been increasingly exploited in the 20th century for irrigation purposes after blending with other water resources or treatment through reverse osmosis or electro-dialysis reversal. Agricultural water demand has been rising through the late 20th century to produce highly valuable winter crops for export. Desalination units were installed in the 1980s to meet irrigation water demand, resulting in considerable exploitation of local brackish groundwater.

Intensive exploitation of groundwater resources for agricultural production, but also for increasing population and tourism, has led to a continuous lowering of the groundwater levels, decreasing spring flows, drying out springs, and threatening coastal areas with saline intrusion from the ocean. Costs of producing water has increased with the deepening of wells and water galleries. To meet demand, other sources are increasingly exploited, including desalinated seawater and treated waste water.

Sources: Veza (2006); Custodio and Cabrera (2013)

According to the 2nd RBMPs, almost 7% of the total GWB area in EU 27 was in less than good groundwater status, due to agricultural water abstraction. This area included 9% of the porous aquifer area, 7% of the fissured and karstic aquifer area, and lower shares for the other aquifer types. Less than good status due to agricultural water abstraction was reported most commonly in the Flanders region of Belgium, Cyprus, in northern and western France (e.g. Beauce Aquifers, Moselle, Plaine du

Roussillon), eastern Greece (e.g. Thessaly), Hungary, southern Italy, Malta, and across eastern, southern and central parts of Spain (e.g. Mancha and lower Guadalquivir aquifers) (see sub-study 1, Psomas et al., 2021a). Furthermore, 4% and 5% of the total GWB area in the EU 27, linked with GWAAEs and GWDTEs respectively, has less than good groundwater status due to agricultural abstraction. Agricultural abstraction most commonly affects porous and fissured aquifers linked with GWAAEs/GWDTEs (see sub-study 2, Psomas et al., 2021b).

Over-abstraction of water from coastal freshwater aquifers can result in a progressive salinisation of these aquifers due to upward intrusion of underlying denser sea water. At particular risk are the karstic aquifers of the Mediterranean coast which are extensive in Spain, France, Italy, Croatia, Malta and Greece. In the 2nd RBMPs, specific regions affected by coastal saline intrusion were reported along the Spanish coast, the Baleares, the Pô and the Seine delta, and the Italian Adriatic coast (see sub-study 1, Psomas et al., 2021a). These aquifers tend to be under intense pressure from agriculture and drinking water abstraction, due to population growth and tourism. The vulnerability of coastal karstic aquifers is higher, compared to porous or fractured aquifers, because intrusion of seawater is easier in karstic channels (EUWI, 2007).

However, saline intrusion may also be linked with the upwelling of deeper salt waters. For instance, through mixing of groundwater with layers of brines from “ancient seas” or through dissolution of evaporitic formations in sedimentary basins. This is visible in the case of the Alsace valley between France and Germany, along the Rhine. In addition, saline intrusion can be caused through mobilisation of highly mineralised connate water, which is trapped in the rock matrix during its formation, as a result of over-abstraction. In addition, in regions with dry climates, irrigation with groundwater can sometimes exacerbate the salinisation of soils and, ultimately, of the underlying aquifers, if salts are not washed out of the groundwater basin. It is estimated that 25% of the irrigated cropland in the Mediterranean region is affected by moderate to high salinisation. However, such cases of salinisation also occur in northern European countries such as Denmark, Poland, Latvia and Estonia (Tsanis et al., 2016).

Impacts on GWAAEs and GWDTEs

It is also important to note that over-abstraction for irrigation causes severe imbalances in the supply of groundwater to GWAAEs and GWDTEs. The natural flow regime of various Spanish rivers has been severely altered by over-abstraction, turning normally perennial rivers into intermittent flow streams. Furthermore, in locations with high water abstraction fish populations were significantly affected (Benejam et al., 2010). In addition, in mountainous streams affected by over-abstraction, reductions were observed in the breakdown of organic matter and the population of shredder insects (Arroita et al., 2015). The wetlands of Tablas de Daimiel, which are situated over the Western La Mancha aquifer, and Doñana, which takes up a coastal area in lower Guadalquivir, are indicative cases of affected ecosystems by over-abstraction in Spain (López-Gunn et al., 2013; Muñoz-Reinoso, 2001). Impacts on GWAAEs and GWDTEs have also been observed in much northern and wetter climates. For instance, drainage for forestry activities over the Rokua aquifer in Finland is considered to be one reason for having caused the decline of stages in unique oligotrophic “kettle” lakes (Box 2.2).

In other cases, irrigation with groundwater can be indirectly beneficial to downstream GWAAEs and GWDTEs. For instance, the application of irrigation can generate surface runoff and baseflow recharging downstream SWBs and GWBs. Some unique semi-natural ecosystems are now dependent on such irrigation-fed groundwater flows and levels, including large deltas, such as the Camargue delta of the Rhône river basin in France. Increasing irrigation efficiency, without re-allocating the saved water resources to the water environment, can reduce the above-mentioned return flows.

Box 2.2 Impacts on GWAAEs and GWDTEs from forestry drainage in Rokua esker aquifer in Finland

The Rokua aquifer, which is one of the largest esker GWBs in Finland, discharges into a natural reserve, whose western part has been designated as Natura 2000 area and part of the esker is protected as a national park. The esker is unconfined and discharges into peatlands that confine the groundwater. The Rokua area includes unique dune formations created after deglaciation and unique oligotrophic “kettle” lakes. Between 1950-1980, drainage for forestry was allowed, as well as supported with government subsidies. Large scale drainage activities caused severe impacts on springs and have been associated with frequent decline of lake levels in subsequent years, especially after dry periods. The Rokua area is a popular attraction for tourists, including hikers and skiers.

Sources : Rossi (2014); Klöve et al. (2011)

2.1.4 Responses and solutions

Since the enactment of the Nitrates Directive in 1991 and under the WFD RBMPs, models and tools have been developed to quantify and apportion sources and pathways of nutrients, vastly increasing the capacity of responsible authorities and other actors such as drinking water providers, to identify and select agricultural pollution measures, and measure their potential effectiveness (Buchanan et al., 2019). The Nitrates Directive also requires the adoption of specific farm management practices in nitrate vulnerable zones to reduce the level of nitrate pollution. However, ensuring compliance with mandatory farming practices designed to protect the water environment has been shown to be a challenge from the experience of enforcing the Nitrates Directive and cross-compliance of water legislation requirements under the EU Common Agricultural Policy (ECA, 2016).

At EU level, management of pesticide pollution has focused on the market regulation of pesticides. The Directive on the Sustainable Use of Pesticides 2007/128/EC promotes more integrated pest management (IPM) which prioritises the use of non-chemical methods for pest control such as biological controls and specific crop rotations. However, IPM is not yet widely implemented.

Under the WFD, countries are required to meter and license groundwater abstraction from agriculture. Although progress has been made in the most impacted river basins, major gaps remain on the metering and reporting of individual abstractions. Authorities often do not have the resources to monitor the large number of abstraction points, which may exist in any one river basin. Illegal water abstraction is widespread in some European countries, such as Spain (De Stefano et al., 2015; Schmidt et al., 2020). A combination of innovative technologies and new forms of governance may contribute to improved implementation (Box 2.).

Box 2.3 Restricting groundwater abstraction in the Mancha Oriental, Spain

The Mancha Oriental aquifer underlies a circa 700 m altitude semi-arid plateau. This large aquifer (10,000 km^2) consists of seven GWBs, the largest of which (Aquifer 19) is in poor quantitative status. The other GWBs are connected to Aquifer 19, potentially contributing to its recharge. A Water User Association (WUA) (Junta Central de Regantes de la Mancha Oriental, JCRMO) was formed in the 1990s leading to a stabilisation of groundwater levels, thanks to a self-imposed restrictions and an advance satellite monitoring system to estimate water use at plot level and identify sites with illegal irrigation. Every year before the irrigation season, the JCRMO calculates the available water for each irrigator based on the winter’s groundwater recharge. Farmers are responsible for adapting crops and irrigable areas to meet their individual cap. Abstraction levels are now at around 300 Mm^3 in the last 10 years. However, the target to achieve WFD objectives is 260 Mm^3 in 2027. It is planned that 80 Mm^3 of water should come from new sources, either additional water transfers (e.g. from Segura) or desalinisation plants.

Sources: López-Gunn and Cortina (2006); Calera et al. (2017)

Gaps exist in linking agricultural pressures on groundwater and subsequent impacts on GWAAEs and GWDTEs. For instance, in the Danish Horsens Estuary example mentioned previously, threshold values for nutrients in groundwater have been set to avoid impacts on GWAAEs and GWDTEs. However, the long lag time from introducing a measure to the improved conditions of the downstream ecosystems means that is not yet possible to understand how much actual progress is being achieved (Buchanan et al., 2019).

Overall, measures taken under the WFD RBMPs have given more emphasis on increased efficiency of fertiliser, pesticide and water use. Precision farming techniques are already available, and combine remote sensing and in-situ measurements of soils to optimise application of fertilisers, pesticides and water. More generally, the uptake of sustainable agricultural methods such as organic farming, agroecological practices and nature-based solutions, are needed over much of Europe to manage pressures on the water environment (EEA, 2020f). Sustainable farming practices have multiple benefits of reducing nutrient and pesticide use, building organic matter (and hence nutrient retention) and improving soil health, and building resilience in farming systems to climate change impacts (EEA, 2019).

To facilitate the uptake of sustainable agriculture, there needs to be local cooperation between farmers, authorities and food chain actors (e.g. supermarkets, food industry), and broad support from agricultural and food policies (e.g. market facilitation, economic incentives, financing), in particular stemming from the so-called second pillar of the EU Common Agricultural Policy (EEA, 2020f).

2.2 Supply of water to the public

2.2.1 Supply of water to the public and groundwater

The supply of high quality and sufficient water to the public is essential for domestic uses, such as drinking, food preparation, washing, cleaning and hygiene. The supply of water to the public for use in households, as well as in commercial and touristic areas, usually takes the form of tapped water produced by water utilities. Connection of the public to centralised water supply systems exceeds 80% in all EU 27 Member States, except for Romania (Eurostat, 2021). The supply of water to the public for tourism and recreation activities can be quite diverse, comprising of water used in hotels and other accommodation facilities, restaurants, bars, cafes, swimming pools, saunas, and spas, as well as water used for the irrigation of green spaces. In broader sense, the supply of safe water to the public may also include the bottled water industry, as well as the wellness and spa industry, where this depends on thermal and mineral springs and spring pools. For example, nearly 1,400 thermal springs exist in Hungary, supporting an important branch of the national tourism sector (MfE&W, 2006). For all above cases, water supply is required to meet drinking or bathing water quality standards. There are also cases, where centralised water supply systems cover a part of the needs of the industry and agriculture. However, water quality requirements are lower for these cases of non-potable water.

Untreated raw groundwater may not necessarily have the quality required to be used as drinking water, for domestic purposes or for bathing. Thus, various methods are used to process the groundwater prior to its supply to the end-users. In low-lying coastal areas of Finland, groundwater in aquifers covered with clay and peat is generally low in oxygen or entirely anoxic, and it may contain high concentrations of solute iron and/or manganese. In other areas, groundwater may contain excessive concentrations of arsenic, fluoride, radon or other substances (EuroGeoSurveys, 2016). Apart from these cases of naturally elevated concentrations of pollutants, groundwater may also be polluted from various land-based human activities (e.g. agriculture, urban waste water). Furthermore, groundwater over-abstraction may trigger additional pollution issues (e.g. sea water intrusion into coastal aquifers, inland saline intrusion from deeper brines from “ancient seas”, dissolved evaporites and connate waters) or it may enhance the concentrations of existing natural and human-induced pollutants (see sub-study 1, Psomas et al., 2021a).

Over-abstraction for supply of water to the public can be a side-effect of significant surface water pollution problems. In many areas of Europe, groundwater typically provides a cleaner and safer option for public water supply. If no other alternatives are available or more affordable in the area, then public water supply may be more oriented towards groundwaters (Buchanan et al., 2019). It should be noted that meeting the demand of the public for drinking water is first in priority in the water supply hierarchy. Therefore, there is not much leeway to impose cuts at times of water crisis (e.g. severe droughts).

2.2.2 Impairment of supply of water to the public by pollution

Where present, lower permeability soils and overlying geological strata can provide some protection to groundwater which reduces its vulnerability to pollution compared to surface waters. Additionally, slow travel times for recharge through the unsaturated zone of an aquifer can allow time for attenuation of the concentrations of some pollutants. This means that less treatment is needed for drinking water produced from groundwater, compared to surface water. However, changes in groundwater quality can result in expensive treatment operations or may lead to the temporary or permanent closure of wells, which are expensive to replace.

Agricultural pollution is a key pressure on groundwater (see previous section) which poses significant costs to drinking water utilities. Costs arise from denitrifying water or removing pesticides, or blending with cleaner water. New infrastructure may be needed to secure cleaner supplies in impacted areas. It was estimated that the cost of nitrate and pesticide pollution in France represent between 640 to 1,140 million EUR per year for customers of drinking water utilities (Laperche, 2013). On average, 440 drinking water abstraction points were closed every year in France between 1998 and 2008, mostly due to contamination from nitrates, pesticides and pathogens (Laperche, 2013).

Urban pollution, pathogens emitted through septic systems and animal wastes, as well as physical disturbances to groundwater flows, can disrupt drinking water supplies and spa activities. Addressing the above challenges may require additional treatment, so that polluted raw water achieves the required quality standards. Alternatively, the water supply for the above uses may need to be relocated away from the pollution pressure (Box 2.).

Box 2.4 Pressures on the production mineral and thermal waters in Slovenia

Mineral and thermal waters in Slovenia are used in the bottled water industry, spa facilities and providers of geothermal heat. In 2014, thermal water was produced at 32 sites, providing also geothermal heat for bathing, balneology, greenhouses, district heating systems, and air cooling. However, increased exploitation of GWBs together with and land reclamation projects along rivers have increased aquifer depletion and lowered groundwater levels. This has resulted in the drying of several springs and in the inflow of less mineralised and colder water.

Source: EuroGeoSurveys (2016)

The vulnerability of drinking water supplies depends on the type of geological formation of the exploited aquifer and well characteristics. Wells designed to abstract large volumes of groundwater for supplying drinking water for large networks usually mix water from a wider and deeper aquifer area. Thus, concentrations stay relatively stable over months or years. In contrast, wells for small networks or individual households may see pollution concentrations vary significantly on short period of times because they tend to abstract from smaller and shallower areas of the aquifer.

Furthermore, most threats to drinking water supplies are in shallower, unconfined aquifers which are directly exposed to land-based pollution. According to the 2nd RBMP, less than good groundwater status is more likely for GWBs closer to the ground surface or for GWBs with links to the shallower ones (see sub-study 1, Psomas et al., 2021a), compared to much deeper horizons. Deeper, confined aquifers may also be affected when changes in aquifer pressure gradients (e.g. due to over abstraction) lead to a downward gradient and flows of contaminants across semi-permeable layers (Box 2.5).

Box 2.5 The strategic importance of deep aquifers in southwestern France

The Aquitaine region in France includes a series of deep aquifers layered across a complex geological sequence associated with the uplift of the Pyrenees mountains. The most exploited of these deep aquifers is the Sub-Molassic Sands (SMS) aquifer, which comprises several sandy and sandstone formations covered by a protective impermeable sedimentary layer, producing groundwater of excellent quality. The deep aquifers are a strategic source of water for many communities with 70,000 inhabitants now entirely dependent on the deep aquifers for their drinking water supply.

The SMS aquifer is in poor quantitative status. Piezometric levels of the SMS aquifer have been dropping by 60 cm on average every year over the last 20 years, with no sign of stabilization despite a ban by the state on new borehole drilling. Over-abstraction is responsible for 90% of this drop and the remaining 10% is due to natural drainage. Increased abstraction in the SMS aquifer has led to upward intrusion of deeper lower quality rock formation water and increased infiltration of polluted water from shallower layers. Contamination of the deep aquifer layers can affect drinking water supply and the spa industry. Drinking water wells have been abandoned in recent years, and spas have been forced to drill deeper wells as existing ones were affected by contamination.

Source: Neverre et al. (2020)

2.2.3 Pressure on groundwater from supply of water to the public

The EU 27 Member States have abstracted annually around 37-39 billion m^3 of water for supply to the public between 2010-2017. EU Member states, such as Italy, France, Germany, Poland and Hungary, rely heavily on groundwater for supply to the public (>65%), while they also abstract the highest volumes in the EU 27 for this use. Furthermore, water abstraction for supply to the public is one of the most significant pressures for GWBs in the EU 27, since it causes less than good groundwater status in approximately 7% of the total GWB area. However, it affects proportionately larger parts of the national GWB area in Hungary, Luxembourg, Spain and Malta, France, and Belgium (>10%). In other countries, such as Bulgaria, Croatia, Czechia, Denmark, Estonia, Germany, Greece, Italy and Slovakia, this pressure is more localised (see sub-study 1, Psomas et al., 2021a). In terms of aquifer types, water abstraction for public water supply affects 10% of the area with porous aquifers and 8% of the area with fissured and karstic aquifers (see sub-study 1, Psomas et al., 2021a). About 4% and 5% of the total GWB area in the EU 27 EU 27, linked with GWAAEs and GWDTEs respectively, has less than good groundwater status due to abstraction for supply of water to the public. This pressure affects most commonly porous and fissured aquifers linked with GWAAEs/GWDTEs (see sub-study 2, Psomas et al., 2021b).

Drinking water abstraction can lower groundwater levels, subsequently impacting groundwater-fed springs and groundwater–surface water interaction exchanges. The most important contribution of GWBs to SWBs is during the dry season of the year or during prolonged periods of drought, when surface run-off and rainfall are low.

In coastal and islandic areas of the Mediterranean the influx of tourists has increased rapidly over the past decades. As a follow-up, seasonal water demand associated with tourism also increased, especially during the warm and dry summer months. This has caused negative impacts on southern

European GWBs (Box 2.6). However, reductions in the volume of freshwater in the coastal aquifers can reverse the flow and allow seawater to intrude deeper into the GWB, causing salinisation of the groundwater. Furthermore, groundwater discharges into transitional and coastal zones, for instance in the form of (karstic) springs and seepage, can create zones of mixed brackish water (e.g. areas of marine upwelling, lagoons).

Box 2.6 Impacts of tourism on groundwater resources on Mediterranean islands

In the majority of EU Member States, the number of tourists has grown significantly – by 40% from 2008 to 2016 for the EU28. However, tourists typically need more water per person compared to local residents, leading to higher water use for washing, laundries, spas, and swimming pools. In Cyprus, for instance, it was estimated that the average tourist staying in a hotel consumes 30% more water than the local resident. Indirectly, tourism also increases water demand for green spaces (e.g. golf courses, hotel gardens), cooling water to produce energy for drinking water production, waste water treatment, food production and electricity production (hot water, air conditioning, etc).

Because tourism demand typically occurs in summer months and in specific areas (e.g. coastal areas), it can create significant challenges on local water supplies of water scarce regions, such as the Mediterranean. The challenge is even greater on islands where surface water resources are limited and groundwater resources are heavily exploited. For example, in Greek islands, attracting high levels of tourism, summer water demand can be 5 to 10 times higher compared to winter. As a result, tourism can intensify groundwater over-exploitation, water scarcity and water shortages, especially on small semi-arid islands. With sea level rise, climate change may further exacerbate the risks of seawater intrusion, leading to further contraction of the fresh groundwater lenses, salinisation and decrease of the suitable freshwater for drinking.

Sources: De Stefano (2004); Gössling et al. (2012); Mangion (2013)

In Europe, 2% of the GWB area suffers from saline intrusion, mainly in the coastal aquifers of the Mediterranean, although it also occurs in northern Europe along the North Sea and Baltic coasts (e.g. Denmark, the Netherlands, northern Poland, Estonia and Latvia; see **Error! Reference source not found.**7) and Western Europe along the Atlantic coast (e.g. deep aquifers under Bordeaux) (see sub-study 1, Psomas et al., 2021a). Saline intrusion into GWBs can also be the result of upward movement of highly mineralised waters from deeper geological layers into the overexploited shallower aquifers, mixing of clean groundwater with layers of brines from "ancient seas" or dissolution of evaporitic formations in sedimentary basins.

Box 2.7 Sea water intrusion in Estonia

The Cambrian–Vendian aquifer system covers almost all of Estonia, and is heavily used for drinking water purposes, especially from the confined layers in Northern Estonia. However, historical exploitation has resulted in the formation of regional depressions in groundwater levels. Near the capital Tallinn, groundwater abstraction reached more than 40,000 m^3 per day in 1991, when levels were lowered to 30 m below sea-level. Since then, groundwater levels have been recovering thanks to water savings and reductions in abstraction, which are associated with the introduction of water metering and market pricing of water.

Source: EuroGeoSurveys, 2016

Impacts on GWAAEs and GWDTEs

The storage potential of groundwater in aquifers, and the relatively slow time for its discharge, mean that the baseflow contribution of groundwater continues even when the SWB is not directly fed by recent rainfall. Therefore, GWB discharges to linked SWBs play a significant role in supporting minimum ecological flows ("e-flows"). For instance, the Viinivaara esker in Finland discharges into a Natura 2000 peatland (fen) and several headwater streams. However, the city of Oulu planned to increase the drinking water abstraction from this GWB. Local concerns about impacts on streams, lakes, springs, local wells and groundwater-dependent peatlands led to an environmental impact assessment to identify such risks and recommend compensation measures (Klöve et al., 2011).

Over-abstraction from coastal aquifers for the supply of drinking water can cause saline intrusion into the groundwater, and may lead to damages to GWAAEs and GWDTEs. For example, such problems have been reported in coastal wetlands in the Apulia region, in southern Italy. The local wetlands are fed from local karstic aquifers, which have been impacted significantly by drinking water abstraction during drought events in the past decades (Polemio et al., 2009; Fidelibus et al., 2011).

2.2.4 Responses and solutions

Until recently, the focus of action to maintain drinking water supplies has been on end-of-pipe measures, such as treatment of abstracted water, or abandonment of wells for deeper wells or alternative better quality resources. Increasingly, strategies also aim to take preventative measures at source by changing land management activities which pose a risk to groundwater quality.

Under the WFD, countries can designate safeguard zones and drinking water protected areas to regulate land use activities in areas where there is high risk for infiltration of pollutants and groundwater contamination; in particular, in areas closest to abstraction wells, where risk of pollution is greatest. These zones typically focus on the control of point source pollution such as landfill or sewage discharges to ground, and working with the farming community to control the intensity and appropriate use of manure, mineral fertilisers and pesticides. Much work focuses currently on promoting more sustainable farming practices, including the uptake of organic farming (EEA, 2020f). Land use planning is thus a key instrument to manage groundwater quality for drinking water purposes.

In some cases, a larger area may be designated to account for the hydrogeological nature of the aquifer (e.g. a large, fractured aquifer which allows for pollutant contamination over long distances) or the diffuse nature of the polluting activities (e.g. nitrate emissions from agriculture). In Belgium, for instance, a surveillance zone was established over 14,000 ha to protect the 300 springs of the town of Spa, a thermal town of important historical and economic significance in the spa industry (EuroGeoSurveys, 2016). Authorisations are required for drilling and some underground structures in order to preserve the upper protective geological layers.

Because the provision of sufficient and safe drinking water is a human right (UN, 2010), managing the impacts of potable abstraction on groundwater depletion is complex and requires appropriate consideration of alternatives to the closure of drinking water wells. Therefore, much emphasis is currently placed on increasing efficient water use, through water efficient technologies or pricing policies, or the development of alternative supplies to reduce over abstraction from specific drinking water wells (e.g. desalination or water re-use).

2.3 Urban and industrial development, and emerging pollutants

2.3.1 Urban and industrial development and groundwater

Aquifers situated beneath urban and industrial areas can represent a strategic resource for local supply of potable water. However, point and diffuse source emissions of contaminants from urban areas can significantly impact the quality of groundwater and, hence, its suitability for human consumption. The list of chemicals that pose a risk to groundwater quality in urban areas typically includes nutrients, heavy metals (e.g. arsenic, nickel and lead), hydrocarbons, chlorinated solvents and pathogens, amongst other organic and inorganic substances (EEA, 2018b). So-called emerging pollutants, which are either new pollutants or more recently understood as harmful to human or aquatic health, including the PFAS (i.e. Per- and polyfluoroalkyl substances) group of chemicals, pharmaceuticals and microplastics. Although these may not be routinely monitored, they pose environmental and health risks. Developing a risk strategy for emerging pollutants is of critical importance for safeguarding Europe's groundwater resources. PFAS, pharmaceuticals and pesticide non-relevant metabolites are already being considered for addition to the GWD annexes, as substances which put groundwater at risk of not achieving the WFD objectives.

2.3.2 Urban development pressures on groundwater

Pollutants from urban areas may find their way into GWBs through atmospheric deposition of substances (e.g. combustion products), infiltration of urban runoff, discharges and leakages of waste water from sewers and septic systems, reuse of poorly treated sewage sludge, and percolation of accidental spills through soils. Such pressures affect a variable portion of the total GWB area in EU 27, ranging between 0.6%-5% (see analysis below). In terms of types of aquifers, which are most commonly affected by urban development pressures, no particular patterns were observed in this series of studies (see sub-study 1, Psomas et al., 2021a).

According to the 2nd RBMPs 5% of the GWB area in the EU 27 was in less than good groundwater status affected by diffuse source pollution from scattered dwellings non-connected to sewerage networks. Non-connected dwellings can be a source of diffuse source pollution, where individual or other appropriate systems are not maintained or operated in a suitable manner and the pollution load from all discharges adds up in the catchment (Brebot et al., 2019). Another 2.5% of the GWB area was in less than good groundwater status affected by point source pollution from urban waste water.

Managing these pressures related to waste water requires, for instance, further expansion and upgrade of urban waste water collection and treatment facilities. This could include centralised (community-level) systems for small agglomerations, as well as well-maintained and monitored individual or other appropriate systems for households in scattered dwellings. In addition, improvements in treatment technology will be needed to address the new and emerging substances identified in waste water.

In addition, urban areas are characterised with hard impermeable surfaces, which seal the soil and lead to decreased groundwater infiltration and increased urban runoff and floods. Short and intense urban floods may not be easily accommodated by combined sewage systems, where these have been designed to address more moderate flood events. This causes overflow of storm waters and discharge of poorly treated sewage to the environment. Pollution from urban runoff and storm water overflows were also affecting 1.6% and 0.6% of the total GWB area.

Current approaches favour the use of sustainable urban drainage systems (SuDS) and nature-based solutions which increase the temporary storage of urban runoff and allow its infiltration into soils and to groundwater. The contamination risk posed to GWBs is dependent on the type of pollutants (e.g. toxicity, mobility, biodegradation potential), purifying capacity of the protective soil layer and the appropriate management of the SuDS. It is essential to minimise the use of those substances that pose the highest risk of reaching GWBs.

The implementation of, primarily, the Urban Waste Water Treatment Directive (UWWTD) and, supplementarily, the WFD has resulted in great improvements in the collection and treatment of urban waste water in Europe. However, not all aspects of waste water pollution are covered directly by the UWWTD (e.g. discharges from small agglomerations or scattered dwellings with loads below 2000 p.e.). In addition, some of the above aspects have not been addressed adequately yet, as they have come to the spotlight in more recent years (e.g. storm water overflows and urban runoff) (EC, 2019b).

Furthermore, caution is required with the use of sewage sludge as a fertiliser in agriculture, as it may contaminate soils and groundwater with contaminants that are not (sufficiently) yet regulated, as part of the EU's Sewage Sludge Directive and other national regulations (Inglezakis et al., 2014; Hudcová et al., 2019; Bauer et al., 2020). Emerging risks from PFAS, pharmaceuticals and microplastics also need to be further addressed (see section 2.3.4).

In addition, urban areas are responsible for the production of large amounts of domestic and industrial waste. Historically uncontrolled disposal in landfills or relevant landfill accidents, as well as cases of disposal in abandoned mining and quarrying sites, can lead to legacy groundwater pollution in current days. In 2.4% of the total GWB area, waste disposal sites were identified as a significant pressure causing less than good groundwater status.

EU level regulation (e.g. the Landfill Directive 1999/31/EC) and national regulations mean that solid waste disposal is better managed with adequate consideration of groundwater flow and protection, and waste containment strategies and technologies.

Regarding atmospheric deposition of nitrogen oxides, sulphur and heavy metals from combustion (e.g. car engines, thermal power plants), this is not identified as a significant pressure for GWBs in the EU 27. The pressure is reported to affect only 0.6% of the total GWB area. It is considered a considerable problem for SWBs, though.

With population growth and the vast expansion of urban areas in the 20th century, urban development pressures have grown in significance. In the densely population region of Wallonia, in Belgium, GWBs were found to be contaminated by a diverse mix of organic compounds, such as naphthalene, toluene, phenanthrene, petroleum hydrocarbons, fluoranthene, chrysene, dichloromethane, pyrene, and fluorine (Gesels et al., 2021). Pollution in urban areas affects primarily shallow aquifers, although they can contaminate deeper and more protected ones. For instance, high levels of solvents and chromium have been detected in the shallow and deeper aquifers below the Milan Metropolitan area (Pollicino et al., 2021).

2.3.3 Industrial development pressures on groundwater

Areas with significant industrial pressures causing less than good groundwater status are mainly found in specific EU Member States, including Belgium, Bulgaria, Czechia, northern Estonia, northern France, northern Germany, Hungary, many parts of Italy, and southern Spain. In terms of types of aquifers, which are most commonly affected by industrial pressures, no particular patterns were observed in this series of studies (see sub-study 1, Psomas et al., 2021a). Moreover, about 3% of the total GWB area in the EU 27 is linked with GWAAEs or GWDTEs, and its groundwater status is less than good, due to pressures related to industrial development (e.g. point source pollution by contaminated sites or abandoned industrial sites, point source pollution by plants regulated under the Industrial Emissions Directive, industrial abstractions). These pressures affect most commonly porous aquifers linked with GWAAEs/GWDTEs (see sub-study 2, Psomas et al., 2021b).

According to the 2nd RBMPs, point source and diffuse source pollution from abandoned industrial or contaminated sites cause less than good groundwater status in nearly 4% and 0.6% of the total GWB area in EU 27, respectively (see sub-study 1, Psomas et al., 2021a). It should be noted that past industrial activity, as well as the historic use of chemicals which are now banned, can be a significant source of legacy pollution in many parts of Europe nowadays. Uncontrolled backfilling in contaminated industrial sites– a practice that was common in the past- is also a major source of groundwater and soil pollution (Boudjana et al., 2019). As a result, water authorities are required to deal with a driver which is no longer present, but whose impacts on the environment are still observed (Buchanan et al., 2019).

The emissions of pollutants to the atmosphere, water and soils from large, active industrial sites are regulated under the Industrial Emissions Directive (IED) in Europe. Almost 4% of the total GWB area is affected significantly by point source pollution from plants regulated under the IED. In addition, non-regulated industrial plants cause less than good status in 1.2% of the total GWB area (see sub-study 1, Psomas et al., 2021a).

Point source pollution from industrial waste water can be tackled by phasing out of the substances causing the contamination by biodegradable alternatives or through additional treatment. This requires the use of Best Available Techniques (BAT) and strict permitting regimes for industrial emissions under the Directive on industrial emissions (2010/75/EU). Although reclaiming contaminated industrial sites can be costly, several member states have adopted legislation to encourage and, in some cases, require reclamation of brownfield sites.

In addition, water abstraction for industrial purposes causes less than good groundwater status in about 4% of the total GWB area. This pressure affects a large share of the national GWB area in Hungary, Spain, Belgium (see sub-study 1, Psomas et al., 2021a). It may also create more localised water imbalances and other physical alterations. For instance, the Venice Lagoon, in Italy, suffered from accelerated land subsidence, due to the establishment of the Marghera industrial settlement in the early 20th century, and the significant groundwater abstraction that followed. A small elastic rebound has been observed since the 1970s, following regulation and diversification of water supply. This trend continues to nowadays (Da Lio et al., 2013; Gatto and Carbognin, 1981).

2.3.4 Emerging pollutants

Emerging pollutants encompass a wide range of compounds, which are not yet regulated, but may be of current or future concern (Geissen et al., 2015; Lapworth et al., 2019). They include as diverse products as pharmaceuticals (e.g. antibiotics, hormones, anti-inflammatory), ultra-violet filter, insect repellents, industrial compounds (e.g. flame retardants, PFAS), plastics, and “lifestyle” products (e.g. caffeine, sweeteners).

Emerging pollutants have high importance for groundwater management, but significant knowledge gaps exist regarding their concentration and behaviour in groundwater. Additional monitoring and development of conceptual models are necessary to better understand sources, pathways and impacts (EC, 2019). Stricter regulation and application of the precautionary principle may also be warranted, through authorisation procedures and marketing of new chemicals (pharmaceuticals, pesticides).

2.4 Mining activities

2.4.1 Mining and groundwater

Safe operation of surface and sub-surface mining sites requires long-term dewatering operations through pumping that depresses the normal groundwater table. The purpose of dewatering is to keep the mine infrastructure and galleys dry and more stable, as well as to facilitate extraction. This may result in significant changes in the local groundwater flow regime, causing decreased flows in rivers, lakes and linked wetlands.

When the mining activities cease, the phasing out of pumping leads to the rebound of the groundwater table. This process can cause the ingress of impaired groundwaters in the mining site. For example, there can be an influx of polluted or saline groundwaters. Furthermore, as groundwater flushes back through the fractured mined rocks, which were once dewatered, acidification processes can take place. The mineral hosting rocks usually contain highly oxidisable metal sulphides (e.g. pyrite), which have oxidised when the water table was lowered during dewatering. The cessation of pumping and rebound of groundwater flushes out the soluble metal oxides leading to poor quality groundwater with low pH and a high concentration of dissolved metals. The groundwater is known as acid mine or rock drainage and may collect in the disused mine galleys and tunnels and discharge to the surface from “adits” (i.e. openings of the mining site). Mine water rebound is a potential source of pollution for receiving rivers and adjacent groundwaters. Some examples of the impacts of acid mine drainage include the blanketing of river and stream beds in “metal ochres”, which effectively destroy invertebrate life, pollution from low pH discharges with high dissolved metal concentrations and the abandonment of drinking water abstractions.

In general, processing waste takes many forms such as waste water, slurries of ground particles, industrial additives and chemical reagents (e.g. cyanides, acids, alkalis) (Younger and Wolkersdorfer, 2004). Surface and groundwater pollution can be caused also from acid mine drainage originating from rain falling upon unmanaged (e.g. uncapped) heaps of mine waste, or from leachates from detention ponds with mine residual slurries (Tayebi-Khorami et al., 2019; Briere and Turrell, 2012).

The operations of most modern mines are now strongly regulated, both during and after completion of the mining activities. However, until the second half of the 20th century, most mines would be abandoned without appropriate reclamation. Thus, reported pressures from mining sites may originate from either current activities or past activities still impacting on groundwaters. However, intervention in abandoned mines is more difficult due to lack of liability.

According to the 2nd RBMPs, the pressures from mining activities are less widespread at the level of the EU 27. Notably, they can be more important for specific EU Member States and regions. Almost 3% of the total GWB area in the EU 27 is affected by diffuse source pollution from mining, 1.5% by point source pollution from mine waters, and another 1.3% by alteration of water levels/volumes, which is usually related to drainage of mining sites (see sub-study 1, Psomas et al., 2021a). In addition, about 1.5% and 2.5% of the total GWB area in the EU 27, linked with GWAAEs and GWDTEs respectively, has less than good groundwater status due to diffuse source pollution from mining. Alterations of groundwater levels/volumes (usually related to drainage of mining sites) affect approximately 1% of the GWB area, either linked with GWAAEs or GWADTEs. These pressures from mining activities affect most commonly porous aquifers (see sub-study 2, Psomas et al., 2021b).

The most impacted country by diffuse source mining pollution is Bulgaria, with almost 50% of its GWB area being significantly affected. Other significantly affected areas are found in northern Estonia, northern Germany, western Macedonia in Greece, western Hungary, central and southern Poland, western Slovakia and parts of Spain, such as Catalonia and Andalusia (e.g. Rio Tinto). Furthermore, areas affected significantly by water level /volume alteration, which is usually linked with mining, are found in northern France and northern Germany, central Greece, eastern Hungary, central and southern Poland, and Catalonia in Spain. Mining activities commonly affect all types of aquifers, with the exception of insignificant aquifers. (see sub-study 1, Psomas et al., 2021a).

2.4.2 Pressures from current mining operations

Today, 32,000 extraction sites exist in Europe, covering a large range of minerals (Table). The most common mining operations are based on surface excavation in quarries and open pits. Underground mining sites are also significant in number. In contrast to underground mining where the overlying rock is left in place, surface mining involves the removal of soil and the rock overlying the desired mineral deposit.

Most current mining sites in Europe focus on the extraction of aggregates such as sand and gravel with Poland and Germany having the highest number of sites (Table). Many sand and gravel deposits are also high yielding porous aquifers, widely used for the supply of drinking water. Therefore, extraction of aggregates can represent a direct threat to drinking water supplies (Box 2.8).

Other current mining operations include mining for hydrocarbons, metals and coal, and shale oil and gas exploitation. Although extensively mined in the past, few metal ores and coal mines still operate in the European Union. The main extracted metals are copper, chromium, lead, silver and zinc. Finally, the extraction of shale oil and gas cause major environmental risks to groundwater due to the risk of contamination from chemicals used in the hydraulic fracking process. In addition, fracking requires the extraction of large quantities of water, which can put additional stress on local aquifers.

Table 2.1 Existing extraction sites in EU-28 (modified from: Kampa et al., 2019; EEA, 2021a)

	Aggregates	Industrial and other construction	Peat	Hydrocarbons	Coal and lignite	Ag, Au, Pt, ores	Cu, Ni, Pb, Sn, Zn ores	Bauxite, alumina, magnesite, ilmenite	Fe, Co, Cr, Mn, Mo, V, W ores	Oil Shale	Other metalliferous ores	Uranium ores
Number of sites	25740	4157	1340	557	250	108	59	47	23	16	7	3
Countries with most sites	PL, DE, FI, FR, ES	UK, FR, ES	FI	PL, CZ	PL, UK, CZ	FR	BG, SE, UK	EL	HR, PT	EE	PT	CZ, RO

Box 2.8 Eskers under quarrying pressure in Sweden

Groundwater represents the main source of drinking water for around 60% of the Swedish population (~6 million). The main porous aquifers are situated in sand and gravel deposits, mainly glacially formed esker deposits, which cover 4% of Sweden's land surface. These provide large storage volumes thanks to their sandy gravelly matrix and thickness. Many towns and villages in Sweden are situated near eskers as they provided excellent quality water. The main pressure on eskers is from quarrying of sand and gravel for buildings and infrastructure, which removes the protective layer, shortening infiltration pathways, increasing pollution risks and modifying groundwater recharge.

Source: EuroGeoSurveys (2016)

Impacts on GWAAEs and GWDTEs

Peat is now mainly extracted in Finland, and to a lesser extent in Ireland, but has almost disappeared in the rest of Europe. Its extraction can modify groundwater flows and impact dependent peatlands and wetlands, which can last a long time after extractive activities are ceased. In Ireland, two GWBs are classified in poor quantitative status, including a GWB linked to the GWDTE of Clara bog . The GWB is in poor quantitative status, due to hydrological alterations resulting from drainage operations for safe peat cuttings. Drainage affects the hydrology of the bog, resulting in compaction, land subsidence and loss of soil carbon (Crushell et al., 2008).

2.4.3 Pressures from abandoned mines

Mining in Europe has a long history dating back to the Chalcolithic and Bronze Age and has played a significant role in the modern industrialisation of the European society. It has been estimated that more than half of the mining sites within the EU that operated in the last century are now closed, in particular coal and metal mines (BRGM, 2001). More than 8,000 flooded mines have been reported in 24 EU countries, although the number of abandoned mines is likely to be much higher (Stasi et al., 2018).

Because mining is nowadays heavily regulated, most mine water discharges represent legacy issues from the past. There are multiple examples of groundwater pollution from mining waste. In the upper Rhine valley for instance, the extraction of potash has led to extensive contamination of 60 km of alluvial aquifer due to infiltration of salt waste from the surface as brine, combined with rapid lateral movement in the aquifer (Kloppmann et al., 2011). In Portugal, uranium mines, which operated in the 20th century and have since closed, produced around 3 million tonnes of solid waste dumped in several sites across the country (Neiva et al., 2015). In addition, contamination from antimony mining is a major issue in the Slovak Republic (Box 2.9).

Box 2.9 Historical mining and lack of remediation in Slovakia

Antimony (Sb) is commonly used as an alloy with lead and tin. It can be found in a wide variety of products, from batteries to fire retardants and electronics. Historically, it was also used in medicine and cosmetics. Antimony has been mined extensively in the Slovak mountains where large deposits are found, but all facilities were closed in the 1990s without remediation. Their long-term exploitation produced large amounts of waste rock which contribute to the contamination of the adjacent environment by antimony, arsenic, lead and zinc. The closed Dubrava deposit is considered to be one of the most serious sources of antimony contamination in the world through outflows from the old mine adits.

Source: Ondrejková et al. (2013)

Impacts on GWAAEs and GWDTEs

Discharges of contaminated mine waters into neighbouring surface waters can lead to precipitation of metal ochres, which blanket the entire river and lake beds. Metal ochres include dissolved oxidised metals, which are toxic and harm aquatic flora and fauna. Apart from the damage to river and lake ecosystems, metal ochres may disrupt other water-dependent activities, such as irrigation, livestock watering, inland aquaculture, fishing, water sports and industrial or drinking water supply (Box 2.10).

Box 2.10 Heavy metal pollution through shallow groundwater flows in Silvermines mine in Ireland

The Silvermines mine site near Tipperary in Ireland, now abandoned, had been exploited since 1298 with the last operation of a Barytes mine closing in 1993. The water environment was heavily polluted with heavy metals, in particular cadmium, lead and zinc. In particular, contamination has occurred where groundwater polluted from the mine sites forms shallow water tables and seepage zones along the base of hillsides, stream sources and along the river valley. Bio-availability of metals was found to be higher in the areas of groundwater seepage and in soils of low pH. Hence, floodplains are considered as hazardous areas for cattle grazing, tillage or gardening. Alternative uses have been recommended, such as sheep farming, since grazing results in less soil being ingested. Other recommendations include additional drainage and soil pH correction by adding lime, in order to reduce biologically available metals.

Source: Aslibekian and Moles (2002)

2.4.4 Responses and solutions

Management solutions differ between current mining operations, which are now strongly regulated and should avoid environmental damage, and historical mining, where past operations have lead or are currently resulting in severe environmental problems.

Current mining operations, and the mineral industry at large, are the target of multiple EU policies which aim, amongst other objectives, to prevent groundwater pollution (see Annex 1 and EEA, 2021a). For instance, the Directive on the Management of Waste from Extractive Industries 2006/21/EC requires the implementation of Best Available Techniques for the management of waste (EU, 2018), which is the key issue to reduce pollution risks posed by mining on groundwater. Impacts of mining on groundwater levels remain a significant challenge with few available solutions.

Regarding historical pollution, solutions are also complex to implement. In heavily polluted aquifers, a common technology has been to pump groundwater and treat it at the surface before reinjection. However, this costly procedure has rarely restored the GWB to good status (Naidu et al., 2019). Other approaches have focused on drainage outlets, involving collection and treatment systems, together with passive technologies such as limestone channels to neutralise acids and reed beds and wetlands or bioreactors to immobilise heavy metals (Mayes, 2011). Different waste disposal facilities exist, such as ponds/lagoons, heaps, lake and riverine disposal. These systems must be monitored, and accumulated metal must be removed regularly. Infiltration areas of mines and waste dumps can be covered to prevent influx of oxygen and reduce rate of water infiltration and subsequent discharge.

In-situ approaches have also been developed, involving permeable reactive barriers placed in the subsurface and filled with reactive material to intercept pollution plumes and transform the contaminants into less harmful (non-toxic) or immobile species. Active materials include zero valent iron, activated carbon, calcium carbonate, and microbes (Naidu et al., 2019). Using such membrane barriers together with a pump and treat technology can increase water reuse and recovery of resources such as sulphuric acid, metals and rare earth elements (Baena-Moreno et al., 2020).

Rehabilitation requires important resources, expertise and adequate financing schemes, which can be challenging in the case of abandoned mines, where liability is difficult to ascertain. Hence, in some countries, legislation has been created to fund the rehabilitation of abandoned mines. For instance, the UK has created a specific authority to deal with the legacy of coal mining (Box 2.11). Fees can be applied on existing operations to fund rehabilitation of abandoned sites. A successful rehabilitation example of an abandoned mining site is the regeneration programme of the Lusatian lignite opencast mine in north-eastern Germany. Pollutants were removed from local soil and water using engineering and mechanical approaches. Furthermore, the area was planted and flooded, creating 26 artificial lakes within a lake district, which is surrounded with forests, crops and green spaces (MELE, 2019).

Box 2.11 Managing the legacy of coal mining in the UK

In the UK, mine operators are responsible for pollution from ongoing mining operations only since 1999. Liability for abandoned coal mines is entrusted in the Coal Authority. In 2017, it operated about 80 mine water treatment plants protecting 350 km of rivers and several important regional aquifers. Treatment is based on a combination of aeration, settlement ponds and reed beds. Constructed wetlands, associated with the treatment process as a nature-based solution, can deliver additional biodiversity and amenity benefits.

Source: UK Coal Authority (2017)

2.5 Climate change and groundwater

2.5.1 Projected changes in future climate conditions

According to current observations and past trends from recent decades, temperature and evapotranspiration in the EU 27 have increased across most of its territory. In fact, the recent decade was the warmest of the latest century. Furthermore, annual and summer precipitation have decreased in southern Europe, as well as in parts of central and eastern Europe. Droughts have become more frequent and intense over the same areas roughly. Moreover, mountainous areas, such as the Alps, have experienced reduced snow cover and earlier snow melting. Annual and summer precipitation have increased only in parts of northern Europe, and droughts have become less frequent and intense in Scandinavia and north-eastern Europe (EEA, 2021b - forthcoming).

Climate change is intensifying the temperature and evapotranspiration patterns. Seasonal temperatures are projected to increase further in most areas of the EU 27, and particularly in Iberia and other parts of southern Europe. Evapotranspiration is also expected to increase further, with significant increases expected during the wettest season of the year. Annual and summer precipitation are projected to decrease in southern Europe, while reduced summer precipitation is additionally expected in western Europe, the Balkans and the Black Sea. Droughts are projected to affect southern Europe longer, more frequently and more intensely. Snow mass and snow cover are expected to decrease further. However, in northern and north-eastern Europe, climate change is projected to cause an increase of annual and summer precipitation, with many parts of these areas also projected to have less frequent and intense droughts. Moreover, climate change affects the seasonal patterns of extreme events. In general, more droughts are expected during the already warm and dry period of the year, whereas more floods are expected during the cooler and wetter period (EEA, 2021b – forthcoming; Bisselink et al., 2020).

It is important to note that there are significant uncertainties when downscaling global or regional climate projections and modelling their impacts. Therefore, scientists usually run different scenarios with a group of models(“ensemble”) to get a better insight of average situation and associated uncertainties. Therefore, the above conclusions should be read with this note in mind. If global temperature rises by 3^{o}C in the future decades, compared to the pre-industrial levels, then the impacts of this warming are projected to be more intense and extended. If the temperature rise is limited up to 1.5^{o}C, then the impacts will still be significant, but less intense or extended (Bisselink et al 2020).

2.5.2 Impacts of climate change on groundwater recharge and pollution

In the past decades, the average annual soil moisture has shown decreasing trends in many parts of Europe, with the exception of areas mainly in the Balkans and eastern Europe (EEA, 2021b – forthcoming; EEA, 2017). Furthermore, a modelling study by the Joint Research Centre (JRC), using the LISFLOOD-EPIC model for the 1990–2018 period, has shown that groundwater depletion can be found in coastal Bulgaria, Cyprus, southern Germany, central and southern Greece, southern Iberia, south-eastern Ireland, Sicily, Switzerland. Climate change has been found to contribute to the modelled groundwater depletion, but the major pressure is asserted by over-abstraction (which may be an indirect result of warmer and drier conditions due to climate change, though). The role of climate change in groundwater depletion was found to be more dominant around the Rhône river basin (Gelati et al., 2020). It should be noted that the above results are based on modelling and collected data from various countries, but the work is not exhaustive. Thus, additional cases of groundwater depletion can be expected the in EU 27.

Climate change is projected to decrease the soil moisture in parts of southern Europe (most prominently in Iberia), especially during the warmer and drier period of the year. As agriculture is a key driver for water abstraction in southern Europe (see section 2.1), the decrease in the rainfed part of crop cultivations is expected to increase the demand for irrigation using surface and groundwaters, which depends on the local management practices. However, groundwater recharge is projected to decrease significantly in southern and western Europe. Areas in France, Italy and Spain are expected to be affected significantly (Box 2.12). Thus, those GWBs impacted by lower recharge and increased abstraction will be faced with additional water stress than today (EEA, 2021b – forthcoming; Bisselink et al 2020).

Box 2.12 Climate change impacts on groundwater recharge

Spain (Pulido-Velazquez et al., 2015, 2018; Touhami et al., 2015; Hiscock et al., 2011; Aguilera and Murillo; 2009)
Spain is expected to be heavily impacted by climate change, with an average reduction of 12% in groundwater recharge by 2050 over mainland Spain.
Some areas may be more affected than others:

- In Andalucia, groundwater recharge may diminish;
- In Alicante, some aquifers were predicted to have a reduction in mean annual groundwater recharge by 3%-17% over the course of the 21st century, and up to 58% depending on rainfall characteristics.

These aquifers have already experienced significant reductions in groundwater recharge in the 20th century. This occurs in a region which is highly dependent on groundwater due to the lack of large permanent rivers. Some aquifers have already been nearly exhausted due to over-exploitation from agriculture and tourism, resulting in their closure or in substantial decreases in abstractions. Alternative sources are now used to replace the loss of groundwater availability, including transfers from other freshwater sources, desalination and reuse of treated waste water.

France (BRGM, 2021)
The French Explore 2070 project estimated that groundwater recharge could vary between +10% to -30% between 2045 and 2065 compared to 1960-1990 in the optimistic scenarios, and -20% to -55% in the pessimistic scenarios. Other studies have estimated potential changes in groundwater recharge from -1.2 to +67.4% by 2080 compared to 1961-1990.

Bagnara springs and alluvial plains in Italy (Cambi and Dragoni, 2000)
A study examined the impact of climate change on the Bagnara springs and alluvial plains near Mount Pennino in Italy. They showed that any decrease in the annual recharge will lead to a larger decrease in the spring discharge and to a smaller decrease to the regional groundwater flows, which are feeding the alluvial plains. As drinking water supply is dependent on the springs, climate change may cause a shift to abstraction from local wells, which capture the regional groundwater flows.

Climate change may also affect groundwater quality, through the interdependencies between pollution and over-abstraction. For example, concentrations of nutrients and chemicals may increase in groundwater, because of lower dilution capacity of pollutants in depleted aquifers. Lower groundwater levels may also lead to extreme low flows in surface waters, where pollutant concentrations (e.g. from waste water effluents) may also increase due to lower dilution in the available surface water. Furthermore, if groundwater table decreases significantly, leaving the associated SWB perched, then the SWB will start recharging the GWB. Polluted SWBs may also cause pollution to linked GWBs (Cantor et al., 2018). In water-stressed areas, groundwater pollution may also occur after over-abstraction (e.g. for drinking or agricultural purposes). Over-abstraction can lead to the ingress and mixture of polluted waters with clean groundwaters, including upwelling of ancient brines, dissolved evaporites and connate waters, as well as sea water intrusion into coastal aquifers.

As climate change is expected to cause the rise of the average sea level and increase storm surges, coastal areas across the EU 27 may be further impacted by sea water intrusion. Coastal aquifers, which are already over-exploited, may be particularly in danger (Clifton, 2010) (see sub-study 1, Psomas et al., 2021a).

In northern and north-eastern Europe, GWBs are not expected to face additional water stress compared to nowadays. In these areas, groundwater recharge is projected to increase in the future. However, in the colder climates of northern Europe, warmer winters may also lead to retreat of the permafrost and earlier start of snow melting. This might shift groundwater recharge with melted snow from spring currently, closer to winter in the future. Increased recharge in winter may also increase the seasonal groundwater levels and favour the leaching of pollutants to the groundwater through shorter pathways in the unsaturated zone (Box 2.3). Furthermore, reduced spring recharge, combined with more frequent droughts during summer months, may increase water deficits in summer and autumn (Clifton, 2010; Klöve et al., 2014). For shallow aquifers linked with surface water bodies, lower groundwater levels will intensify the low flows in summer and autumn, thus impacting GWAAEs and GWDTEs during these periods.

Moreover, higher temperatures and earlier retreat of the snow cover may allow the expansion of agricultural activities in northern latitudes, thus increasing irrigation demand. However, there is currently now evidence that the projected increase in the groundwater recharge will not be able to offset any additional abstraction pressures (EEA, 2021b – forthcoming; Bisselink et al 2020). However, increased precipitation and recharge in northern and north-eastern Europe may cause more frequent inundation due to rising groundwater tables. In urban areas, the rise of the groundwater tables can damage building basements and public infrastructures, such as sewer pipes. It may also increase the loading to waste water treatment works through infiltration of groundwater into the sewerage network (see sub-study 1, Psomas et al., 2021a).

Box 2.13 Climate changes impacts on groundwater quality or flooding

Impacts of higher groundwater levels in winter, Finland (Klöve et al., 2014)

It is expected that increased rainfall and higher temperatures will cause the water table to rise above normal levels even in wintertime. This may have a number of consequences on groundwater quality and flood risk. Shallower groundwater levels may reduce the residence time of contaminants in the unsaturated zone, resulting increased leakage into the aquifer and lower water quality. Higher water tables combined with more frequent rain and quicker snow melting may increase risk of flooding.

Impacts on infiltration of nitrates, Germany (Ortmeyer et al., 2021)

Simulations of different climate scenarios for the Lower Rhine Embayment indicate that nitrate concentrations will increase, due to changes in rainfall and infiltration patterns. Although a 20% reduction in agricultural nitrogen input can reduce nitrate concentrations, the nitrate concentration in groundwater could remain insufficient to comply with drinking water standards. The study concludes that input loads should be defined according to future recharge variations, governed by climate change, in order to meet pollution environmental goals.

Climate change may also influence groundwater more indirectly:

- Land use may change with the expansion of irrigated agriculture, thereby increasing water demand and possibly groundwater abstraction (Taylor et al., 2013). In southern Europe, drier conditions may increase water demand, further exacerbating abstraction pressure on groundwater. Water demand for groundwater may also increase as surface water availability reduces or its quality worsens (Clifton, 2010).
- Demand for groundwater may increase both in absolute terms and as a proportion, especially in drier regions, due to the frequency and intensity of droughts and the rise of population and

living standards, as well as due to the projected expansion of irrigated land (Taylor et al., 2013).

Impacts on GWAAEs and GWDTEs

It should be highlighted that GWAAEs and GWDTEs are rarely affected only by climate change. GWAAEs and GWDTEs are usually impacted by climate change in combination with other human pressures, such as land use changes, water abstraction, water pollution, atmospheric deposition, etc. These pressures may exacerbate and possibly override the impacts of climate change alone (Klöve et al., 2014).

According to the 2020 EEA report on the State of Nature, 5.4% of the habitats and 4.6% of the species are already affected by climate change. In particular, droughts and decreases in precipitation are identified as the most common climate-related pressure on species and habitats, representing nearly half of the reported climate-related cases. Other significant, but less common pressures include temperature changes, increases or changes to precipitation, sea-level and wave exposure (EEA, 2020d).

Rising temperatures and droughts affect significantly several types of species that dwell in GWAAEs (e.g. fishes, amphibians, molluscs, and waterbirds). In addition, they affect habitats which can be designated as GWDTEs (e.g. reedbeds and reedy ponds). Furthermore, decreases in precipitation affect significantly GWDTEs, such as bogs, mires and fens (EEA, 2020d). Between 2000 and 2016, water deficits due to severe droughts affected a considerable part of Iberia and south-western France. Areas in central Europe and the Balkans were also commonly affected. This caused a decline in the growth of natural vegetation (EEA, 2021b – forthcoming; EEA, 2020e).

Sea water intrusion, due to higher sea levels, storm surges and reduced recharge of coastal aquifers, can damage groundwater-fed transitional and coastal ecosystems, such as coastal karstic springs, spring-fed lagoons, and wet dune slacks. Coastal habitats in the Atlantic and the Boreal region have been found to be at higher risk of sea water intrusion due to climate change (EEA, 2020d). However, similar cases are also located in the Mediterranean (Box 2.14). Salinisation of transitional and coastal ecosystems can damage flora and fauna with low sensitivity to saline conditions.

Box 2.14 Climate change impacts on groundwater-fed coastal wetlands in the Mediterranean

Gialova lagoon, south-western Peloponnese, Greece (Manzoni et al., 2020)

The Gialova lagoon is a Natura 2000 site separated from the Navarino bay to the south and the Voidokoilia beach to the northwest by narrow wet dune slacks, which provide part of the groundwater flow to the lagoon. The lagoon is also fed with groundwater from artesian springs located to the eastern and south-eastern boundaries, where the lagoon meets with neighbouring wetlands. At least during the wet season, a portion of groundwater is recharged from an alluvial aquifer to the north. Both the lagoon and the wetlands are also supplied with water from precipitation, local streams, as well as marine upwelling, especially during the dry period. The Gialova lagoon shows seasonal fluctuations in salinity, which is expected to increase significantly under climate change. It has been estimated that warmer climate conditions in the future will increase evaporation by 10% and salinity by 5%. The mitigation of further salinisation of the lagoon requires up to 50% increase in freshwater inputs.

Albufera National Park, Mallorca, Spain (Riddiford et al., 2014 ; Candela, 2009)

Albufera de Mallorca is the largest wetland in the Balearic islands, which has also been designated as a National Park. A belt of coastal dunes separates the wetland from the sea. Else, the wetland is flat lying slightly above the average sea level. The wetland mainly consists of freshwater, but there are also a large saltmarsh and saline lagoons to the north-east, as well as abandoned salt pans to the south-east. To the south, there is a strip of dune woodland. The catchment includes several settlements, intensive agriculture that developed over the last 50 years, and highly seasonal tourism at the coastal strip of the Alcudia Bay. In summer, tourists outnumber permanent population by tenfold. The wetland is affected by high water abstraction pressure and climate change risks. For instance, it has been estimated that groundwater recharge to the wetland may decline significantly. Therefore, without any cut in groundwater abstractions, the relevant aquifers could be depleted and further intruded by the sea water. In addition, increased evapotranspiration, due to temperature rise, could enhance the dry-up of the wetland and increase its salinity.

The impacts of climate change on groundwater storage depend on the aquifer size, type and properties. Small, unconfined aquifers, especially shallow aquifers composed of unconsolidated sediment or fractured bedrock, will respond more strongly to climate change, whereas larger and confined systems will show a slower response (Klöve et al., 2014). Shallow aquifers however are often interconnected with surface water bodies and are more heavily exploited by human activities, such as abstraction for agriculture or public water supply. Therefore, any climate-related impacts on their recharge rate may impact GWAAEs and GWDTEs rapidly (see sub-studies 1 and 2, Psomas et al., 2021a).

Climate change and its impacts are expected to increase the current biodiversity problems. For example, increased water temperature could affect the dissolution of oxygen, nutrients and other chemical substances, impede ecosystem functions, and facilitate the migration and establishment of invasive or alien species in habitats (Taylor et al., 2013). In addition, projected changes in precipitation and groundwater recharge patterns may distort the influx of groundwater and its specific properties (e.g. temperature, oxygen level, salinity, acidity/alkalinity, nutrient load, etc.). GWAAEs/GWDTEs, which rely on this supply and its specific properties could be seriously damaged. For example, in colder climates, earlier snow melting is expected to cause shift of groundwater recharge from spring to winter (see section 2.5.2). This may increase the seasonal baseflow to rivers during spring months, but it would further decrease baseflow during low flows in summer months.

2.5.3 Responses and solutions

Thanks to their storage capacities, GWBs can play a critical role in buffering the seasonal impacts of climate change, enhancing the reliability of water supply, and maintaining GWAAEs and GWDTEs. Therefore, a balance needs to be maintained between long-term groundwater recharge and abstraction levels, so as not to compromise interactions between groundwater, surface waters and GWAAEs/GWDTEs. In the 2nd RBMPs, Member States reported that they have established or they were establishing water allocation regimes (e.g. permits, concessions, water rights), whose objectives include meeting ecological flow requirements (EC, 2019). However, the link between GWBs and GWAAEs/GWDTEs is not always made, with several countries not accounting for GWAAEs/GWDTEs in their groundwater quantitative status assessments (EC, 2019). In addition, challenges remain in the implementation and effective enforcement of existing water allocation regimes (EC, 2019).

Many managed aquifer recharge (MAR) schemes have been trialled in recent years (see for instance MARSOL, 2021). MAR is the artificial storage of water in aquifers, in order to maintain a balance between recharge rates and abstraction levels. Due to higher winter rainfall in northern Europe, MAR can be helpful for the partial storage of excess winter flows. The stored runoff would then help to meet increased water demand in summer (Taylor et al., 2013). Available methods include: infiltration ponds to increase the percolation of flood waters, rain or runoff; enhanced river channel infiltration; induced bank filtration; and direct pumping into an aquifer through boreholes.

MAR can have substantial benefits, including stabilising or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water (Klöve et al., 2014). Nevertheless, it is critical to adequately consider the risk of using waters of poorer quality in MAR schemes, such as polluted flood waters, storm waters or treated waste water. Recognising the risks posed by the infiltration or injection of pollutants in groundwater, the recently adopted EC Regulation 2020/741 provided minimum water quality standards for the reuse of water in crop irrigation. It is noted that EU Member States may apply stricter standards, e.g. by integrating the risks associated with emerging pollutants.

There is a growing interest in more coordinated ("conjunctive") use of surface waters and groundwaters, which involves the regional joint management of both resources. This aims at increasing the yield and the reliability of water supply to support societal and ecosystem demands (Klöve et al., 2014). Although many countries now consider the whole hydrological cycle in planning measures to restore groundwater, under the WFD RBMPs, few have attempted to optimise water allocation and promote alternating use of surface water and groundwater, according to sustainability objectives (Box 2.5).

Box 2.15 Ecological flows, groundwater abstraction and climate change in the Marais Poitevin, France

The Marais Poitevin is the second largest wetland in France, located on the Atlantic coast. Its ecological balance is dependent on a vast hydrological network of surface and groundwater flows. Maintaining good quantitative status in the relevant GWBs is a major challenge for the preservation of the wetland biodiversity and human activities benefiting from the wetland, including tourism, fisheries, and aquaculture. However, water abstraction by agriculture lowers the water table of the aquifers, which can lead to the seasonal reduction of baseflow to rivers, thereby impacting the fragile water balance sustaining the wetland. With increasingly drier springs and summers since the 1970s, climate change is adding further pressure on the wetland system, and increases the likelihood of more severe summer and autumn low flows.

Since 1992, a collaborative approach between authorities and agricultural users has gradually been put in place to regulate agricultural abstraction. Authorisations to abstract water have been restricted, in the form of seasonal and annual allocations, which are co-designed between the state and groundwater users and meet the estimated sustainable yield of the aquifers. Sustainability is defined taking into account the necessary discharges to GWAAEs and GWDTEs.

The scale of reductions needed in allocations to meet this sustainable yield, and alternative solutions, are a source of tension. Agricultural users seek the construction of new basin storagethat will be filled with groundwater abstracted in winter, when the levels are higher and abstraction has less impact on baseflows and GWAAEs/GWDTEs. Ongoing work includes improving knowledge of the impacts of climate change on the hydrological balances of groundwater and surface water, ecological flows and GWAAEs/GWDTEs. This improved knowledge should help quantify the effectiveness of alternative measures and optimise the design of groundwater and surface water allocations under a changing climate.

Source: Rouillard (2019)

Land use planning can also have a major role in protecting groundwater from climatic risks. However, the regional planning decisions largely fail to integrate climate change impacts (Buchanan et al., 2019). For instance, land use planning decisions should integrate climate change vulnerabilities by controlling the development of groundwater-fed irrigated agriculture in areas likely to suffer from extreme reduction in groundwater recharge. Coastal aquifers and small islands should also receive particular attention, due to higher risks of sea water intrusion and contraction of freshwater lenses with sea level rise.

Responding to climate change through improved planning and control of pollution and abstraction pressures, as well as improved conjunctive use of groundwater and surface waters will require new institutional and regulatory frameworks. Institutional collaboration, wider societal participation, training and education, and innovative policy instruments will be key in building local, regional and international adaptive capacities.

3 EU action on groundwater protection

Through a range of new strategies and policies, the European Green Deal has re-emphasised the need to manage water resources sustainably, tackle chemical pollution and water stress, so as to ensure sufficient, good quality water for the environment and for people. Specifically, the EU Biodiversity Strategy to 2030 and the new EU Climate Change Adaptation Strategy emphasise the need to preserve ecological flows and regulate groundwater abstraction to protect and restore GWAAEs/GWDTEs. Several upcoming EU initiatives will further contribute to protecting and restoring fragile GWAAEs and GWDTEs, such as the Nature Restoration Plan and its legally binding targets, the EU Climate Law and the need to preserve carbon rich ecosystems, as well as the Zero Pollution Action Plan, the Soil Thematic Strategy and the revision of the Urban Waste Water Treatment Directive, which will provide additional instruments to manage emissions and pathways of contaminants into groundwater.

The EC has established an elaborate environmental policy framework that contributes to protecting groundwater resources and GWAAEs/GWDTEs. The WFD provides a comprehensive strategy to manage European waters sustainably, considering the whole hydrological cycle across surface waters and groundwater. For groundwater, it sets out the goal to achieve good quantitative and chemical status. The EU has also passed a specific Groundwater Directive to further support the achievements of the EU WFD environmental objectives for groundwater and ensure the reversal of worsening pollution trends. Table lists these policies and their relationship to sustainable groundwater management.

Table 3.1 Key EU policies relevant for groundwater management in Europe (more details in Annex 1)

Directive / policy	**Key pressures / impacts directly tackled**			**Key sectors/drivers directly tackled**				
	Pollution	**Abstraction**	**Dependent ecosystems**	**Agriculture**	**Drinking water**	**Mining**	**Urban areas / industrial sites**	**Climate change**
Green deal								
Farm-to-fork strategy	X	X		X				
Biodiversity strategy for 2030	X	X	X	X				
New Circular Economy Action Plan (2020)	X	X		X	X		X	
Chemicals strategy for Europe (2020)	X			X	X	X	X	
Climate Change Adaptation Strategy to 2030								X
Zero Pollution Action Plan (2021)	x			x			x	
Pre-existing environmental policies								
Water Framework Directive (2000/60/EC)	X	X	X	X	X	X	X	
Groundwater Directive (2006/118/EC & 2014/80/EU)	X				X	X	X	
Drinking Water Directive 2020/2184	X			X	X		X	
Nitrates Directive (91/676/EEC)	X			X				
Urban Waste Water Treatment Directive (91/271/EEC)	X						X	
Birds and Habitats Directive			X					
Pre-existing circular economy policies								
Regulation on the minimum requirements water reuse (2020/741)	X	X		X	X			
Waste Framework Directive (2006/12/EC)	X					X	X	

Landfill Directive (99/31/EC)	X					X	X	
Sewage sludge directive (86/278/EEC)	X						X	
Sectoral policies								
Common agricultural policy 2022-2027	X	X		X				
Directive Sustainable Use of Pesticides (2009/128/EC)	X			X				
Regulation authorisation of PPPs (1107/2009)	X			X				
Directive on industrial emissions (2010/75/EU)	X						X	
European Mine Waste Directive (2006/21/EC)	X					X		

Challenges

Managing groundwater in an integrated, sustainable way faces major operational challenges. Detailed mapping and monitoring are costly and technically complex, and although numerically modelling is used extensively to conceptualise flow and interaction with other water bodies, it can also be a costly investment to develop and maintain. Therefore, it is difficult to assert with certainty the spatial flow dynamics of every single GWB, especially for aquifers which are less productive or exploited. In particular, it is difficult to assess the interactions between abstraction points and their impact on total aquifer storage or on patterns and speed of contaminant diffusion and pollution plumes.

Data from WFD and HD reporting differ greatly in terms of: a) spatial units for reporting and assessments; and b) timetables and periods for reporting. The spatial scale used for the assessment of the conservation status of habitats is gridded and coarse, and it does not match the geometry of water bodies (e.g. lines for rivers, and polygons for groundwaters, lakes, transitional and coastal waters). In addition, any spatial overlaps between the vertical projections of the boundaries of GWBs upon the boundaries of river basins and habitats on the ground surface can be hardly studied visually. This task requires more sophisticated understanding and conceptual modelling. To add to this complexity, different horizons can be located on the same location in the vertical plane, making it strenuous to distinguish the exact GWB interacting with a SWBs or a GWAAE/GWDTE. As the reporting and assessment units are incompatible, the uncertainty on which water bodies are linked with which ecosystems becomes challenging. Under the WFD, Member States have to define GWAAEs and GWDTEs, and assess their condition. Furthermore, under Art.17 of the HD they have to report data on the conservation status of those types of habitats included in Annex I of the HD. However, potential GWAAEs and GWDTEs are not explicitly distinguished as a special category of the reporting of conservation status, making the review of relevant WFD assessments less transparent and straightforward. Moreover, the reporting obligations under the WFD and the HD have different timetables, which creates a gap when trying to compare data from exactly the same period. Although both Directives have 6-year cycles, there is a lag time of two years in the reporting periods.

For further details on challenges during the cross-walk between the WFD and HD, please read further *Annex 6* of sub-study 2 (Psomas et al., 2021b).

As stakeholders and decision-makers rely heavily on scientists and technical experts to understand groundwater, their management becomes a highly technical exercise. At the same time, the depletion of aquifers does not always create immediate visible impacts for policy makers and the public. Such impacts may only materialise when the dependent economies are seriously locked in particular patterns of development. Stakeholders and decision-makers may not necessarily realise the risks resulting from the overexploitation of groundwater, including its interdependency with water quality, GWAAEs/GWDTEs, and potential economic side-effects. As a result, willingness to develop restrictive groundwater management plans may be low. Nevertheless, the WFD and the Groundwater Directive have increased knowledge and awareness, and promoted action towards sustainable groundwater management.

Future prospects

The strategic importance of groundwater is increasingly recognised nowadays. Several countries now plan to reserve the exploitation of selected GWBs for exceptional situations, which might render other water sources unsuitable for human consumption (e.g. after major disasters, such as terrorist attacks or nuclear accidents) (Hérivaux and Rinaudo, 2016). The strategic role of groundwater needs to be further consolidated in the policy agenda, especially in the context of discussions on climate change adaptation and water security.

The conjunctive exploitation of groundwater and surface water resources must be optimised through the development of adaptable allocation regimes. Similarly, their conjunctive protection needs to follow an integrated approach, that acknowledges the interdependencies between the status of GWBs and SWBs and manages them efficiently.

Because of the risk of irreversible damage to groundwater, national strategies must be designed based on the precautionary principle. Land use planning should integrate climatic and non-climatic risks to groundwater, seeking to ensure that water intensive activities (e.g. irrigation, urbanisation) are controlled in water-stressed areas with high risk of groundwater over-exploitation. Furthermore, land use planning can support the protection of groundwater quality by restricting polluting activities (e.g. agriculture, wastewater discharges, waste disposal) over sensitive recharge areas. The WFD safeguard zones for drinking water sources have performed such spatial restrictions to land use types.

Poorly or completely unregulated pressures must be monitored, given the costs of restoring groundwater quality and the long timescale involved in groundwater restoration. This requires maintaining a European watch list of emerging pollutants and improving their regular measurements. Other pressures, such as fracking and geothermal energy production, may also pose significant risks on groundwater balances and quality, as well as on receiving GWAAEs and GWDTEs. Inventories and studies are needed for these pressures also.

The components of the groundwater balance needs to be better monitored and understood, especially at those low spatial resolutions where water stress impacts are experienced by the public (e.g. at catchment and water body level). Furthermore, the analyses should take into account both the current and future climate conditions. Better understanding is also needed for the interactions between GWBs, SWBs and GWAAEs/GWDTEs.

Tackling the main pressures affecting groundwater status will require innovative approaches, investments and stricter law enforcement. In particular, more focus is required on the pressures originating from agriculture and public water supply, which are now the most widespread pressures in the EU 27, affecting the status of GWBs significantly.

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