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TACTIC Guidance Document

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
EGDI	European Geological Data Infrastructure
GC	Global change (climate change together with anthropogenic impacts)
GCM	Global Climate Model
GSO	Geological Survey Organisation
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
RCM	Regional Climate Model
RCP	Representative Concentration Pathway (of climate prediction)
TACTIC	Tools for Assessment of Climate change ImpacT on Groundwater

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BLOCK I: GENERAL INTRODUCTION

1. TACTIC Toolbox

1.1 Summary of the Toolbox

The TACTIC toolbox[1] is a collection of approaches and tools used for assessment and adaptation of climate change impacts and issues. Information and knowledge of the tools and their use have been supplied by Geological Surveys (GSOs) across Europe, both TACTIC and non-TACTIC partners. In this context, a tool is defined as an algorithm being applied for climate change assessment and/or adaptation. The tools range from complex numerical models embedded in computational programs, code strings or scripts or simpler formulas incorporated into excel. The TACTIC Toolbox contains 57 tools and consists of an overview file and fact sheet documents. The overview file contains a list of all the tools in the toolbox, structured in a consistent manner, defining the main features of each of the tools. These main features make it possible to immediately identify important functionalities or limitations in using the tools. These features e.g., include information on intended use/user, availability, scale and transferability. The fact sheet documents consist of a one-page description of each of the tools. Here a more detailed explanation of the functionality and use of the tool is given, also included is relevant links to user examples, complementary material or downloads and contact information to relevant GSO tool users/owners.

1.2 Introduction

The goal of the TACTIC Toolbox (located on the European Geological Data Infrastructure, EGDI repository[1]) is to collect and make available to all European Geological Survey Organisations (GSO) tools and approaches for Climate Change impact and adaptation assessments, and thereby advancing the assessments to be carried out across Europe. The toolbox is populated by tools that are already used for climate change assessment and adaptation. The tools are either used directly for assessment of climate change impacts, or assessment of adaptation effects; or supplementary tools used for climate projection and bias correction; or supporting tools e.g., tools used for pre- and/or post-processing or uncertainty assessments.

The tools come from two main sources of input: 1) Tools currently/previously used by TACTIC partners; 2) Tools applied in other studies and/or by non-TACTIC-partner GSOs. In total 57 tools have been collected and incorporated into the toolbox.

The toolbox consists of two parts (Figure 1.1). One part is the excel sheet (The Toolbox) containing the collection of tools in a structured and consistent overview. Here tools are categorized, and important features of the tools are specified. This includes e.g., functionality, type, intended user, scale, accessibility and available documentation. The information in this

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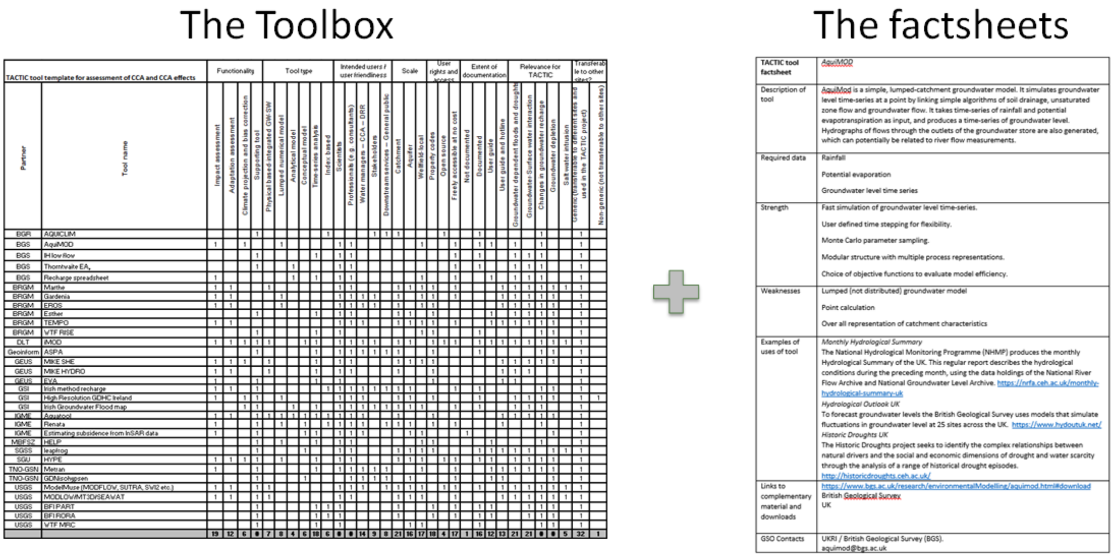
[1] https://repository.europe-geology.eu/egdidocs/tactic/tactictoolbox_oct2021.pdf

part of the toolbox makes it possible to easily assess the overall characteristics of the tools, and any limiting factors that may be for a potential user.

The second part is the factsheets, this is a document containing a more detailed description of the tools. For each tool 1-2 pages of description is available including, e.g., strength and weaknesses of the tools and relevant links and examples of use. Important information on the required input to run the tool is also supplied. A potential user may thus learn more about the tool and its requirements and limitations before trying to apply the tool to their specific case, both through the information in the factsheet and through the links supplied. The factsheets also contain contact information to a GSO user and/or owner of the tool, to whom a potential user may refer questions relating to the application of the tool.



The Toolbox

TACTIC tool template for assessment of CCA and CCA effects		Functionality				Tool type						Intended users / user friendliness					Scale			User rights and access			Extent of documentation				Relevance for TACTIC					Transferable to other sites?	
Partner	Tool name	Impact assessment	Adaptation assessment	Climate projection and bias correction	Supporting tool	Physical based-integrated GW-SW	Lumped numerical model	Analytical model	Conceptual model	Time-series analysis	Index based	Scientists	Professionals (e.g. consultants)	Water managers – CCA – DRR	Stakeholders	Downstream services – General public	Catchment	Aquifer	Wellfield-local	Property codes	Open source	Freely accessible at no cost	Not documented	Documented	User guide	User guide and hotline	Groundwater dependent floods and droughts	Groundwater-Surface water interaction	Changes in groundwater recharge	Groundwater depletion	Salt water intrusion	Generic (transferable to different sites and used in the TACTIC project)	Non-generic (not transferable to other sites)
BGR	AQUICLIM				1						1				1	1	1				1			1					1			1	
BGS	AquiMOD	1		1			1					1	1						1			1		1	1		1		1			1	
BGS	IH low flow				1					1		1	1									1		1			1	1	1			1	
BGS	Thorntvaite EA,				1			1				1	1									1		1			1	1	1			1	
BGS	Recharge spreadsheet	1						1		1		1	1						1			1			1		1	1	1			1	
BRGM	Marthe	1	1			1						1	1				1	1	1	1		1				1	1	1	1	1	1	1	
BRGM	Gardenia	1	1				1					1	1	1	1		1		1	1		1				1	1	1	1	1		1	
BRGM	EROS	1	1				1					1	1	1	1		1		1	1						1	1	1	1	1		1	
BRGM	Esther				1					1		1	1				1	1		1					1		1	1	1	1		1	
BRGM	TEMPO	1	1									1	1	1			1	1	1	1		1			1	1	1	1	1	1		1	
BRGM	VTF RISE				1					1		1							1	1				1					1	1		1	
DLT	iMOD	1	1	1	1	1			1	1		1	1	1	1		1	1		1	1	1		1	1	1	1	1	1	1	1	1	
Geoinform	ASPA				1					1		1	1	1	1	1	1			1				1					1	1		1	
GEUS	MIKE SHE	1	1	1		1				1		1	1				1	1	1	1						1	1	1	1	1		1	
GEUS	MIKE HYDRO	1	1			1				1		1	1				1			1						1	1	1				1	
GEUS	EVA	1			1					1		1								1						1	1					1	
GSI	Irish method recharge	1	1		1						1	1	1	1	1	1	1	1				1		1					1	1		1	
GSI	High Resolution GDHC Ireland	1		1	1		1					1	1	1			1	1		1				1			1	1	1	1		1	1
GSI	Irish Groundwater Flood map			1	1			1		1		1	1	1	1	1	1	1	1			1		1			1	1	1			1	
IGME	Aquatool	1	1		1	1	1	1	1	1	1	1	1	1			1			1						1	1	1	1	1		1	
IGME	Renata	1			1		1		1		1	1	1	1		1	1	1		1		1				1			1			1	
IGME	Estimating subsidence from InSAR data	1			1				1	1		1	1	1				1	1				1							1		1	
MBFSZ	HELP				1		1			1		1	1						1	1					1				1			1	
SGSS	leapfrog				1				1			1	1				1	1	1	1				1	1	1	1	1		1	1	1	
SGU	HYPE	1	1	1	1		1			1		1	1				1	1	1		1	1		1	1		1	1	1	1		1	
TNO-GSN	Metran	1			1					1		1	1	1	1	1			1			1			1	1	1	1	1	1		1	
TNO-GSN	GDNisohypsen				1				1				1	1	1	1		1				1			1	1				1		1	
USGS	ModelMuse (MODFLOW, SUTRA, SWI2 etc.)	1	1		1	1						1	1	1		1	1	1	1		1	1		1		1	1	1	1	1	1	1	
USGS	MODLOW/MT3D/SEAWAT	1	1		1	1						1	1				1	1	1			1				1	1	1	1	1	1	1	
USGS	BFI PART				1					1	1	1					1			1		1		1	1			1	1	1		1	
USGS	BFI RORA				1					1	1	1					1			1		1		1	1			1	1	1		1	
USGS	VTF MRC				1					1		1						1	1					1					1	1		1	
		19	12	6	[illegible]	7	8	4	6	10	6	[illegible]	[illegible]	14	9	8	21	16	17	18	4	17	1	16	12	13	21	21	[illegible]	[illegible]	5	32	1

The factsheets

TACTIC tool factsheet	*AquiMOD*
Description of tool	AquiMod is a simple, lumped-catchment groundwater model. It simulates groundwater level time-series at a point by linking simple algorithms of soil drainage, unsaturated zone flow and groundwater flow. It takes time-series of rainfall and potential evapotranspiration as input, and produces a time-series of groundwater level. Hydrographs of flows through the outlets of the groundwater store are also generated, which can potentially be related to river flow measurements.
Required data	Rainfall Potential evaporation Groundwater level time series
Strength	Fast simulation of groundwater level time-series. User defined time stepping for flexibility. Monte Carlo parameter sampling. Modular structure with multiple process representations. Choice of objective functions to evaluate model efficiency.
Weaknesses	Lumped (not distributed) groundwater model Point calculation Over all representation of catchment characteristics
Examples of uses of tool	*Monthly Hydrological Summary* The National Hydrological Monitoring Programme (NHMP) produces the monthly Hydrological Summary of the UK. This regular report describes the hydrological conditions during the preceding month, using the data holdings of the National River Flow Archive and National Groundwater Level Archive. https://nrfa.ceh.ac.uk/monthly-hydrological-summary-uk *Hydrological Outlook UK* To forecast groundwater levels the British Geological Survey uses models that simulate fluctuations in groundwater level at 25 sites across the UK. https://www.hydoutuk.net/ *Historic Droughts UK* The Historic Droughts project seeks to identify the complex relationships between natural drivers and the social and economic dimensions of drought and water scarcity through the analysis of a range of historical drought episodes. http://historicdroughts.ceh.ac.uk/
Links to complementary material and downloads	https://www.bgs.ac.uk/research/environmentalModelling/aquimod.html#download British Geological Survey UK
GSO Contacts	UKRI / British Geological Survey (BGS). aquimod@bgs.ac.uk

Figure 1.1 Example of the structure of the toolbox. Left: The structure overview of the toolbox itself given as an excel file. Vertical columns to the left indicate the partners supplying the tool, followed by the tool name. Horizontally are the different features of the tools. Right: An example of one accompanying factsheet providing detailed information about each tool in the Toolbox. The column to the left indicates the information reported on, and the description is located to the right.

1.3 Methodology

Generally, a tool can be anything supporting an operational action (e.g. a guideline, a procedure or protocol, a method or technique, a device or a software program). In TACTIC, the focus is mainly on “tools” that are an algorithm and that may be embedded in computer codes. They may take different forms, such as simple formulas in excel or complex software packages, and thus cover a range of complexities, programs and systems.

As mentioned, the Toolbox overview sheet contains general information about the tools, structured to give a consistent overview of the tool features. The information covers eight main features: Functionality, Tool type, Intended users/user friendliness, scale, User rights and access, Extent of documentation, Relevance for TACTIC and Transferable to other sites. In the following section explanations of the different features of the toolbox are given:

Functionality: The functionality or use of tools can be impact assessment (e.g. assessment or simulation of effects of climate change on hydrology and groundwater), and/or for adaptation assessment (e.g. assessment or simulation of effect of various adaptation measures). Furthermore, tools used for climate projection and bias correction as well as supporting tools used for data processing are included in the toolbox and be categorized. An example of a supporting tool is e.g., the “IH low flow”, a base flow separation tool used to estimate “rapid” flow, which is then used as input to an impact assessment tool, but it may also be tools used in data analysis, e.g. statistical tools. The tools may have more than one functionality.

Tool type: Models/tools may be sub-classified in many ways. Within hydrological modelling three common groups of model types are: (a) empirical or statistical models (black box); (b) lumped conceptual models (grey box); (c) distributed physically based models (white box). These categories may then be subdivided again following many different approaches. In the TACTIC Toolbox a sub-division according to the tools already applied in several GSOs has been selected, leading to the following six tool types: 1. Physically based models; 2. Lumped model tools; 3. Analytical tools; 4. Conceptual models; 5. Time series analysis tools; and 6. Index based tools.

Intended users /user friendliness: The TACTIC Toolbox operates with five different categories of intended users: 1. Scientists, i.e. tool developer, advanced user and domain expert. 2. Professionals, which are experienced tool users and mediators of results to decision-makers. 3. Water managers, climate change adaptation (CCA) managers and/or disaster risk reduction (DRR) managers, who are the ones that have to take actions and are responsible for their consequences. 4. Stakeholders, who are persons, groups or organizations affected by a management plan, e.g. professional bodies, government authorities, resident organizations, farmers groups, individual landowners or residents. 5. Downstream Services - General public, unorganized groups of individuals in the community, who nevertheless have a stake in the management of the river basin, referred to as the general public.

Scale: The TACTIC toolbox distinguishes between three classes of scale: 1. Wellfield-local, refers to tools used at the wellfield scale, and results may only be representative for the wellfield. 2. Aquifer, refers to tools used on aquifer scale, where it is assumed that the results are representative for the entire aquifer, or for a well-defined subdivision of the aquifer. 3. Catchment/basin, here defined as tools used for assessments at all larger scales, i.e. may cover one or more river basins or countries.

User rights and access: TACTIC Toolbox here operates with three different types of access: 1. Property tools/codes where the user has to pay for access to the code and possibly for yearly licenses. 2. Freely accessible tools at no costs, where use is free, but there is no access to the code and the user thus cannot change the source code. 3. Open source tools, where use is free of charge and the user can change the source code.

Extent of documentation: Here the TACTIC Toolbox differentiates between four different levels of documentation: 1. No documentation, these are often research codes developed by a single person or research groups. The only documentation is the code, if accessible. 2. Documentation, the code may be documented in journal papers or reports but does not include exhaustive documentation on how to use the tool. 3. User guide, a dedicated user guide for the tool is available. 4. User guide and hotline, a dedicated user guide for the tool is available, and there is access to a hotline. This is often only available for property codes that include a yearly licensing.

Relevance for TACTIC: This feature describes whether or not the tool is a part of one or more of the following five topics, these topics relate to different work packages in TACTIC, and thus some tools may not have a category for this feature if they have not been applied within the TACTIC project. The five topics include: 1. Groundwater dependent floods and drought. 2. Groundwater-Surface water interactions. 3. Changes in groundwater recharge. 4. Groundwater depletion. 5. Saltwater intrusion.

Transferable to other sites: Here the TACTIC Toolbox distinguish between transferable (generic) and non-transferable tools (non-generic). The generic and transferrable tools are in focus for the TACTIC Toolbox. Generic tools describe generic relations and can be transferred between different study sites. A generic tool applied at a specific location becomes a site-specific tool that is tailored to a specific site and/or specific conditions. An example of a generic tool is a software code for groundwater flow, e.g., MODFLOW, which can be used anywhere. However, the model must be adapted to the specific conditions by including a hydrogeological model and associated parameters, whereby it becomes a site-specific model, or site-specific application, that cannot be transferred to other sites. Another example is statistical modelling, where a software program provides a generic tool, but a regression model developed in the tool will describe site-specific relations between in- and outputs that cannot be transferred. However, the tool itself is still generic.

The aim of having the category non-generic is to ensure that the TACTIC Toolbox can also contain examples of non-transferable tools. E.g., new tools/codes may be developed targeting a specific challenge for a specific purpose, which cannot immediately be transferred. It is thus encouraged that development of new site-specific codes/tools are included in the template, while site-specific applications of generic tools are not included.

1.4 Example of Toolbox content

The Toolbox in its current form can be seen in the EGDI repository[2], while some general characteristics of the tools in the Toolbox can be seen in Figure 1.2. Generally, half of the tools

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[2] https://repository.europe-geology.eu/egdidocs/tactic/tactictoolbox_oct2021.pdf

in the toolbox are impact and adaptation assessment tools; a large part of the tools is supporting tools, and a few percent are climate projection and bias correction tools. The majority of the tools have multiple functionalities, and about half of all impact/adaptation assessment tools have supporting tools incorporated into their setups. Except for one case, all climate projection and bias correction tools are associated with an impact assessment tool.

The TACTIC toolbox holds information about all tool types defined here. While there is an overweight of Time series analysis tools and a few Analytical tools, the rest of the tool types are equally well represented. The users of the tools are heavily dominated by professionals and scientists making up for 65 % of the intended users. Tools that are usable on catchment, aquifer and well field scales are equally well represented in the toolbox, and out of these tools half of them are usable on more than one scale.

The two last categories illustrated on Figure 1.2 are related to the accessibility and usability of the tool. The access to the tools is divided equally between freely accessible tools (and open source) and property own tools, meaning that half of the tools can be used without costs. The majority of the tools have some form of documentation or manual to help guide users of the tools.

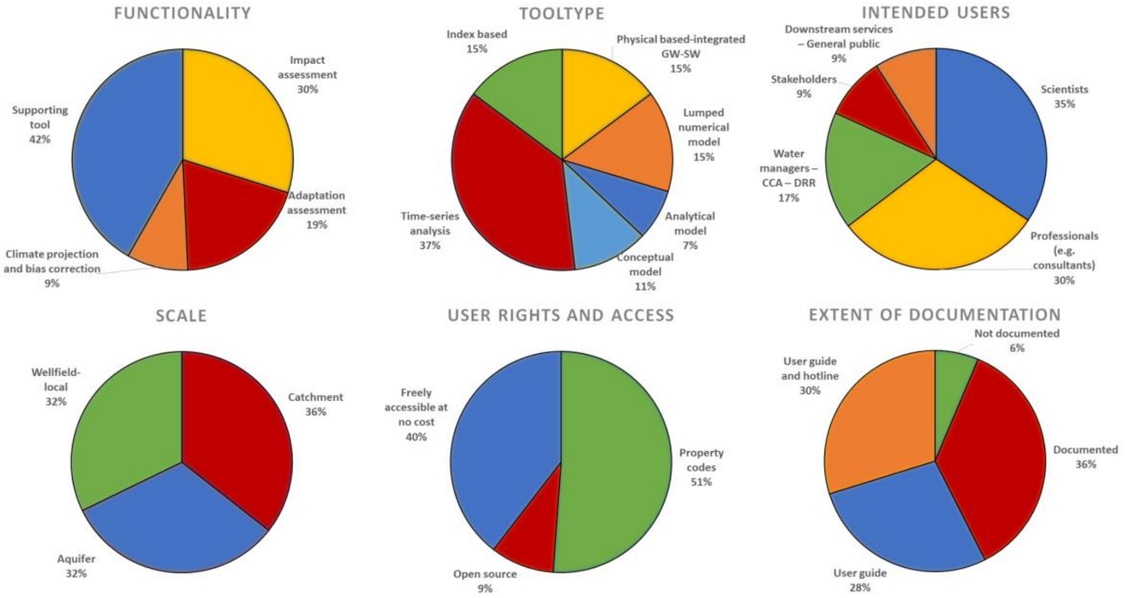


Figure 1.2 Overview of the general characteristics of the tools in the TACTIC Toolbox.

1.5 Conclusion

The TACTIC toolbox contains 57 tools all classified and organized in a consistent manner, making it suitable for potential users to identify which tools to use for climate change impact assessment and adaptation. The toolbox furthermore compiles more detailed information (in the factsheets), making it possible for interested user to ascertain more information by using the supplied links and contact information given for each tool. The TACTIC Toolbox is thus a solid starting point or steppingstone for Geological Surveys or other potential users wishing to start conducting or further developing climate change impact assessment or adaptation.

2. Climate Change data & generation of future local scenarios

2.1 Summary

Projections of future climate can be used in (geo) hydrological models in order to predict impact on (ground)water resources and related socio-economic consequences. The data of the future climate originates from Global and Regional Climate Models. Usually, the data consists of an ensemble of predictions with spatio-temporal precipitation, temperature, and evapo-transpiration and they may be complemented by socio-economic projections that contain e.g. water use predictions. Such datasets cannot be used directly in (geo) hydrological models, but review, selection and interpretation or translation to a suitable spatial and temporal scale and resolution is necessary.

This process of translating climate (and socio-economic) predictions into input data of precipitation, temperature, and evapotranspiration for a (geo) hydrological model can be done with different methods. The so-called indirect method relates the future quantities to the current ones using a delta change factor or difference. The so-called direct method uses distribution-based scaling. The former is more easily obtained, transparent and suitable for assessments of future average groundwater conditions. The latter is more suitable for analysing the impact of extreme weather events on the corresponding groundwater extremes.

When we focus on the analyses of climate change impacts on droughts, there are different approaches developed to generate future local climate scenarios for a better assessment of those (Collados-Lara et al., 2018). A general tool (Collados-Lara et al., 2020) has been developed to generate those potential scenarios (see section 2.3.3) with a better approximation of drought statistics.

2.2 Introduction

To assess future change in groundwater conditions from a changing climate, estimates of precipitation, temperature and potential evapotranspiration for the chosen future period is needed. This data should be obtained from Global Climate Models (GCMs) downscaled to the required area and resolution possibly by using an intermediate Regional Climate Model (RCM) applying boundary conditions from the GCM and translating the results from the RCM to the area of interest. For interpretation and comparison of the results, it is important to properly document the climate change data used in the groundwater application.

2.3 Methodology

There are different ways of creating a dataset that represents future climatic conditions. The most simplistic way is to apply a multiplication factor. This is often used for the critical rainstorm depth for the design of stormwater runoff systems. The determination of the multiplication factor requires more complicated modelling and proper risk assessment.

A less simple method is the so-called indirect method or Delta Change. In this method future timeseries for precipitation, evapotranspiration and temperature are constructed by applying delta changes to time series of precipitation, evapotranspiration and temperature, for a historical period. The factors are all derived from comparisons between simulated historical and future periods by climate models.

A direct method is the use of the outputs for a future period from the climate models directly in the (geo)hydrological model. It may be necessary to apply a bias correction if the climate model output for a historical period deviates systematically from observed values. The same (bias) correction is then assumed for the future.

Both the indirect (Delta change) and direct (Distribution based Scaling) methods can be used to assess impacts on groundwater, although the value differs for specific applications. This is illustrated in the following section.

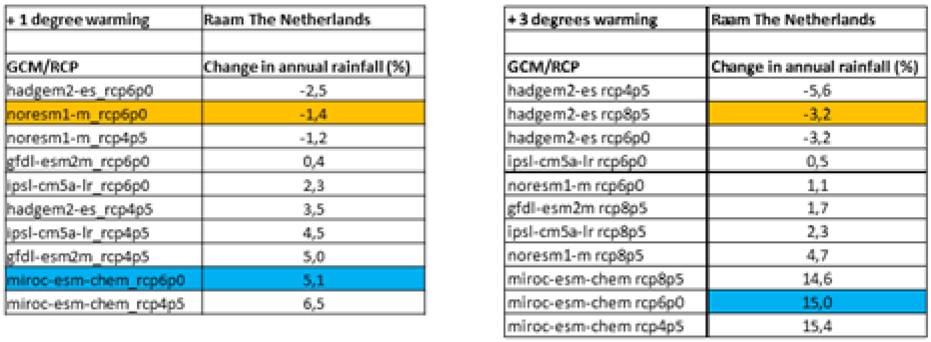
2.3.1 The indirect method, Delta Change tool (TACTIC standard scenarios)

In order to arrive at results that are intercomparable for all of Europe, a new procedure for selection of climate change scenarios has been developed within TACTIC.

The climate change scenarios have been based on climate data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP: https://www.isimip.org/). These data consist of ensembles of 15 datasets: three Representative Concentration pathways (RCP) simulated with five Global Climate Models. The spatial resolution is 0.5° and the temporal resolution 1 day, the data are bias-corrected considering bias in mean and variance. Two criteria were used to select an ensemble member (Sperna Weiland et al., 2021):

- For each dataset the time-horizon at which a global warming level of +3 degrees and +1 degrees was reached, relative to a reference period (1980-2010), was selected.

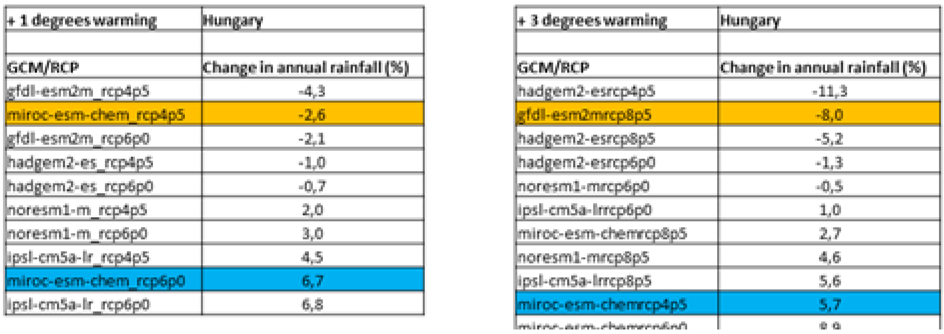
the 2nd highest and 2nd lowest scenario for precipitation change are then selected at the regional scale, using the case-study specific precipitation change. This procedure leads to a different ensemble member for each scenario and often also to different ensemble applied between different European areas (Figure 2.1 and 2.2).



+ 1 degree warming	Raam The Netherlands
GCM/RCP	Change in annual rainfall (%)
hadgem2-es_rcp6p0	-2,5
noresm1-m_rcp6p0	-1,4
noresm1-m_rcp4p5	-1,2
gfdl-esm2m_rcp6p0	0,4
ipsl-cm5a-lr_rcp6p0	2,3
hadgem2-es_rcp4p5	3,5
ipsl-cm5a-lr_rcp4p5	4,5
gfdl-esm2m_rcp4p5	5,0
miroc-esm-chem_rcp6p0	5,1
miroc-esm-chem_rcp4p5	6,5

+ 3 degrees warming	Raam The Netherlands
GCM/RCP	Change in annual rainfall (%)
hadgem2-es rcp4p5	-5,6
hadgem2-es rcp8p5	-3,2
hadgem2-es rcp6p0	-3,2
ipsl-cm5a-lr rcp6p0	0,5
noresm1-m rcp6p0	1,1
gfdl-esm2m rcp8p5	1,7
ipsl-cm5a-lr rcp8p5	2,3
noresm1-m rcp8p5	4,7
miroc-esm-chem rcp8p5	14,6
miroc-esm-chem rcp6p0	15,0
miroc-esm-chem rcp4p5	15,4

Figure 2.1 ISIMIP ensemble members for the Dutch TACTIC pilot "de Raam".



+ 1 degrees warming	Hungary
GCM/RCP	Change in annual rainfall (%)
gfdl-esm2m_rcp4p5	-4,3
miroc-esm-chem_rcp4p5	-2,6
gfdl-esm2m_rcp6p0	-2,1
hadgem2-es_rcp4p5	-1,0
hadgem2-es_rcp6p0	-0,7
noresm1-m_rcp4p5	2,0
noresm1-m_rcp6p0	3,0
ipsl-cm5a-lr_rcp4p5	4,5
miroc-esm-chem_rcp6p0	6,7
ipsl-cm5a-lr_rcp6p0	6,8

+ 3 degrees warming	Hungary
GCM/RCP	Change in annual rainfall (%)
hadgem2-esrcp4p5	-11,3
gfdl-esm2mrcp8p5	-8,0
hadgem2-esrcp8p5	-5,2
hadgem2-esrcp6p0	-1,3
noresm1-mrcp6p0	-0,5
ipsl-cm5a-lrrcp6p0	1,0
miroc-esm-chemrcp8p5	2,7
noresm1-mrcp8p5	4,6
ipsl-cm5a-lrrcp8p5	5,6
miroc-esm-chemrcp4p5	5,7

Figure 2.2 ISIMIP ensemble members for the Hungarian TACTIC pilot.

In the next step for a selected scenario, monthly change factors are determined for the area to be modelled for the precipitation, temperature, and reference evaporation. The change factors allow for the transformation of existing meteorological data to time series belonging to the selected scenario for that area. A period with a length of at least 30 years should be used to include sufficient meteorological variation. The correction factors for temperature are additive, the correction factors for evaporation and precipitation are multiplicative to avoid negative future values.

All delta change values (precipitation, temperature and evapotranspiration) for the standard TACTIC climate change scenarios can be downloaded and use in future assessments here.

2.3.2 The Direct method, Distribution Based Scaling (DBS) tool

For some of the case-study areas alternative climate change scenarios were developed following the direct method. This method implies that outputs from global or regional climate models are used directly (almost) in the application model, e.g. in a groundwater or other kind of hydrological application model. Because the outputs from the climate models locally can be different or biased compared to observed values, the outputs from the climate models are bias-corrected. The bias-correction is based on a climate model run for a historical period where observed data are available. The bias-correction is not uniform for the whole distribution but can be targeted to different parts, e.g. dry or wet parts. In practice this results in different correction values for different events. The argument for this is that the climate model biases are often different for the upper tail of the distribution, e.g. for daily rain events in the 95 % quantile than for the lower parts of the distribution, e.g. 20, 50 or 70 % quantile of daily rain events. Often, the direct method bias corrects the climate model data with one factor representing the upper tail of distribution (e.g. Q90) and another factor representing lower order events (e.g. <Q90). In principle, the distribution of the climatic variable in focus could be divided into more than 2 groups.

For several of the TACTIC pilots, e.g. The Netherlands, Spain, and Denmark, a direct method of applying climate model data to predict future conditions has been used in other projects outside TACTIC. Denmark used the freely available EURO-CORDEX dataset (https://www.euro-cordex.net/), which can be found in Pasten-Zapata et al. (2019). Lenderink et al. (2014) describe the preparation of input data based on climate projections for the Netherlands.

2.3.3 Drought extremes tool

This task is focused on the generation of climate change scenarios (developed in section 3). A method to generate ensemble scenarios to assess drought, reducing the bias in drought statistics (frequency, duration, magnitude and intensity) was developed and published in a research paper (Collados-Lara et al., 2018).

The objective of the paper is to investigate different methods to generate future potential climatic scenarios at monthly scale considering meteorological droughts. We assume that more reliable scenarios would be generated by using regional climatic models (RCMs) and statistical correction techniques that produce better approximations to the historical basic and drought statistics. A multi-objective analysis is proposed to identify the inferior approaches. Different ensembles (equifeasible and non-equifeasible) solutions are analysed, identifying their pros and cons. A sensitivity analysis of the method to spatial scale is also performed. The proposed methodology is applied in an alpine basin, the Alto Genil (southern Spain). The method requires historical climatic information and simulations provided by multiple RCMs (9 RCMs are considered in the proposed application) for a future period, assuming a potential emission scenario. We generate future series by applying two conceptual approaches, bias correction and delta change, using five statistical transformation techniques for each. The application shows that the method allows improvement of the definition of local climate scenarios from the RCM simulation considering drought statistics. The sensitivity of the results to the applied approach is analysed.

A tool (GROUND tool; Collados-Lara et al., 2020) has been developed in the framework of the project. It allows to generate local future series of precipitation, temperatures (minimum, mean, and maximum), and potential evapotranspiration. It is a valuable tool for assessing the impacts of climate change in hydrological applications since these variables play a significant role in the water cycle, and it can be applicable to any case study. The tool uses different approaches and statistical correction techniques to generate individual local projections and ensembles of them.

2.4 Conclusion: Pitfalls, pros and cons

The direct (Distribution based scaling) and indirect (Delta change) method of applying climate change scenarios are different and the decision to apply one or the other depends on the objectives of the climate change assessment. For an overall trend assessment of groundwater resources in the future or whether the groundwater tables generally move up or down, the indirect method can provide as reliable results as the direct method. An advantage of the indirect method is the transparent changes applied to the historical dataset with monthly factors in order to produce a dataset of a future climate. The monthly factors provide seasonal changes which are then propagated through the application model. Steady-state groundwater models will produce the same output for meteorological input from an indirect method and from a direct method. If the goal of the modelling is to assess sub-monthly extreme events, the direct method is more suitable because it better reflects the expected distribution of extreme meteorological conditions, while the indirect method only changes the size of events from the historical period but not their frequency. In TACTIC, the indirect method has made it possible to make intercomparable studies between different regions of Europe, within the available time. The preparation of the Delta Changes takes less time than creating input data using the direct method, and the Delta Changes can be applied more easily in each of the pilots, despite the large range in formats used for the various tools. Also, simulations based on the originally applied meteorological datasets of pilot studies can easily be reused in quantification and visualization of the groundwater impacts.

Datasets of climate change have been produced for more than 40 pilots in the project. The assessments from the different pilot areas are intercomparable because the procedure for selecting the simulated ensembles and the method to apply the change factors to a local dataset, are the same across all pilots.

Finally, we have developed a specific method (Collados-Lara et al., 2018) and tool (Collados-Lara et al., 2020) that helps to generate local climate change scenarios for a better assessment and analyses of climate change impacts on droughts. We also study the benefit of using more reliable local climate scenarios to analyse hydrological responses (Collados-Lara et al., 2021). It assumes that Regional Climate Models (RCM) simulations are more reliable when they provide better approximations to the historical basic and drought statistics after applying bias correction to them. The application performed shows that the best solutions in terms of their approximation to the local meteorology also provide the best hydrological assessments.

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BLOCK II: GROUNDWATER – SURFACE WATER INTERACTION BY INTEGRATED MODELS

Climate change already has widespread and significant impacts in Europe, which is expected to increase in the future. To reduce the damage, detailed assessments, based on a thorough understanding of the hydrological system, are required for the planning of optimal adaptation strategies. Groundwater plays a vital role for the inland freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Integrated models are indispensable in this assessment because of the interconnectivity of the groundwater with surface water, soil water, evapotranspiration and crop growth, land subsidence, etc. Successful application does require sufficient knowledge of the groundwater system and adequate input data.

3. Climate Change data + Socio-Economic scenarios

The climate change data from the climate models can be transformed into meaningful hydrological land-based evaluations with integrated models. As described in block I, section 2, a careful downscaling and bias-correction is needed to use the climate model data on the variety of special and temporal scales that integrated hydrological models are used for.

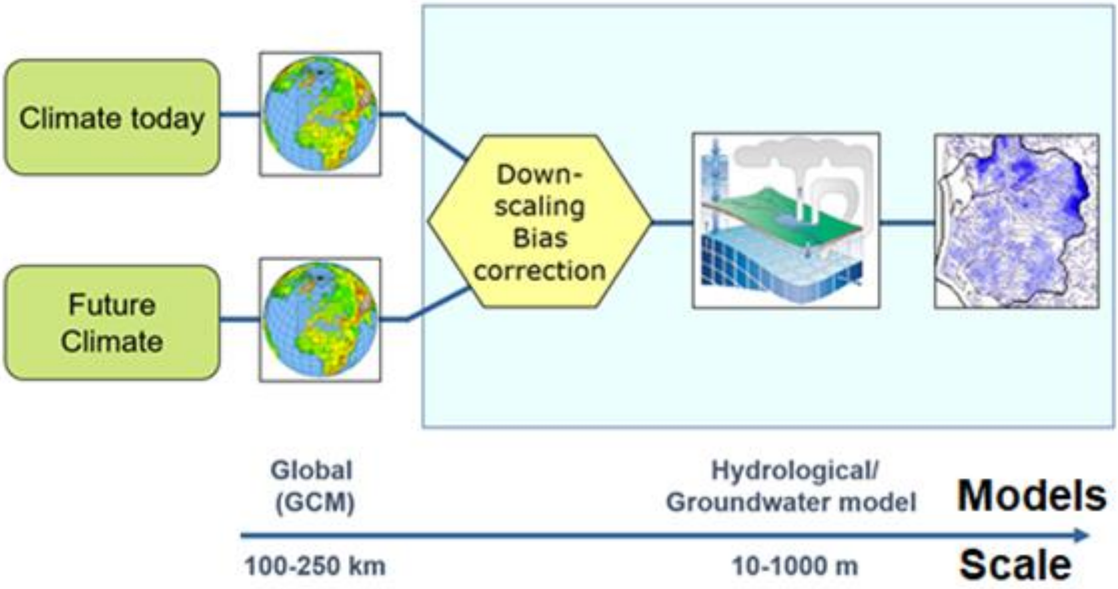

Figure 3.1 Overview of Calculation of climate change effect on groundwater with integrated groundwater and hydrological models. Especially the downscaling and/or bias correction can be done in multiple ways as explained in section 2.3.

3.1 Summary of the Toolbox

The following section summarizes the integrated modelling tools used by the GSO's within TACTIC. Further descriptions can be found in the TACTIC toolbox/factsheets where further references to documentation can be found at:

https://repository.europe-geology.eu/egdidocs/tactic/tactictoolbox_oct2021.pdf.

iMOD: The Dutch Hydrological Instrument (NHI) is the national integrated subsurface and surface water model of the Netherlands. Within NHI, the open source software iMOD is used. This software is based on the USGS MODFLOW-source, and adapted (iMODFLOW), to apply for (extreme) large modelling areas.

MARTHE: MARTHE is a BRGM software developed for the flow and transport modelling in three-dimensional and multilayer porous media. It is an integrated hydrological / hydrogeological model that can simulate the hydrosystem as a whole. MARTHE is designed to address underground hydrodynamic problems in various contexts: planning and management of water resources, environmental problems related to groundwater and surface water.

MIKE SHE: MIKE SHE is an integrated hydrological modelling system for building and simulating groundwater and surface water flow. MIKE SHE can simulate the entire land phase of the hydrological cycle and allows components to be used independently and customized to local needs. MIKE SHE can be used for the analysis, planning and management of a wide range of water resources and environmental problems related to groundwater and surface water.

Visual MODFLOW: Visual MODFLOW is Graphical User Interface (GUI) that helps to design, calibrate, validate and simulate groundwater flow and transport models in porous medium. The non-density-dependent flow is approached by using the MODFLOW code developed by the USGS: https://en.wikipedia.org/wiki/MODFLOW. Other graphical interface employed to simulate aquifer evolution that use MODFLOW are: PMWIN, Vistas, GMS, SIMTRA, etc.

ModelMuse: ModelMuse is a graphical user interface (GUI) that helps to design, calibrate, validate and simulate groundwater flow and transport models in porous medium. It is a GUI for the U.S. Geological Survey (USGS) models MODFLOW–2005, MODFLOW-LGR, MODFLOW-LGR2, MODFLOW-NWT, MODFLOW-CFP, MODFLOW-OWHM, MODPATH, ZONEBUDGET, PHAST, SUTRA, MT3D-USGS, SWI2 and WellFootprint and the non-USGS model MT3DMS.

MODFLOW/MT3D/SEAWAT, GMS, Groundwater Vistas (GV): MODFLOW is the USGS's modular hydrologic model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management. GMS is a modeling interface (GUI) for advanced three-dimensional groundwater modeling with MODFLOW/MT3D/SEAWAT including a full 3D visualization. GV is a pre- and post-processor (GUI) for MODFLOW/MT3D/SEAWAT models with focus on new technology for model calibration, optimization, and uncertainty analysis.

Besides the different integrated hydrological and groundwater models, a number of supporting tools to, for instance, create recharge to a 3D groundwater – surface water model, are listed in the TACTIC toolbox.

3.2 Introduction

The tools in the TACTIC toolbox offer freedom in the conceptual schematization of the interaction between groundwater and surface-water. Some of the tools also offer possibilities to include other interactions in an integrated model, such as a crop growth model for more detailed modelling of evapotranspiration.

The selection of the conceptual schematization of the surface-water interaction and of other processes to include in the model is an important aspect for the applicability of the results and of the data requirements (or the added uncertainty when data is not available). This selection can only be made with sufficient knowledge of the groundwater system, which in turn does not only depend on data, but also on experience and modelling. Therefore, a step-wise approach of starting simple and gradually exploring and expanding complexity is practical.

3.3 Methodology

For obtaining insight in the effect of climate change on groundwater and groundwater resources, knowledge of the hydrogeology, models, and climate change scenarios are needed.

3.3.1 Hydrogeological information

The basis of the knowledge of groundwater systems is the geology. Specifically, information on the hydraulic properties of the geological units and geological features like faults is necessary. In addition, data on the external influences on the groundwater are important. The collection of these often lies (at least partly) outside the task of the geological surveys, so cooperation and coordination are necessary.

Precipitation and evaporation usually are the most important external influences. Precipitation is measured routinely, but evaporation is more difficult. Reference evaporation can be determined from standard meteorological quantities, but the difference between the actual evaporation and this reference evaporation can be large. Information on land use, crop type, soil moisture may help to get more accurate evaporation, but this does require additional knowledge of processes and associated parameters.

Information on the presence and properties of surface water and drainage systems is also needed for proper assessment of groundwater systems. Drainage level and drainage capacity are relatively simple types of data, but often not systematically registered and made available. Depending on the geologic and hydrologic settings, it may vary strongly what data on surface water is relevant. This usually includes location, width and depth and the surface water level. Topographic maps can be used for the former two, measurements of the latter may be available. Surface water fluxes, presence of sludge and frequency of dredging are examples of additional data, that may be useful.

The last group of external influences is groundwater extraction and irrigation. Usually, data on large extractions is available, especially when a licence is required. Smaller extractions and irrigation generally are less well known.

The quality and quantity of hydrogeological information used to setup and calibrate integrated models are generally reflected in the uncertainty or the trustworthiness of the model-predictions.

It must be noted that modelling also provides information about the groundwater system, so that data collection benefits from insights obtained from modelling, and modelling can be improved with additional insight from data suggesting a repetitive and cyclic process (e.g. Hill & Tiedeman, 2007; Haitjema, 1995).

3.3.2 Model concepts

A model is a system conceptualization together with process parameters and input variables. The included processes as well as the time and space resolution are important aspects of the model and determine the usability of the results together with their reliability.

Recharge from precipitation

The conceptualization of the recharge from precipitation defines largely, how effectively the effects of climate change on the groundwater can be determined. This is illustrated by Figure 3.2.

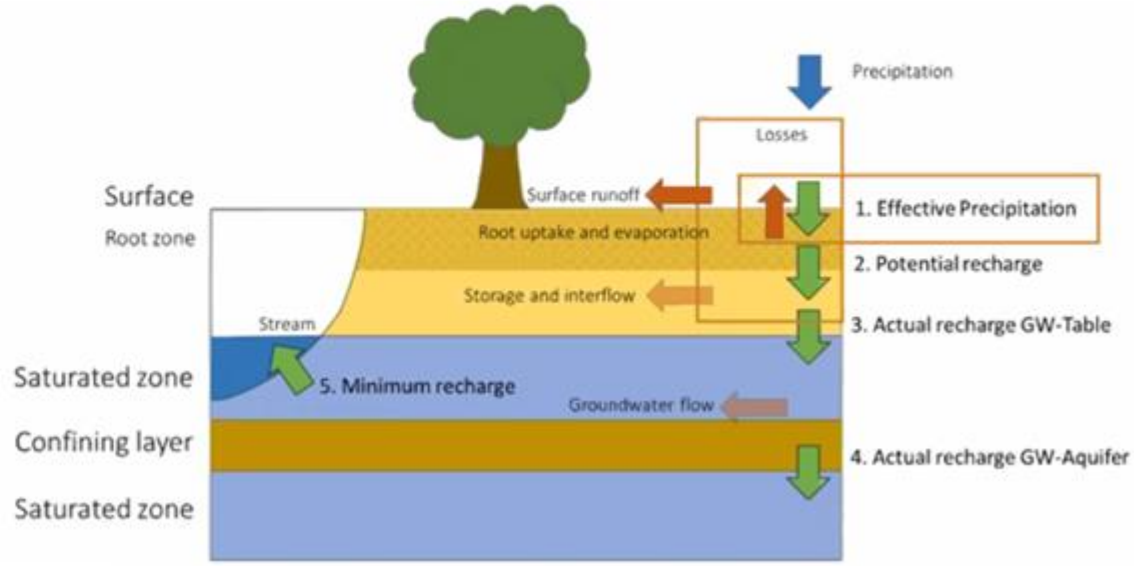

Figure 3.2 Groundwater recharge

The effective precipitation, 1. in figure 3.2, is equal to the precipitation minus the actual evapotranspiration, in which more or less elaborate modelling concepts may be used to determine the actual evaporation (from reference evaporation, land use, etc.). If surface runoff is calculated, then potential recharge, 2. in figure 3.2, is obtained which is smaller than the effective precipitation. Also simulating rootzone storage and interflow, leads to yet another value for the actual recharge at the groundwater table, 3. in figure 3.2. Finally, in a multi-aquifer approach, the recharge to deeper aquifers has a different value, 4. in figure 3.2. The minimum recharge to the surface water, 5. in figure 3.2, is a groundwater discharge to the surface water system.

Surface water interaction

From the viewpoint of the groundwater, the interaction with surface water consists of water fluxes generated by head differences. The fluxes are either a groundwater loss feeding the surface water, or a groundwater gain fed by surface water.

An undisputable part of these water fluxes is the water exchange through the contact surface between surface water and groundwater. For many practical purposes, it is not useful to consider only the interface with surface water on the one and saturated groundwater on the other side (figure 3.3, yellow ellipse). Often, a useful extension is to include the groundwater outflow through seepage faces in river banks above the surface water level and infiltration through lake and river beds that lie above the phreatic groundwater table (Figure 3.3, orange ellipses). Furthermore, depending on circumstances, surface runoff, interflow, and drainage that ends up in the surface water can be included in the definition of the surface water exchange flux in a groundwater model (Figure 3.3, red ellipse).

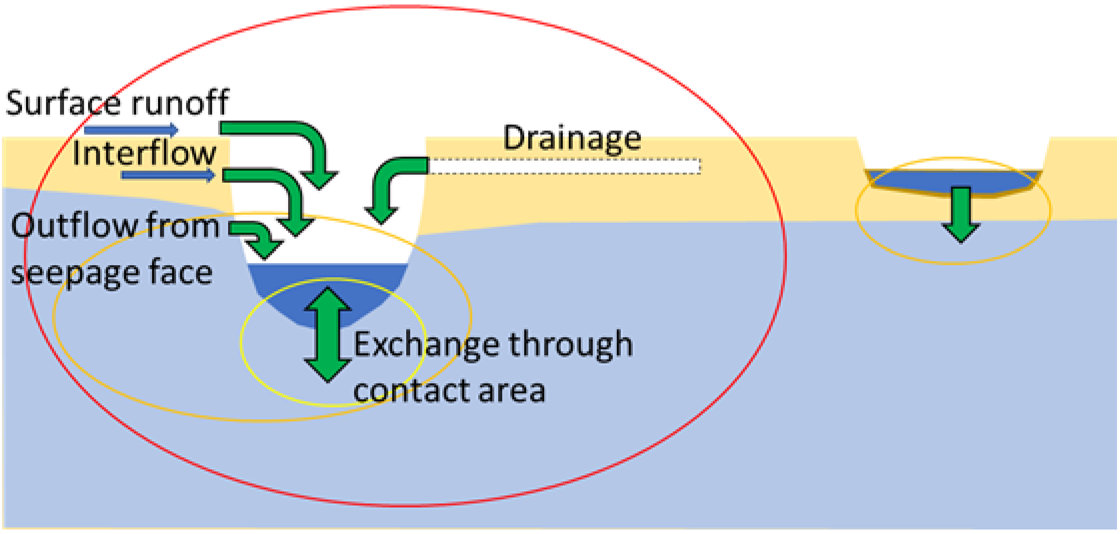

Figure 3.3 Various scopes in groundwater - surface water exchange (indicated by ellipses of different color; groundwater is light blue; surface water dark blue)

A special case is hyporheic exchange, which does not result in a net flux but is ecologically important (see e.g. Woessner, 2017). Hyporheic flow is flow in a stream bed of water that originates from the stream and flows back into the stream. For streams with large head gradients and meanders the water may flow back further downstream, while the return flow occurs at a later time after recession of the water level in the stream after a flood. In the streambed and floodplain mixing of the stream water with groundwater may occur.

The influence of surface water may be included in different ways in groundwater flow modelling:

- Implicitly as is done in simulating groundwater head time series with a transfer function noise model; the transfer functions reflect the surface water control together with other properties of the groundwater system;
- Explicitly as the outflow of a groundwater reservoir in lumped modelling;
- Explicitly using spatiotemporal boundary conditions as done in distributed groundwater modelling.

The latter may be formulated as a prescribed head, a prescribed flow or a combination of these two. According to Jazayeri & Werner (2019) the following names apply for the versions of the spatio-temporal boundary conditions:

- Type 1: Dirichlet – specified head;

- Type 2: Neumann – specified flux;
- Type 3: Robin – linear combination of specified head and flux.

The boundary conditions may be non-linear. The most common form is piecewise linearity in which the exchange coefficient has different values for separate ranges of the groundwater head. Examples are the MODFLOW (McDonald & Harbaugh, 1988; Harbaugh & McDonald, 1996); Harbaugh et al., 2000; Harbaugh, 2005) packages DRN and RIV and combinations of these (Zaadnoordijk, 2009). The GHB package implements a linear combination of head and flux (Robin boundary). Causes of non-linearity are change of the surface water – groundwater contact area and formation of seepage zone depending on the groundwater head (see e.g. Rushton 2007).

In addition to non-linear relations, the parameters of the surface water interactions may change in time. This occurs e.g. when the surface water bottom changes due to dredging, sedimentation, or clogging.

More complex schematisation of the groundwater – surface water interaction can be used in integrated models using e.g., SHE (Abbott et al., 1986), NHI (De Lange et al., 2014) or HydroGeoSphere (Therrien & Sudicky, 1996). The surface water is no longer an external model boundary like it is in a pure groundwater model but may be an internal boundary to which specific conditions apply. Moreover, it is still necessary to choose a conceptualization in order to extract the groundwater – surface water interaction from the results of such an integrated model. In practice, an integrated model is necessary when the interaction has an important influence not only on the groundwater but also on the surface water.

Note that simulation programs like Mike SHE do allow the user to create simple non-integrated groundwater models as well, allowing to start simple and gradually increase the complexity of the model together with the growing understanding of the groundwater system (together with available data of the physical groundwater system).

The goal of the simulations determines which fluxes need to be separated and which detail in time or in space is needed. This will vary strongly for e.g. change of the long-term water balance, evaluation of agricultural water supply during the growing season, or impact assessment for riparian ecology of climate change.

3.3.3 Shallow and deep groundwater

In many groundwater systems, there are multiple aquifer systems (see figure 3.2) and the impact of climate change on shallow aquifers and deeper (often confined) aquifers are not alike. Here, we define a shallow aquifer, or shallow groundwater (not necessarily being an aquifer with high permeability), as the level of the upper most groundwater, in figure 3.2 noted as the groundwater table. Deeper aquifers often have different groundwater heads (level) and react differently to climate change than the shallow groundwater. The shallow groundwater table or level is sometimes referred to as the phreatic surface. Depending on the purpose of the simulations, a particular aquifer may be more important and be modelled in more detail in an integrated model. Often, deeper groundwater levels react slower to weather events than the shallow groundwater where a clear correlation to precipitation events are often observable. The shallow groundwater in humid areas is often to some degree controlled by drainage from natural, e.g. surface waters, and anthropogenic drainage systems, storm sewers, tile drains and ditches. The fluctuations of the deeper groundwater levels, far away from discharge zones, can be more sensitive to climate change and thereby show a higher change signal. In order to make intercomparable results, it is therefore important to indicate if results from an integrated model represent shallow, deep, or something in between because they are not necessarily alike. Also, the spatial distribution of the changes simulated are often different for the shallow groundwater table and the one representing deeper conditions.

3.3.4 Groundwater dependent ecosystems

Groundwater dependent ecosystems are sensitive to phreatic groundwater levels. In addition, they may have groundwater quality requirements (e.g. pH or iron content) for which upward seepage of (deeper) groundwater is needed. The importance of proper function of these ecosystems is underlined by the EU Water Framework Directive, Natura 2000, and Habitat Directive. This means that the groundwater conditions have to be modelled in detail which may require feedback between groundwater level and evapotranspiration and lateral leveling out of the phreatic surface due to flow at the surface and interflow.

Impacts of climate change on groundwater and surface water systems will directly affect groundwater dependent ecosystems (Earman & Dettinger, 2011; Kløve et al., 2012, 2014). Impacts will depend on the extent of change in groundwater and surface water levels, but also on location in the landscape and land use changes.

To assess impacts of climate change on groundwater dependent ecosystems it is necessary to evaluate all pressures and their potential consequences. Apart from direct impacts of climate change on groundwater and surface water regimes - as a consequence of change in precipitation distribution, evapotranspiration and surface runoff, there are also other indirect influences such as land use changes and changes in groundwater abstraction for irrigation in response to droughts induced by CC. These can considerably affect groundwater balance and consequently GWDEs. Ideally, all these factors should be included in the integrated assessment. However, the lack of information, e.g. groundwater withdrawals and use, renders quantification a difficult but necessary challenge (Treidel et al., 2012), usually limits the scope of assessment to the analysis of changes in groundwater balance due to climate change induced changes in groundwater recharge and their impact on groundwater dependent ecosystems.

The potential impact is scale-dependent. Groundwater dependent ecosystems fed by local and intermediate scale aquifer systems are expected to be more affected by climate change induced changes in groundwater hydrology than those connected to regional scale aquifer systems with flow paths on the order of many tens of kilometers (Waibel et al., 2013). The propagation of climate change signals in numerical groundwater flow models provides essential insights in how particular aquifer system will react to projected climate change. However, to evaluate the comprehensive impact of groundwater level changes on any particular groundwater dependent ecosystem, it is critical to consider its ecological needs in terms of both groundwater quality and quantity. As illustration, the effects on some trees may be negligible in the case of a general decrease of groundwater level, while, on the contrary, it may as well provoke a total extinction of the original ecosystem (Naumburg et al., 2005).

3.3.5 Groundwater flooding and drought

Climate change can influence precipitation amounts, timings, and intensity, and indirectly affect the storage of water in surface and subsurface reservoirs. The greater variability in rainfall could lead to more frequent and prolonged periods of high or low groundwater level, which may cause groundwater flooding, or groundwater drought. Groundwater flooding occurs because of water rising up from the subsurface reservoirs towards the surface. This tends to occur after much longer periods of sustained high rainfall. On the other side, groundwater drought typically refers to a period of decreased groundwater levels, which lead to problems to meet the underground water needs for humans and the environment.

The groundwater sensitivity to climate change and meteorological extreme events varies according to the aquifer system. Sensitivity is very low in confined groundwater reservoirs whereas in the case of unconfined groundwater reservoirs (phreatic aquifers) several configurations can be encountered. Indeed, karstic aquifers could be very sensitive to seasonal meteorological droughts and rainy intense events; whereas the great extension phreatic aquifers having a significant inertia (i.e. chalk aquifers) will be more sensitive to a wet year's succession or a succession of dry years. As extreme events are expected to increase under future climate, hence the interest of using the integrated groundwater models to assess the effects of climate change on the evolution of the groundwater flood/drought occurrence.

Groundwater flooding usually occurs as a response to extreme precipitation and has a time scale of hours to days, which is much less than the relevant time scales for most other groundwater related issues. Therefore, other processes are important, and the schematization groundwater recharge has to be adapted e.g. by including routing of precipitation, water repellency of the soil and surface ponding.

Drought has a longer time scale but does trigger additional processes too. Wilting or even dying of vegetation reduces evaporation. Drying of the soil may induce cracks, which cause the precipitation after the drought to infiltrate directly into the deeper subsurface and provide very little moisture to the soil. During extreme drought, the groundwater flow can be influenced by the increase of hydraulic conductivity related to higher temperatures. Also, anthropogenic water use will increase. This may especially impact deeper groundwater heads.

3.3.6 Results from climate change assessments

Relevant quantities for climate change assessment are:

- Groundwater table (elevation with respect to datum like mean sea level);
- Depth of the groundwater table (previous value subtracted from the surface elevation);
- Groundwater heads (elevation with respect to datum; in deeper layers);
- Various recharge fluxes (length per time = volume per area per time);
- Fluxes between groundwater and surface water (totals or separated into sub-fluxes as described in sub-section;
- Depending on additional processes included in the model other specific quantities such as sea water intrusion, water quality changes, subsidence, agricultural yield (losses).

The quantities should be calculated for the reference period and for the climate change scenario(s). The quantities have both temporal and spatial aspects.

Temporal aspects

For long-term averages, steady state calculations can be appropriate if the system is sufficiently linear. For strongly non-linear models, transient calculations are necessary even for the calculation of long-term averages (e.g. Witte et al., 2019). This does not only depend on the physical non-linearity of the system, but also on the understanding of the system and available data.

Transient calculations are necessary to account for variability. In many cases, the seasonal variability will be important with more risk of water shortages in summer and in winter more risk of groundwater flooding. In general, flood risks require a higher temporal resolution (e.g. days) than risk of water shortage during droughts (e.g. weeks). Risks of extreme events and return times require a long period (minimally the 30 years of the climate definition, but preferably 100 years for which both data for a reference period and a climate projection are needed).

It should be noted that the effective model parameters depend on the temporal schematization, e.g., because it influences the surface water exchange fluxes that are calculated. This relates mostly to the separate quantification of flux in both directions instead of calculating the net exchange. This may be illustrated by the hyporheic exchange connected to a flood wave in a river: no exchange will be calculated if monthly time steps are used when the infiltration into the ground and subsequent exfiltration takes place within days.

The relevant time resolution is related to the output or analysis time steps. The calculation timesteps in the numerical scheme of the simulation software may be much smaller in order to get a numerically accurate solution. Depending on the output time steps, it may be important to distinguish between instantaneous or time integrated or averaged values. For flooding, peak values are more important while integrated fluxes are needed for water balance assessments.

Spatial aspects

The spatial resolution has different aspects:

- The amount of detail in the geography (long straight-line segments – detailed area of river bed; e.g. for major rivers or large lakes);

- Inclusion of all individual surface water features or representing spatially averaged effect (e.g. for fine drainage network).

- Subgrid processes are not simulated (e.g. only net flow from groundwater to surface water instead of both outflow and inflow).

In the Netherlands, drainage and surface water networks often have a finer resolution than groundwater models. This makes it more efficient to use one effective boundary condition (a so-called 'top system' per point, node, or cell) than to represent the influence of each drain, ditch, and stream individually. Several authors have published analytic solutions which are used to calculate the parameters of a Robin boundary condition for the top system of a regional distributed groundwater model to reflect a dense system of drains or ditches (Ernst, 1978; Bruggeman – see Kovar & Rolf, 1978; de Lange, 1996).

Schematization as a line (or string of model nodes or cells) is appropriate for rivers and canals that are much longer than the model resolution, but have a width that is smaller. In this case longitudinal variations can be included, but the transverse variation is lumped together with an effective width. The model will produce a net value per river section while there may be both exfiltration and infiltration depending on regional flow and local groundwater abstractions. Other models do not use the size of the numerical grid as river minimum width but simulate rivers "between" numerical grid cell as a 1D models (Mike11/Mike Hydro integrated in Mike SHE). In the 1D model, cross-sections define the widths of the river.

When not only the length but also the width of surface water is larger than the model resolution, details of the variation can be specified in all directions. Benoit et al. (2019) and Ghysels et al. (2019) give an example of a very detailed schematization of an individual river bed. In such a case, the model will produce insight in the local variation in exchange fluxes, which may be important for groundwater quality issues.

Uncertainty

Confidence or uncertainty assessment is an essential part of (groundwater) modelling (e.g. Hill & Tiedeman, 2007). It feeds the cyclic process that modelling necessarily is, because of the invisibility of the groundwater and the subsurface and the limited data that is available. Usually, the a priori knowledge of model parameters is insufficient and needs to be improved by calibration of model output with independent observations. Also, it is impossible to determine beforehand how accurate results will be for a specific schematization. So, model output is necessary to determine whether required assessments can be made, e.g., if future water shortages under climate change can be determined accurately enough to decide that measures are necessary or to decide on the budget for the design of measures.

For climate projections, it is especially important to include the assessment of the model schematization and the included processes. The more the climate scenarios differ from the reference situation, the more likely it is that more processes need to be included or that different effective values are needed for a parameter. An example is the use of a single crop factor evaporation coefficient to determine actual evapotranspiration from data available for reference evaporation (see e.g. Allen et al., 1998). This is reasonable when the actual evapotranspiration is not limited by water shortages. So, crop factors for the reference period cannot be used for a climate change scenario if water shortage increases strongly in a climate change scenario. A simple solution would be to use different values of the crop factors. However, it may be more appropriate to use a different description for evapotranspiration in the model, that does account for evaporation reduction when crops have water stress.

3.4 Case studies/Examples

Table 4.1 lists examples where integrated models are used to assess effects on groundwater conditions from climate change. The tools used for the assessment as well as the general issue (focus) addressed in the examples are noted. The full assessment report for each example is also a link in the table, where the full detail of the modelling tool, available data, applied climate change data both the TACTIC standard climate change data and others used, are documented.

Table 3.1 Examples of integrated modelling

Example/pilot Name	Tool used	GW focus	Hyperlink	Scale and model grid size
Avre Basin, France	Marthe	Shallow / Deep	link	Catchment
Boutonne, France	Marthe	Shallow / Deep	link	Catchment
De Raam, The Netherlands	iMOD	Shallow / Deep	link	Catchment / Country
Denmark	Mike She	Shallow / Deep	link	Country
Drava Mura, Croatia	MODFLOW	Shallow / Deep	link	Catchment
Hungary	MODFLOW	Shallow / Deep	link	Country
Gort Lowlands, Ireland	'High Resolution GDHC Ireland	Shallow	link	Catchment
Segura, Spain	MODFLOW	Deep	link	Catchment
Storåen Sunds, Denmark	Mike She	Shallow / Adaptation	link	Sub-Catchment

Upper Guadiana	MODFLOW	Deep	link	Catchment

3.5 Conclusion

Hydrological modelling is necessary for the assessment of the impact of climate change on groundwater and groundwater resources. The choice of model schematization, temporal and spatial resolution does not only depend on the groundwater system and the goal of the modelling but also on the understanding of the system, the available data, and the time and resources available for the assessment.

The developed method for selection of climate change scenarios provides a basis for a uniform assessment of climate change effects throughout Europe.

For assessment of climate change, a period of at least 30 years needs to be considered to capture the meteorological variability associated with the climate.

Evaluation of the model and model output are an essential part of the modelling process. Without it, the value of the output remains unknown and the results cannot be used. Groundwater modelling is a cyclic process, which makes it important to store and make available model information.

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BLOCK III: ESTIMATING GROUNDWATER RECHARGE (WP4)

4. Groundwater Recharge

4.1 Summary

Infiltration recharge is the main driver of groundwater flows within an aquifer system. There are several methods used to estimate the recharge values. These methods could be based on conceptual representations of the water processes or could be based on the analysis of the groundwater level time series. In this section we discuss the application of a number of recharge calculation tools that belong to these two groups. However, we start by the definition of recharge types and in this application, we limit them to three types: potential recharge, actual recharge groundwater table and actual recharge groundwater aquifer. This is required because the applied tools deal with different types of recharge.

As it may not be possible to calibrate the recharge models, recharge estimation is usually associated with a lot of uncertainty. We therefore highlight the importance of the application of multiple recharge tools to be able to quantify the uncertainty. A list of case study reports is also provided here together with the important notes the user must be aware of while using the presented tools.

4.2 Introduction and definition of recharge

Recharge is defined as the downward flux of water infiltrated at the ground surface towards the water table (Fitts, 2013) after accounting for soil storage and evapotranspiration. Since this flux of water may get diverted at depth, it may not reach the water table within the aquifer. In addition, part of this water may get held by different groundwater horizons within a layered aquifer system. Thus, the recharge will differ depending on where in the subsurface the infiltrating water is perceived as recharge, and terminology may therefore be unclear or imprecise.

In the TACTIC project we distinguish three types of recharge to provide a transparent approach that allows the comparison of recharge values estimated using the different applied recharge calculation tools. Figure 4.1 shows these three recharge types as calculated from the ground surface and downward. The uppermost is the potential recharge (Type 1), which is effective precipitation minus soil storage. Part of the infiltrating water may get diverted laterally due to preferential flow paths and hydrogeological heterogeneity. The amount of water that reaches the phreatic water table in an aquifer is defined as actual recharge GW-Table (Type 2). The final recharge type is defined based on the infiltrating water going through aquitards and reaching the deep groundwater system. This recharge is referred to as actual recharge GW-Aquifer (Type

3). Depending on the geological setting actual recharge GW-Aquifer, may occur at several depths, when there are multiple deeper aquifers interlayered by multiple aquitards.

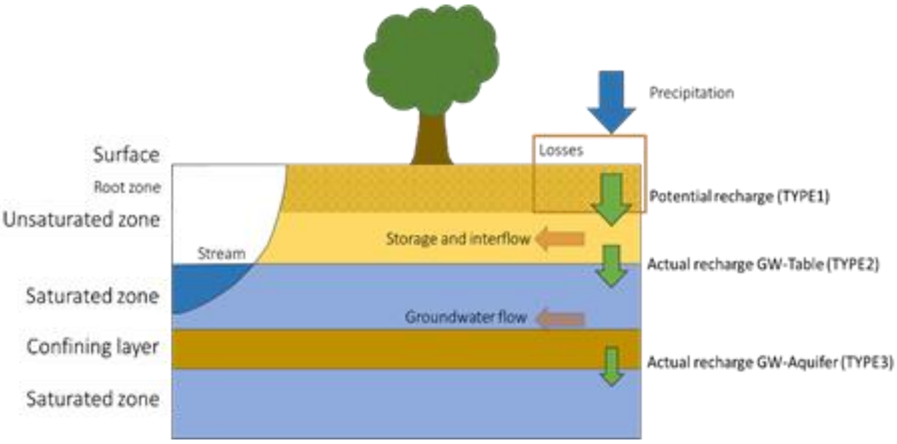


Figure 4.1: Definition of the recharge types used in the estimation of recharge in TACTIC

While the schematic shown in Figure 4.1 clearly shows the three different recharge mechanisms illustrated in green arrows, it must be noted that the data used in the different tools and the approach followed to calibrate them dictates the recharge type each individual tool produces. For example, applying a recharge calculation tool that uses groundwater level fluctuations obtained from boreholes drilled deep into aquifers will produce recharge estimates of Type 2 or Type 3. Applying a different tool that includes climate data and soil storage at the same location will produce an estimate of water infiltration at the ground surface that can be defined as Type 1. It is expected that, at the same location, Type 1 recharge estimates are always higher than Type 2 and Type 3 recharge estimates.

4.3 Methodology on selecting recharge tool

The toolbox developed in the TACTIC project includes a number of tools that can be used to estimate the recharge values. In this section we focus on the tools that are used to estimate recharge values at the selected pilot studies. We provide a brief description of the methods based on which these tools are built, and we provide recommendations regarding their use.

4.3.1 Methodology of the different tools used in estimating recharge in TACTIC

AquiMod is a lumped parameter computer model that has been primarily developed to simulate groundwater level time-series at observation boreholes (Mackay et al., 2014). The simulation is driven by weather data including rainfall and potential evaporation. These drive numerical representation of flow movement in three modules representing the soil zone, the unsaturated zone and the saturated zone to calculate groundwater fluctuations at the borehole. AquiMod is designed to simulate groundwater levels, the soil zone module calculates the infiltration recharge, evapotranspiration, and runoff components of the water balance. It calculates recharge estimates as a bi-product for the simulation of groundwater levels.

AquiMod is usually run in Monte Carlo mode in order to optimise the hydraulic parameter values of the different modules. Its execution time is insignificant, which allows the execution of many simulations in relatively small time. The user can use dotty plots, plots that show the value of performance measure against the hydraulic parameter values used in the Monte Carlo simulation to select an optimised value that produces the best model performance.

The computer code GARDÉNIA (modèle Global A Réservoirs pour la simulation des Débits et des Niveaux Aquifères) is a lumped hydrological model for the simulation of relationships between time series of stream or spring flow data at the outlet of a watershed, and/or groundwater level data at an observation, and the rainfall received over the corresponding catchment. Groundwater abstractions can be included if necessary. GARDÉNIA determines the hydrological balance for the basin: actual evapotranspiration, runoff, infiltration, recharge. The hydrological balance can be used for the evaluation of groundwater recharge of aquifers (TYPE 2). The model allows for the calibration against one time series or two time series of observations at once. These are river flows at the basin outlet and representative groundwater levels at an observation well located in the basin.

GARDÉNIA allows an automatic optimisation of the hydraulic parameter values involved without any interference from the user. This functionality gives this model the advantages of ease of setup and seamless optimisation approach.

Transfer noise (Metran): Metran is a software program for modelling groundwater head time series using a Transfer Function-Noise approach with precipitation and reference evaporation data (Zaadnoordijk *et al.*, 2019). The precipitation transfer function is a three-parameter function based on the gamma distribution, which is a flexible unimodal function. The response to the reference evaporation is the same, except for a multiplication factor (fc). As AquiMod and GARDÉNIA, Metran is primarily used to provide explanation to the variation of groundwater heads. The recharge can be then calculated using the multiplication factor as proposed by Obergfell *et al.* (2019). The recharge (R) is calculated as the rainfall (N) minus the reference evaporation (E) multiplied by the evaporation factor (f_e):

$$R = N - (f\_e * E) \qquad \textbf{Equation 4.1}$$

Similar to GARDÉNIA, Metran optimises the values of all parameters involved automatically and provides the user with feedback regarding the performance of the model. The user can assess the validity of the simulation based on this feedback.

Hydrological models NAM, SACRAMENTO, and HYPE:

The NAM model (Nielsen *et al.* 1973) is a lumped conceptual catchment model based on four water storage compartments where water is moved through the system using nine empirical parameters. Recharge is calculated as the water moving from the root zone storage to the groundwater storage.

HYPE is a semi-distributed conceptual hydrological model, which was developed in Sweden, and is now used as the national Swedish hydrological model for discharge and nutrient loads, S-HYPE (Strömqvist *et al.* 2012). The S-HYPE model is used extensively in Sweden and multiple uses have been well documented. In this study, the recharge in HYPE reflects percolation to the groundwater table (TYPE2), where the calculation of net precipitation employs a generalised empirical relationship for evapotranspiration that has been calibrated for the national model (involving a water balance of c. 400 catchments).

The SACRAMENTO model was used in Spain, where it provided the input of groundwater recharge (TYPE2) to the local MODFLOW model setup for the Upper Guadiana Basin (Collados-Lara *et al.* 2021 and Surge 2018).

The Irish recharge calculation based on recharge coefficients: a national recharge map was derived by the Geological Survey of Ireland (GSI) based on existing hydro-geological and meteorological data layers (Hunters et al., 2013). The meteorological data include rainfall and actual evapo-transpiration. The hydro-geological controls on groundwater recharge include the permeability and thickness of superficial deposits, the presence of saturated soils, and the ability of the underlying aquifer to accept percolating waters. A recharge coefficient is established for different hydro-geological scenarios based on combinations of these factors. Spatially distributed values of recharge coefficients are obtained for the different GIS layers used to characterise the hydro-geological settings.

Hydrodynamic models, distributed recharge models, and integrated groundwater flow models: these types of models are usually applied at a large scale either to calculate spatially distributed recharge or to study the movement of groundwater flows at regional scale. BRGM's MARTHE code (Thiéry 2015b, Thiéry *et al.* 2018) is an example of hydrodynamic model and integrated groundwater models where both groundwater flows can be simulated in the saturated and unsaturated zones. Recharge estimates can be obtained as a bi-product of the applications of these models. The Irish model (Hunters et al., 2013) discussed in the previous section and the Zooming Object-Oriented Distributed Recharge Model ZOODRM (Mansour et al, 2018) are examples of models that are built to produce spatially distributed recharge. These models produce infiltration recharge at are driven by hydrogeological data that are translated into factors that control the amount of infiltrated water.

Selection of recharge calculation tool: there are many reasons that require the calculation of recharge values. These include: driving a groundwater model for a specific environmental query or to validate a conceptual model, simulating groundwater flows for groundwater water resources, assessing the status of groundwater resources under future climate data, etc. This could be required at different spatial and temporal scales. The methodology based on which the different tools are built assist to identify whether a tool is suitable for a given application or not. For example, it is necessary to use a distributed recharge model to correctly represent the impact of surface heterogeneity on the estimated recharge values across a large size case study. On the other hand, it may be adequate to use a lumped model to calculate recharge at a point location and then use this recharge estimate to drive a numerical model to simulate flows in a relatively small size catchment. An integrated model adds the benefits of calculating actual recharge volumes as they arrive at the water table, i.e. after attenuation through the unsaturated zone.

The TACTIC toolbox (see Section 1) includes several lumped models that calculate recharge values at a point location or borehole scale. It is not possible to recommend the use of one tool on another, especially AquiMod and GARDÉNIA, as they are very close in their design. However, GARDÉNIA has the advantages of optimising the hydraulic parameter values using the river discharges and also closing the water balance during the calibration process. AquiMod, on the other hand, uses a Monte Carlo approach to optimise the hydraulic parameters. This produces a number of simulations with parameter values that are equally likely. By accepting all the simulations with a performance measure bypassing a set up threshold, it is possible to estimate the uncertainty associated with the estimated recharge values. While Metran produces a long-term average recharge estimate at a borehole, it has the advantage of highlighting the hydrodynamic characteristics of the hydrogeological system. In addition, it is possible to increase the level of model complexity to simulate the fluctuations of groundwater levels in boreholes situated in complex hydrogeological systems.

4.4 Notes on the use of some tools presented in the TACTIC toolbox

This section provides a couple of notes that need to be considered when applying some of the tools included in the TACTIC toolbox.

AquiMod: this model uses groundwater fluctuations to optimise the hydraulic parameter values and does not use the groundwater discharges produced by the saturated module. This may lead AquiMod to estimate an unreasonable storage coefficient value for the aquifer. It is recommended, therefore, to use AquiMod in Monte Carlo mode and produce as many simulations as possible that have an acceptable performance measure and then estimate a range of possible infiltration recharge quantities. The storage coefficient values of all acceptable simulations must be checked against the hydrogeological characteristics of the studied aquifer before the selection of the simulations used to calculate the recharge values. Mackay et al. (2014) state a number of limitations associated with the application of AquiMod. Most importantly is that the model does not account for any source of water other than rainfall. Therefore, an important condition to successfully apply and calibrate AquiMod is to select a borehole with groundwater levels that are not influenced by the presence of any surface feature that may provide water to the aquifer such as rivers and lakes.

GARDÉNIA: this model includes an interface that simplifies the process of building up a model. The optimisation of hydraulic parameters is also done automatically, which adds to the ease of model use. It must be noted that groundwater flows can take a slow or a fast path or both at the same time to reach the discharge point. The model may have the tendency to prioritise one path, or another so care must be taken if this happens.

Metran: This model uses a factor to estimate the amount of recharge using two different equations based on whether this factor is greater or below unity. It may be tempting to use these formulae to produce a time series of recharge values as the rainfall and potential evaporation time series are available. However, it has been advised that this model is used for the calculation of long-term average recharge values only.

The GSI recharge tool: The authors indicate that this is a GIS-based tool for making initial estimations of recharge as part of a project desk study and should not replace the detailed hydrogeological characterization and recharge assessment that are required at any study site. However, the highly transparent data content of the used map allows the user to establish what that map represents, which allows the adaptation of the map output with site specific geological and meteorological data.

Hype: There are no known Hype-specific warnings to watch out for. The model code is open source and describes hydrological processes; however, the algorithms are not purely based on physical laws but of more conceptual nature. The S-HYPE model is continuously developed and improved.

Sacramento: The Sacramento (SAC-SMA) model is a continuous lumped rainfall-runoff model that uses soil moisture accounting to simulate the water balance within a catchment (Balvanshi and Tiwari, 2015; RRL User Manual, 2004). It allows estimating groundwater recharge as a function of the storage in the upper and lower zones by using only rainfall, evaporation and streamflow data. Three of sixteen parameters are used to calculate the percolation of water to the lower stores, but the parameters related to soil and upper stores are important to obtain a correct balance. The calibrated parameter values of a specific catchment is unique to the climate, topography, geology, soil and vegetation type and it should not be transposed to other catchments (RRL User Manual, 2004 https://toolkit.ewater.org.au/Tools/RRL/documentation).

4.5 Recharge tool chart

The recharge tool chart (Figure 4.2) is based on the TACTIC Toolbox (See Section 1.). The Recharge Tool chart was created to facilitate a better overview of the tools, when the main interest is recharge estimation. The chart therefore is focusing on inputs and recharge products generated by the tools. This means that it is structured on required/type of input to the tool and identifies the type of output following the definition of recharge types seen in Figure 4.1. The chart consists of an excel sheet (the Recharge Tool Chart) and can be seen in Figure 4.2.

Knowing the end recharge product from a given tool will help partners decide on an appropriate tool for their assessments, as well as enabling a meaningful comparison of the various results and thus a correct compilation of the pilot results at European scale.

A few of the tools generate an additional type of recharge not described in section 4.2, but this type was necessary to include here. This type is called the minimum recharge. The minimum recharge is different from the other terms by the fact that it does not have a physical meaning in the subsurface flow system. The terminology was adapted to encompass the recharge results from signal treatment methods (Lanini and Caballero, 2016). These methods are based on time series of stream flow, where the groundwater component of the stream flow (baseflow) is filtered out and is assumed equivalent to the groundwater recharge over a substantial amount of time. It is thus the minimum recharge needed to the connected groundwater system to sustain the measured baseflow in the stream.

The chart was filled out by all TACTIC partners that have provided a tool to the TACTIC Toolbox that can estimate recharge. Explanations to the different part of the chart are given here:

Main data: These columns of the chart describe the data needed for the tool. Note, that it is not the complete list of input as that would be too extensive, but rather the climate/measurement data basis.

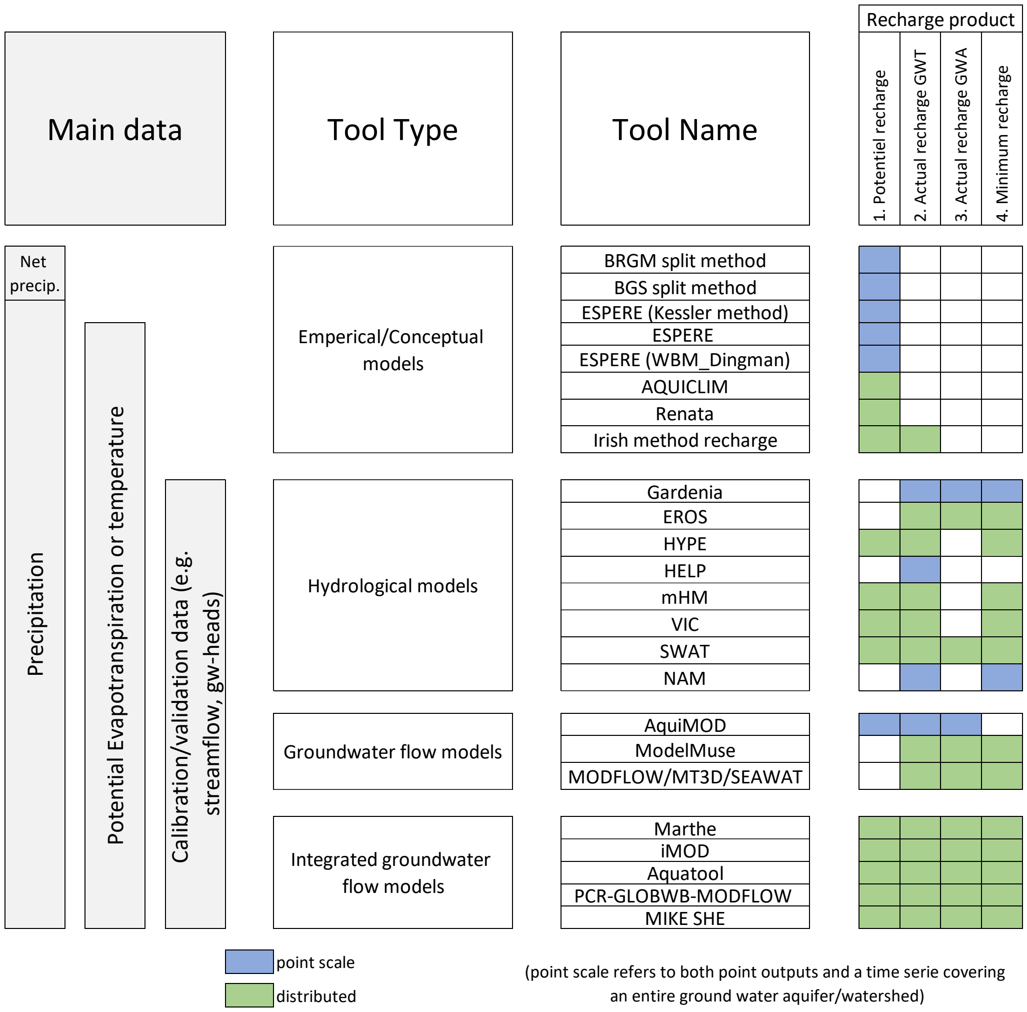
Tool type: In this column, tools are classified into different types. There are numerous ways to categorize tools and models in the literature, and nomenclature is not always consistent. In the first part of the chart, the Climate data driven tool types are listed from the simpler conceptual approaches at the top and more complex modelling systems at the bottom.

Empirical/Conceptual models cover all models and tool that are not process-based. It includes empirical equations based solely on climate data and water balance methods relying on climate and few parameters, as well as index methods. The next three categories cover process-based tools and models differentiated by the hydrological systems they characterize. Hydrological models are models that focus mainly on surface water processes, where rainfall-runoff models are good examples. Groundwater flow models cover mainly groundwater processes and thus not extensively include a surface water part. Integrated groundwater flow models, these models integrate both a surface water and groundwater part.

The next six tool types are all direct measurement driven. They cover both analysis methods for *transport* data (heat, isotopes and tracers) and filtering and fluctuation methods for hydrological data. For some of the tools, the resulting recharge output may depend on where the measuring has been done, e.g. the water table fluctuation methods. Here measurements may come from a phreatic or non-phreatic aquifer and therefore the tools provide a recharge estimate of either actual recharge to ground water table (GWT, Type 2) or actual recharge to aquifer (GWA, Type 3).

Tool Name: Here the tool names are listed. Some tools appear more than once, because they include several tool options.

Recharge product: In these columns colored cells indicate what recharge product the tool can produce. There are four different recharge products and the definition of them is found in section 4.1. A color coding is used, where blue is used for recharge output on point scale. Point scale in this case refers to both point output and a time series representative for an entire groundwater aquifer/watershed. The green color is used when the recharge output from the tool is spatially distributed.



Tool Type	Tool Name	1. Potentiel recharge	2. Actual recharge GWT	3. Actual recharge GWA	4. Minimum recharge
Emperical/Conceptual models	BRGM split method	🟦			
	BGS split method	🟦			
	ESPERE (Kessler method)	🟦			
	ESPERE	🟦			
	ESPERE (WBM_Dingman)	🟦			
	AQUICLIM	🟩			
	Renata	🟩			
	Irish method recharge	🟩	🟩		
Hydrological models	Gardenia		🟦	🟦	🟦
	EROS		🟩	🟩	🟩
	HYPE	🟩	🟩		🟩
	HELP		🟦		
	mHM	🟩	🟩		🟩
	VIC	🟩	🟩		🟩
	SWAT	🟩	🟩	🟩	🟩
	NAM		🟦		🟦
Groundwater flow models	AquiMOD	🟦	🟦	🟦	
	ModelMuse		🟩	🟩	🟩
	MODFLOW/MT3D/SEAWAT		🟩	🟩	🟩
Integrated groundwater flow models	Marthe	🟩	🟩	🟩	🟩
	iMOD	🟩	🟩	🟩	🟩
	Aquatool	🟩	🟩	🟩	🟩
	PCR-GLOBWB-MODFLOW	🟩	🟩	🟩	🟩
	MIKE SHE	🟩	🟩	🟩	🟩

(point scale refers to both point outputs and a time serie covering an entire ground water aquifer/watershed)

Figure 4.2: The recharge tool chart. The chart shows main data necessary for running the tools, followed by the tool type and name. The recharge product (1-4) is indicated by the colored field, colors indicate scale of application.

4.6 Case studies/Examples (multiple tools)

Table 4.1 lists the pilot case studies where multiple tools are applied to estimate recharge. These tools use time series analysis or conceptual approaches that divide effective precipitation into recharge and overland flows at different scales ranging from borehole scale to regional and national scales. The full assessment report for each case study can be accessed through the corresponding link provided in the table. A full description of the tools applied, the methodology and data used are provided in these reports.

Table 4.1 List of pilot case studies where recharge calculations tools are used to estimate the recharge values.

Example/pilot Name	**Tool used**	**Recharge calculation type**	**Hyperlink**	**Scale and model grid size**
Finland	GSI tool	Distributed	link	National
France	Multiple	Time series and distributed	link	National / Borehole
De Raam, Netherlands	Multiple	Time series and distributed	link	National / Borehole
South East Midlands aquifers (Ireland)	Multiple	Time series and distributed	link	National / Borehole
North East Po Plain (Veneto Plain) (Italy)	Lumped	Time series	link	Borehole
Posavina (Serbia)	Lumped	Time series	link	Borehole
Continental Spain	IGME tool	Distributes	link	National
Kinda and Böda (Sweden)	Multiple	Time series	link	Borehole
Chalk aquifer (UK)	Multiple	Time series	link	Borehole
Magnesian aquifer (UK)	Multiple	Time series	link	Borehole
Permo-triassic aquifer, (UK)	Multiple	Time series	link	Borehole
Devonian aquifer (UK)	Multiple	Time series	link	Borehole
Jurassic aquifer (UK)	Multiple	Time series	link	Borehole

4.7 Conclusion: Pitfalls, pros and cons

Infiltration recharge is the main driver of groundwater flows within an aquifer system. Its assessment is crucial to undertake groundwater simulations required for groundwater management or groundwater protection. There are several methods followed to estimate the recharge values and these are usually selected based on the type of the problem being investigated. These methods could be based on conceptual representations of the water infiltration and the partitioning of water into overland flows, interflows, deep water percolation etc. or could be based on the analysis of the groundwater level time series for example the use of lumped compartmental models, impulse function models, analytical models etc. While the latter group of models uses an automatic / objective approach to calibrate the hydraulic parameters, there are still many factors that introduce error in the calculation of recharge. For example, the methodology followed is not complex enough to represent the hydraulic system accurately, reproducing the groundwater fluctuations but with incorrect hydraulic parameter values, etc. The first group of models includes many subjective decisions taken during the development of the conceptual model, sometimes called expert judgement, that introduce a lot of uncertainties in the estimation of recharge values.

Constraining uncertainty while estimating recharge is difficult in both model groups lumped or distributed. In lumped models, the calibration is automatic; however, in this case uncertainties are introduced when upscaling the estimated recharge estimates from borehole scale to regional scale. For the distributed recharge models, it is hard to calibrate the model parameters because no observed recharge values are available and soil moisture profiles are rarely obtained. It is only when the groundwater flow simulator is used, that it is possible to evaluate the validity of the recharge values used to dive it.

The application of multiple recharge tools highlighted the possibility of producing significantly different recharge values at the same location from the different tools. This document highlights the need to differentiate the type of the estimated recharge from the different tools. The tools we discuss focus mainly on infiltration (diffuse) recharge that can be potential recharge, i.e. not necessarily reaching the water table, or actual recharge, which is reaching either the surface or the deep water tables. However, this application showed different recharge estimates from different models for the same type of recharge. It is recommended therefore to apply many tools if possible and calculate a range of recharge values, which will allow the researcher to discuss his work according to the bounds of uncertainty obtained from the application of these tools.

For the calculation of diffuse recharge, the use of distributed recharge models is more preferable to the use of lumped models. The distributed models allow the inclusion of spatial heterogeneity in landuse, soil characteristics, hydrogeology etc. and that will ensure a better representation of recharge processes spatially; however, it is recommended that these calculations are backed up with recharge estimates obtained from lumped models to evaluate the validity of the distributed recharge values as explained above. It must be noted, however, that the lumped models may have the advantage of attenuating the pulse of the recharge signal due to the presence of the unsaturated zone.

The models discussed in this section are also used to estimate recharge values under future climates. The estimated recharge values have to be used within the assumptions and limitations discussed in Section 2. In addition, it is recommended that the user be aware of the following observations when applying models to analyse time series change to long-term time-series evaluation for climate change effects. First, change in measurement frequency: often historic data contain decades of manual observations with low sampling frequency (once a month), which are recently taken over by high-frequency logger sampling. The data abundance of the recent period may cause strong bias and be mistaken for a climate change effect. Second, changes in land use, for example forest-growth cycles and drainage maintenance, or to the stand-pipe installation, for example deteriorating functionality, casing reference, etc., may cause an impact that can be mistakenly attributed to climate change effects. It may be difficult, therefore, to draw conclusions from the analysis of time series if the overall picture of the case study area is not very well known.

5 Impact on groundwater levels

5.1 Summary of vulnerability analysis

The vulnerability of aquifers to climate change has been approached using three distinct methods, all with different objectives.

The first method focuses on the use of satellite imagery to analyze the characteristics of aquifers. InSAR has been used in correlation with several underground and ground measurements for revealing diverse parameters characterizing the dynamics of groundwater, including seasonal and long-term aquifer-system response. Considering recent experiences, an overview of several studies realised in different sites, based on InSAR techniques, is presented. These experiences show that there are two main applications on how InSAR data can be used to derive information on the aquifer: estimation of the aquifer storage coefficient and compressibility from groundwater levels or modelling the groundwater levels within the aquifer from knowing/estimating the aquifer properties.

The second vulnerability analysis, made by BRGM, is described in the French pilot report of WP4: https://repository.europe-geology.eu/egdidocs/tactic/11_wp4_descrip_france_brgm.pdf. It deals with time series analysis of groundwater levels and effective precipitation. The assessment of long-term evolution of groundwater levels is conducted with a non-influenced boreholes database through metropolitan France. The vulnerability of aquifers to climate change is assessed via monotonic and non-linear trend analyses. The monthly groundwater level averages and monthly cumulative effective precipitation are used to conduct the analysis which is performed on two reference periods (1996-2019 and 1976-2019) providing the best compromise between the length of groundwater time series and their spatial distribution through metropolitan France and northern France, respectively.

The third vulnerability analysis of aquifers to climate change, described by BGR, is based on an index-based method. An attempt was made to utilize SLHyM (“Standard Legend of Hydrogeological Maps”, Struckmeyer & Margat, 1995) and attribute thematic map information for a broad evaluation of groundwater vulnerability to climate change using a simple index-based methodology at very small observations scales (<= 1:1 Mil.). More specifically, thematic information (“aquifer type” and “aquifer productivity”) from the “International Hydrogeological Map of Europe” at scale 1: 1,5 Mil. (IHME1500, Duscher et al. 2016) was exploited together with information on climate change represented as groundwater recharge difference between the climatological periods 1971 - 2000 and 2041 – 2060. It has to be recognised that IHME1500 mapping units must be interpreted not to display aquifer structures but rather to characterize the flow regime and the productivity of potential aquifers located in them.

As these methods are completely independent and not applied on the same study sites, it was not possible to compare them. They are therefore presented separately in the following sub-chapters.

5.2 Assessment of bedrock significance to hold groundwater using the InSAR technology

While extreme changes in climate (e.g., decadal drought or sustained intense precipitation) can disrupt the normal seasonal groundwater balance held in aquifer systems, human activities (e.g., agricultural and industrial development) are the primary threat to their stability. Changes in aquifer reservoir volumes may manifest as surface deformation, which can be observed from space using InSAR (Interferometric Synthetic Aperture Radar) techniques. Over the last three decades, many studies have integrated InSAR to analyse groundwater level change data. Some of these studies also used the detected groundwater level changes to estimate the aquifer-system hydrogeological properties. Compared to traditional in-situ surveys (e.g., levelling and GNSS), InSAR has proven to be a cost- and time-effective solution for monitoring ground deformation, such as land subsidence and uplift, with millimetric accuracy, large coverage (in the order of thousands of km^2) and long-term acquisition under all weather conditions.

In the last two decades, InSAR techniques have undergone a dramatic development. This is mainly due to the easier availability to the science community of SAR data with the development of the first medium-resolution C-band data from ERS-1/2, Envisat and Radarsat-1 followed by the advent of high-resolution X-band data coming from TerraSAR-X and COSMO-SkyMed. From 2014, a further and more significant improvement for the use of InSAR is represented by the launch of the two Sentinel-1 satellites from the European Space Agency, equipped with C-band sensors. With respect to the previous satellite generations, Sentinel-1 improved the existing data acquisition performances in terms of area coverage, revisiting time and data throughput, considerably increasing the InSAR deformation monitoring potential. Furthermore, Sentinel-1 data is freely available.

Some examples from the recent InSAR literature to study aquifer properties include:

- Boni et al. (2016) have used InSAR to analyse the relationship between ground motion and hydraulic head changes in the London Basin (UK). The integration of observed groundwater levels and satellite-derived displacement time series has allowed the estimation of the spatio-temporal variations of the Chalk aquifer storage coefficient and compressibility over an area of 1360 km^2.
- BGS has been using InSAR to map groundwater rebounds phenomena in UK abandoned coalfields such as south Wales (Bateson et al., 2015), Northumberland (Gee et al., 2017) and Nottinghamshire (Gee et al., 2020). They found subsidence occurring in correspondence of active collieries where groundwater withdrawal was taking place,

while uplift characterised previously mined areas. Uplift was attributed to a net increase of pore pressure in the overburden following the cessation of groundwater pumping after mine closure and was bounded by impermeable faults.

InSAR has been used in correlation with several underground and ground measurements for revealing diverse parameters characterizing the dynamics of groundwater, including seasonal and long-term aquifer-system response. Considering recent experiences, an overview of several studies realised in different sites, based on InSAR techniques, is presented in this chapter[NA1] . These experiences show that there are two main applications on how InSAR data can be used to derive information on the aquifer: estimation of the aquifer storage coefficient and compressibility from groundwater levels (1) or modelling the groundwater levels within the aquifer from knowing/estimating the aquifer properties (2).

Estimation of the aquifer storage coefficient and compressibility from groundwater levels

The storage coefficient (S) or storativity represents the amount of water stored or released per unit of area of the aquifer and per unit head change. In the saturated zone, the pressure head, acts on the aquifer skeleton and on the density of the water in the pores. When the pressure increases, the aquifer skeleton expands, whilst if it decreases, the aquifer skeleton compacts (Sneed and Galloway, 2000). If the water pressure is reduced, water is released from storage in response to expansion of the water in the pores and compaction of the aquifer-system. Therefore, the aquifer-system storage coefficient S is defined as (Galloway et al., 1998):

$$S = S_k^i + S_k \ + S_w \ = S_k^* + S_w \qquad \textbf{Equation 5.1}$$

Where S_k^i and S_k are the skeletal storage of the aquitard and the aquifer, respectively, while S_w the water storativity. S_k^* is the aquifer-system skeletal storage. Two aquifer-system skeletal storages, S_{ke} and S_{kv}, can be defined for the elastic and inelastic ranges of stress, respectively. The coarse-grained sediments in aquifer-systems deform elastically while the fined-grained sediments that consist on the confining aquitards may deform both elastically and inelastically.

In confined aquifers, even if the head drops and water is released from storage, the aquifer remains saturated. In this case, the storage coefficient can be defined as (Cooper, 1966):

$$S = S_s \ \times b = (\rho_w \times g)(\alpha + \eta\beta)b \qquad \textbf{Equation 5.2}$$

Where S_s is the specific storage, b is the thickness of the saturated aquifer, ρ_w is the water density, g the acceleration of gravity, α is the aquifer skeleton compressibility, η is the porosity and β the fluid compressibility.

In compacting aquifer systems $S_k^* >> S_w$ and, assuming that S_w is negligible (Poland, 1984) the storage coefficient is approximately equal to the skeletal storage coefficient: $S \simeq S_k^*$.

By inspecting groundwater level variations and ground displacement time series for boreholes, stress-strain curves can be derived by plotting the hydraulic head (that represents the applied stress) versus the vertical displacement (that represents the strain). If a direct temporal correlation between start and end dates for rising water level and ground uplift, and falling level and subsidence is found, it means that the deformational behaviour of the aquifer can be considered as mainly elastic (namely equals to S_{ke}).

Under such condition, the relationship between the hydraulic heads changes and the vertical ground motion changes can be applied to compute the storage coefficient (Hoffmann et al., 2001):

$$S = S_k^* = \frac{\mathit{\Delta} d}{\mathit{\Delta} h} \qquad \textbf{Equation 5.3}$$

where $\mathit{\Delta} d$ the vertical displacement as estimated by InSAR data, and $\mathit{\Delta} h$ is the hydraulic head change.

Modelling the groundwater levels within the aquifer from knowing/estimating the aquifer properties

To provide a quantitative estimate of groundwater rise/withdraw ($\mathit{\Delta} h$) across the aquifer, an inversion of both the average InSAR velocities or time-series can be implemented. In this case InSAR identifies changes in the bed thickness ($\mathit{\Delta} b$) which is assumed to be caused by the change in the effective stress ($\mathit{\Delta}_{ps}$) and is calculated as a function of the coefficient of volume compressibility (mv) and the initial thickness of the unit (b_0):

$$\mathit{\Delta} b = s \times \mathit{\Delta}_{ps} \times mv \times b_0 \qquad \textbf{Equation 5.4}$$

where s is a scaling factor to account for predicted inelastic (non-recoverable) deformation. The $\mathit{\Delta} b$ response of the strata to changes in piezometric head are dependent on historical pressure changes. Small-scale variations in$\mathit{\Delta} h$ (e.g. seasonal effects) are elastic and recoverable so the strata expand and contract in equal measure. When variations in head are greater, the expansion and contraction is bigger which results in inelastic, and non-recoverable deformation, therefore limiting future expansion and contraction. Coarse grained strata (e.g. sand, gravel) are more likely to maintain equilibrium under increased effective stress due to their rigid skeletal matrix, however, fine-grained material (e.g. clays) are susceptible to high rates of potential compaction due to their plastic nature (Hiscock, 2009).

The groundwater level changes can then be expressed as:

$$\mathit{\Delta} h = \frac{1}{10s}\left(p - p_{s0} - p_{w0} - \left(\frac{\mathit{\Delta}_b}{mv} \times b_0\right)\right) \qquad \textbf{Equation 5.5}$$

Both the methodologies have been already tested and applied at local and aquifer scale and, however, the examples show that assumptions have to be made (e.g., Sk*>>Sw in compacting aquifers) and groundwater data are necessary for calibration and validation of the InSAR results. BGS has recently developed an in-house built InSAR processor for processing satellite data automatically and quickly. However, the current InSAR hardware facility at BGS do not allow to process data at national scale due to its limited storage capability, so currently BGS InSAR analysis are limited to regional analysis (in the order of thousands of km^2). An analysis of the relationship between InSAR data and groundwater level for such scale would take approximately 15 days, including the downloading, processing and interpretation of the InSAR data by an InSAR specialist.

The upcoming European Ground Motion Service

The analysis of groundwater-related deformation will soon be possible at continental scale. Indeed, by the end of 2021, InSAR-derived ground deformation maps will be available for the whole Europe for free under the European Ground Motion Service (EGMS) funded by the European Environment Agency (https://land.copernicus.eu/user-corner/technical-library/european-ground-motion-service). The EGMS represents the latest and most relevant development in the InSAR community. Over the last 7 years, InSAR techniques have undergone a dramatic development pushed by the huge amount of data collected by the Sentinel-1constellation (Novellino et al., 2017). These techniques have considerably improved the InSAR performance in terms of measurement point density, quality and reliability (Crosetto et al., 2016) and have benefitted from the increase of the InSAR computational capability. The data acquisition capability of SAR sensors has always been overwhelmingly higher than our collective capacity to process SAR data (Del Soldato et al., 2021). Several groups have worked on the exploitation of advanced computational resources, using parallel computing or virtual machines. The net result is that wide-area InSAR deformation monitoring has become a reality in the last years with some countries having already developed nationwide InSAR maps (e.g., Italy, Denmark Germany and Netherlands) which then led to the EGMS currently under development under the responsibility of the European Environment Agency (EGMS, 2017).

The main characteristics of the EGMS will be (Crosetto et al., 2020):

- providing consistent, updated, standardized, harmonized InSAR maps across national borders.

- producing a baseline product, which is composed of all the Sentinel-1 images from February 2015 to the start of data processing, followed by product updates every 12 months.

5.3 Time series analyses

The assessment of long-term evolution of groundwater levels is conducted with a non-influenced boreholes database through metropolitan France (Baulon et al., 2020): 215 boreholes with more than 24 years of data. The selected wells span over multiple hydrogeological contexts: alluvial aquifers, sedimentary aquifers, volcanic and bedrock aquifers. Most of the selected wells are situated into sedimentary aquifers, mainly in the Parisian Basin, and sporadically in the Aquitaine Basin.

The vulnerability of aquifers to climate change is assessed via monotonic and non-linear trend analyses. The monthly groundwater levels averages and monthly cumulative effective precipitation are used to conduct it. Analysis is performed on two reference periods (1996-2019 and 1976-2019) providing the best compromise between the length of groundwater time series and their spatial distribution through metropolitan France and northern France, respectively.

For each groundwater time series, an effective precipitation time series is assigned to it via the development of an indicator (Manceau et al., 2020). The indicator time series (expressing the effective precipitation) allowing the maximization of the correlation coefficient with monthly groundwater levels is selected as it is the most representative mesh of the groundwater level behaviour. Conclusions on the sensitivity of groundwater trends to low-frequency variability (Baulon et al., submitted)

Results of this study highlight the heavy influence of groundwater low-frequency variability (from multi-annual to decadal) on trends estimation. The multi-temporal analysis of trends proves that upward trends displayed in the Seno-Turonian chalk of Artois-Picardy, the limestones of Beauce, and the Jurassic limestones from Sarthe to Bessin, either on one reference period or both, are not stable over time meaning that downward trends are detected on other time periods. Therefore, these upward trends are not necessarily indicative of the real evolution of groundwater levels.

Generally, aquifers displaying inertial (i.e. a predominant low-frequency variability) or combined behaviours (i.e. a well-pronounced low-frequency variability superimposed by annual variability) display unstable trends (i.e. regular changes of direction according study period). These alternative trend directions on decreasing periods (e.g. from 1976-2019 to 2000-2019) arise because the trend estimation can be started during either a multiannual high-level or a multiannual low-level, which highly influence trend direction.

Sometimes, in such contexts, stable trends can be detected (i.e. no changes of direction according to study period) when an underlying trend is present. These underlying trends are very often segments of slower fluctuations that cannot be highlighted by the length of the study window. Then, the weakening of low-frequency variability observed over last decades is the second factor to get stable trends in some hydrogeological entities.

This study also indicates that multiannual (~7-yrs) and decadal (~17-yrs) variabilities affect the general trend in groundwater levels by driving upward or downward levels. Indeed, the multiannual variability drives upward groundwater levels in northern inertial aquifers with accentuated upward trends and attenuated downward trends, while in southern aquifers it drives downward groundwater levels with attenuated upward trends and accentuated downward trends. This north/south discrepancy may be directly related to ETP and/or aquifer properties of the northern hydrogeological inertial system to interfere and reverse the influence of multiannual variability on trends (from a downward influence in precipitation to an upward influence in groundwater). Finally, the decadal variability drives downward groundwater levels in northern aquifers with attenuated upward trends and accentuated downward trends. No conclusion has been attained for southern aquifers due to the lack of data.

The degree of influence of multi-annual and decadal variabilities on trends appears to be related to (i) the proportion of variance that they explain in groundwater levels, (ii) the length of the study period. Thus, the more they explain a large proportion of variance, the greater their influence on trend, and the shorter the study duration, the greater their influence on trend.

Hence, the main issues of trend studies in surface hydrology due to low-frequency variability are also perfectly highlighted in groundwater levels. Therefore, groundwater trend studies must be considered with caution to avoid misleading interpretation, including ours in the section, especially because the low-frequency variability can be exacerbated in aquifers compared to precipitation. It ensures that estimated monotonic trends cannot be extrapolated on other periods, nor used to predict future evolutions.

To overcome issues of the influence of low-frequency variability on trends and detect “real” trends in groundwater levels, we need to remove these variabilities from groundwater levels and effective precipitation. Therefore, the EEMD filtering technique is used to identify “real” and non-linear trends in groundwater levels.

The study of filtered groundwater levels and effective precipitation has been done via several approaches: (i) the estimation of monotonic trends on these filtered data (*i.e.* EEMD residues or non-linear trends), (ii) the clustering of these non-linear trends, (iii) the questioning of if these non-linear trends are “trends” or only segments of lower frequency variabilities.

The monotonic trends detected on filtered data reveal few differences with monotonic trends estimated on raw data (i.e. unfiltered data) on the longest reference period (1976-2019), particularly for groundwater levels. However, in a shorter period (1996-2019), greater discrepancies appear with monotonic trends estimated on raw data: magnitudes of trends are very often accentuated and even trend direction can be impacted. The filtering of low-frequency variability widely impacts the significance of trends, with lots of non-significant trends on raw data becoming significant on filtered data. This phenomenon may be related to data variability that is considerably reduced in filtered data and consequently no longer affects the significance of trends. Therefore, filtering low-frequency variability or not from data can lead to different results in terms of trend magnitude, direction and significance inducing different interpretations.

The opposite detected monotonic trends between filtered groundwater levels and effective precipitation may be related to several phenomena: (i) a wrong selection of effective precipitation mesh at the beginning of the analysis leading to a non-linear trend in effective precipitation that does not represent the non-linear trend in groundwater levels, (ii) a long-term anthropogenic influence on aquifers (e.g. long-term pumping) and the non-linear trend of groundwater levels no longer represents the one of effective precipitation, (iii) a dephasing between the non-linear trend of groundwater levels and effective precipitation due to the response time of aquifers, (iv) a distortion or modulation of oscillation amplitude induced by catchment and aquifers properties, (v) asymmetry discrepancies between non-linear trends of groundwater levels and effective precipitation also induced by catchment and aquifer properties.

The clustering of groundwater and effective precipitation non-linear trends exhibits a heavy predominance of decreasing patterns for both variables. Increasing patterns of non-linear trends are only displayed by groundwater levels, particularly in the Seno-Turonian chalk of Artois-Picardy, and more locally in other hydrogeological entities. Overall, spatial distribution maps of effective precipitation non-linear trends patterns reveal a spread according to geographical location, with a good spatial homogeneity of clusters. For groundwater level non-linear trends, the spread of clusters seems to be more as a function of hydrogeological entities, and their physical properties at local or regional scale.

Generally, we expect a good accordance between groundwater levels and effective precipitation clusters for a given borehole and its corresponding precipitation mesh, because non-linear trends are quite similar. In many cases, this assumption is true, but sometimes this is not the case and several explanations can be provided involving the capability of catchment, vadose zone and aquifers to modulate and delay oscillations from effective precipitation.

Finally, the non-linear trends detected in groundwater levels appear to be part of lower frequency variabilities. Although the EEMD method is a usefulness tool to filter the low-frequency variability, and therefore to limit its influence on the trend estimation, it does not have the capacity to filter an oscillation at a larger scale than the study window. Therefore, monotonic trends that were estimated on EEMD residues are still impacted by low-frequency variability and underline it. Since large-scale atmospheric and oceanic oscillations are expressed over a wide range of timescales, any groundwater trend could be the result of a slower fluctuation (Rossi et al., 2011). For instance, the Atlantic Multidecadal Oscillation (AMO) oscillates on ~60 years timescales (Kerr, 2000; Enfield et al., 2001). Thus, the youth of French piezometric networks does not, in most cases, allow us to grasp such a low-frequency timescale as a fluctuation, but it can grasp it as a trend. Therefore, it highlights the complexity to define whether trends in hydroclimate variables can be related to climate change or simply being part of a lower-frequency oscillation originating from large-scale atmospheric or oceanic circulation. It can be even more complicated when working on groundwater levels that are also subjected to significant long-term anthropogenic pressures (e.g. pumping) not necessarily well referenced.

In summary, multiple interpretations of groundwater level trends can be made. These trends may be linked to (i) anthropogenic impacts (e.g. groundwater pumping, changes in land cover that may generate a decrease in groundwater recharge), (ii) climate change that may result in a decrease in groundwater recharge, (iii) a segment of low-frequency oscillations which could appear as a trend on the short-term. Without considering the anthropogenic impacts (which data are often poorly referenced), the most limiting factor to make the distinction between points (ii) and (iii) remains the availability of groundwater levels data and the length of time series. Works on groundwater levels reconstruction might overcome this constraint via, for instance, deep learning approaches or tree-ring-based reconstruction (Vu et al., 2020; Tegel et al., 2020). However, differentiating between climate change or variability associated to large-scale atmospheric or oceanic circulation could remain difficult, even with longer timeseries, because anthropogenic forcing may also impact these large-scale patterns (e.g. Dong et al., 2011; Caesar et al., 2018).

5.4 Index based assessment

An attempt was made to utilize SLHyM (“Standard Legend of Hydrogeological Maps”, (Struckmeyer & Margat, 1995) and attribute thematic map information for a broad evaluation of groundwater vulnerability to climate change using a simple index-based methodology at very small observations scales (<= 1:1 Mil.). More specifically, thematic information (“aquifer type” and “aquifer productivity”) from the “International Hydrogeological Map of Europe'' at scale 1 : 1,5 Mil. (IHME1500, Duscher et al. 2016, Fig. 5.4.1) was exploited together with information on climate change represented as groundwater recharge difference between the climatological periods 1971 - 2000 and 2041 – 2060. It has to be recognised that IHME1500 mapping units must be interpreted not to display aquifer structures but rather to characterize the flow regime and the productivity of potential aquifers located in them.

SlHyM-symbology consists in six legend classes combining flow regime of “Aquifer Type” and productivity of “Aquifers” (Fig. 5.4.1). Light and dark blue colors refer to “moderate” and “high” productivities of granular “aquifers”, and light and dark green colors refer to fissured flow regimes, respectively. Light and dark brown colors refer to “local groundwater-bearing materials” and “essentially no groundwater”, respectively (Fig. 5.1).

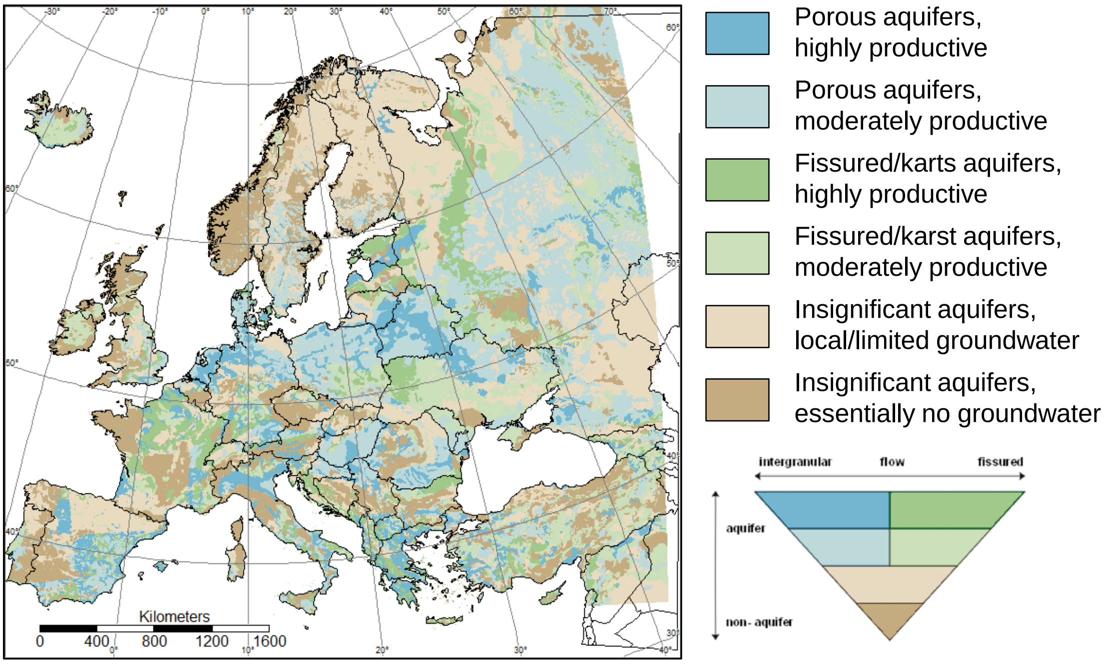


Figure 5.1. IHME1500 with SLHyM classification (map image highly generalized)

The Index consist of a simple weighted linear summation of the three parameters and parameter classes following (Hoebling, 2016):

$$vi = \sum_{j=1}^{3} w_j \times x_{ji}$$ **Equation 5.6**

with w_j: weight of parameter j and x_{ji}: weight of class i in parameter j. parameter- and parameter class weights are assigned following Table 5.1 as below.

Table 5.1. Parameters and their classes with associated weights for index-based GW vulnerability to climate change estimation.

Recharge difference (mm) **w = 0.5**	**x**	**Aquifer productivity** **w = 0.1**	**x**	**Void type** **w = 0.4**	**x**
≤ -15	10	Highly productive	10	Karst / cleft	10
-15 - 0	8	Moderately productive	5	Cleft	5
0 - 15	6	Limited groundwater	2.5	Cleft / pore	2.5
15 - 30	4	No groundwater	nil	Pore	0

30 - 45	2	
≥ 45	0	

The index assessment was performed over Europe (including Turkey, the Caucasus region and parts of the Middle East, Fig. 5.4.1), e.g. a study are covered by the current extent of IHME1500. As a mapping unit, a 1 km X 1 km grid cell (pixel) was used with all spatial data rasterized or sampled to this resolution. The two parameters “aquifer productivity” and “void type” were extracted from IHME1500 information, were in addition to the SLHyM-attributation the lithological information of the mapping units on aggregation level 2 was exploited (Fig. 5.2). According to the scheme in Table 5.1, areas delineated in IHME1500 as “no groundwater” were blanked for the assessment.

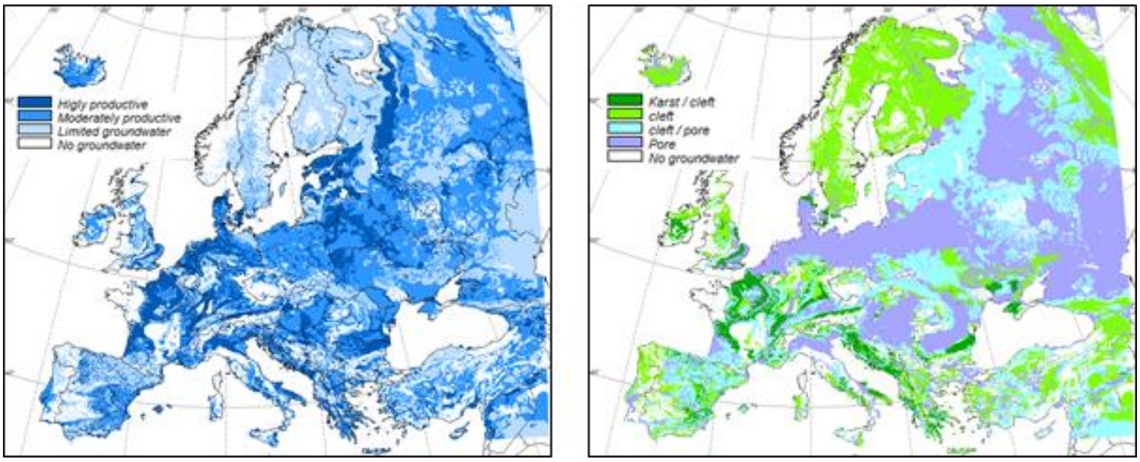


Figure 5.2. Productivity (left) and void type (right) of IHME1500 mapping units

The third parameter required for the Pan-European index-based assessment of groundwater vulnerability to climate change, that is diffuse groundwater recharge difference, was estimated using climatic information (precipitation, temperature) from Worldclim 1.4 (Hijmans et al., 2005) data for the period 2041 – 2060, and Worldcim 2.0 (Fick & Hijmans, 2017) data for the period 1971 – 2000. From Worldclim 1.4, downscaled CMIP5 climate data from GCM HadGEM2-ES was used. It has to be acknowledged here that CMIP5 information is recently notified as obsolete since downscaled CMIP6 data is now available, however not at the required spatial resolution of 30 arcseconds (approx. 1 km) for now. Effective precipitation for the climate scenarios was then calculated on an averaged monthly basis using a temperature-based approach to compute potential evapotranspiration from Hargreaves and Samani (1985) as implemented in the SAGA GIS (Conrad et al., 2015) environment. It has to be acknowledged that mean annual effective precipitation for the two periods calculated in this manner must be more considered a proxy since the calculation was done on a monthly basis using only potential evapotranspiration.

Diffuse groundwater recharge was estimated in accordance to Döll & Fiedler (2008) on an averaged monthly basis using

$$R_g = min(R_{g\,max}, f_g(N - V))$$ **Equation 5.7**

with R_g [mm/month]: diffuse groundwater recharge, $R_{g\ max}$ [mm/month]: soil texture-specific maximum infiltration rate [mm/month], f_g: groundwater recharge factor, N [mm/month]: precipitation and V [mm/month]: potential evapotranspiration. Rgmax was derived from a data product of the Soil Geographical Database of Europe (SGDBE, Panagos et al. 2012) rendering soil texture information (Hiederer, 2013) (Table 5.4.2).
The groundwater recharge factor fg was obtained using several environmental datasets that were classified and class-weighted according to a scheme presented by Döll & Flörke (2005):

$$f_g = f_r f_t f_h f_{pg} f_{lc}$$ **Equation 5.8**

with f_r: factor “relief” ($0{,}15 \leq f_r \leq 1$), f_t: factor “soil texture” ($0{,}7 \leq f_t \leq 1$), f_h: factor “hydrogeology” ($0{,}5 \leq f_h \leq 1$), f_{pg}: factor “permafrost/glaciation” ($0{,}05 \leq f_{pg} \leq 1$), f_{lc}: factor “land cover” ($0{,}3 \leq f_{lc} \leq 1$). The factor class scores are applied following Döll & Flörcke (2005) and are listed in Table 5.2.

Table 5.2. Components of f_g and their classification and scoring (ranges from Döll & Flörcke, 2005) Factor “Relief” from GTOPO 30 (USGS)

Slope [%]	**fr**
0-2	1
2-5	0.95
5-8	0.90
8-16	0.75
16-30	0.60
30-45	0.30
>45	0.15
Factor “Soil Texture” from SGDBE (Hiederer, 2013)	
fraction according to FAO	ft
<18% clay, >65% sand	1
<35% clay, <65% sand	0.95
>35% clay	0.7
Factor “Hydrogeology” from IHME1500 (Duscher et al., 2016)	

Level 2 lithology legend class	fh
Gravels, sands; Limestones (jointed, karstified); Sands, gravels	1
Gravels, sands, clays; Sands; Sands, gravels, clays	0.9
Conglomerates; Conglomerates, sandstones; Conglomerates, sandstones and sands, gravels; Limestones; Limestones and sands; Limestones, marlstones; Limestones, marlstones and sands; Limestones, sandstones; Limestones, sandstones and clays; Limestones, sandstones and marls; Limestones, sandstones and sands; Sands, clays; Sandstones, limestones; Sandstones, marlstones; Sandstones, siltstones; Volcanic rocks; Volcanic rocks (acid); Volcanic rocks (basic); Volcanic rocks, pyroclastic rocks	0.8
Conglomerates and sands, silts; Conglomerates, sandstones and clays; Conglomerates, sandstones and clays, marls; Conglomerates, sandstones and sands, clays; Limestones and clays; Limestones and clays, marls; Limestones and marls; Limestones and marls, clays; Limestones, claystones and marls; Limestones, conglomerates and clays; Limestones, marlstones and clays, sands; Limestones, shales; Sandstones; Sandstones and clays, sands; Sandstones and marls; Sandstones and marls, sands; Sandstones and sands; Sandstones and sands, clays; Sandstones, conglomerates; Sandstones, conglomerates and marls; Sandstones, limestones and marls; Sandstones, limestones and sands, clays; Shales, limestones; Silts, sands	0.7
Clays, boulder clays; Clays, sands; Clays, silts; Claystones, sandstones and clays; Marbles; Marls, clays; Marlstones, limestones and sands, clays; Marlstones, pyroclastic rocks and clays, sands; Marlstones, sandstones; Marlstones, sandstones and clays; Marlstones, sandstones and marls, clays; Marlstones, sandstones and sands, clays; Plutonic rocks (acid); Plutonic rocks (basic); Quartzites; Quartzites, sandstones; Sandstones and clays; Sandstones and clays, marls; Sandstones, claystones; Sandstones, conglomerates and sands, clays; Sandstones, shales; Shales; Shales, quartzites; Shales, sandstones; Silts, clays	0.6
Clays; Claystones and clays; Gneisses, mica schists; Gneisses, plutonic rocks; Marbles, schists; Marlstones, claystones; Phyllites, gneisses; Phyllites, schists; Schists, gneisses; Serpentinites; Shales, phyllites	0.5
Factor “Permafrost / Glaciation” from Circum-arctic permafrost map (Heginbottom et al., 1997)	
coverage	**fpg**
continuous (90-100%)	0.05
discontinuous (50-90%)	0.3

sporadic (10-50%)	0.7
isolated patches (0-10%)	0.95
no permafrost	1
Factor “Land Cover” from GlobCover (ESA)	
Aggregated lc/lu class	flc
artificial areas	0.3
forests	0.7
greenlands	0.8
croplands	0.9
barelands	1

In Fig. 5.3, the spatial distribution of the groundwater recharge factor fg is shown. According to IHME1500, areas without groundwater are blanked.

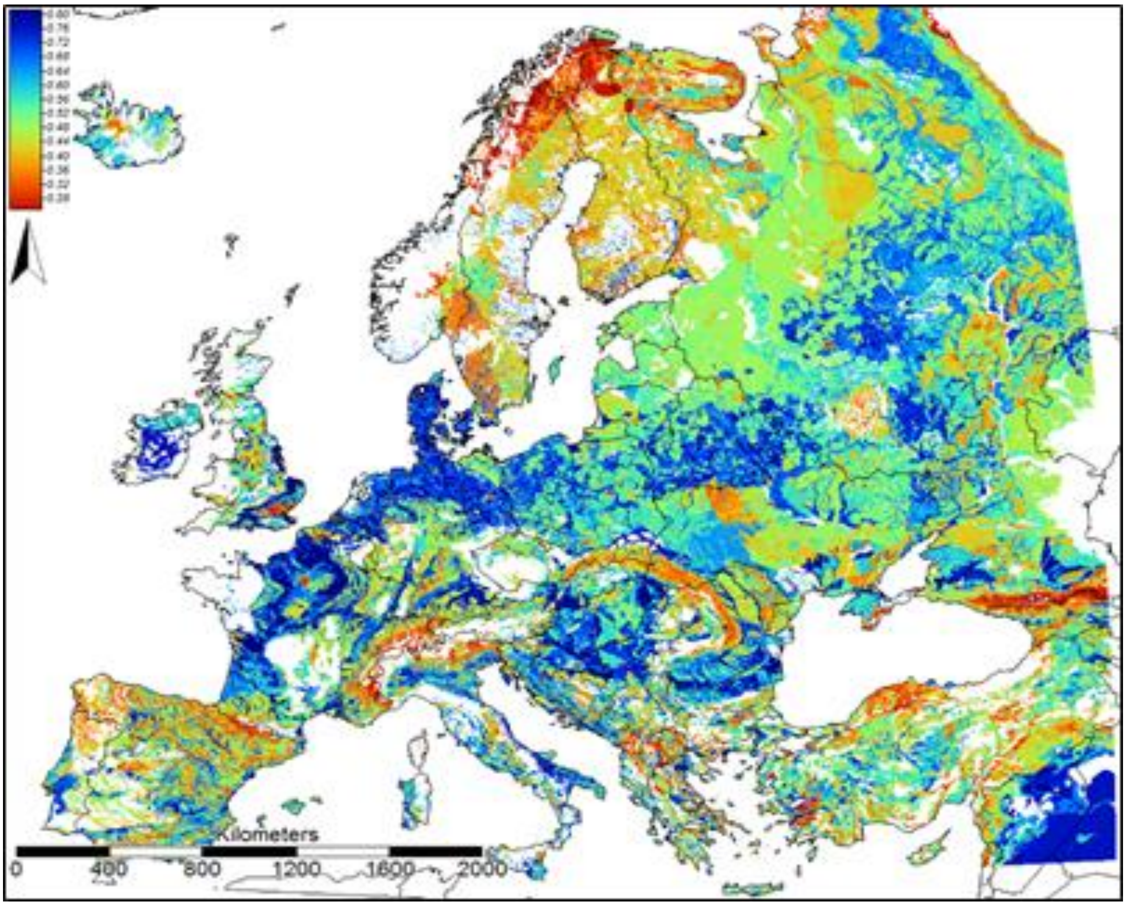


Figure 5.3. Spatial distribution of the groundwater recharge factor fg.

Using effective precipitation from Worldclim data together with fg, mean annual groundwater recharge was calculated over Europe for the time spans 1971-2000 and 2041 - 2060, respectively (Fig. 5.4). Again, areas delineated by IHME1500 as “no groundwater” are blanked.

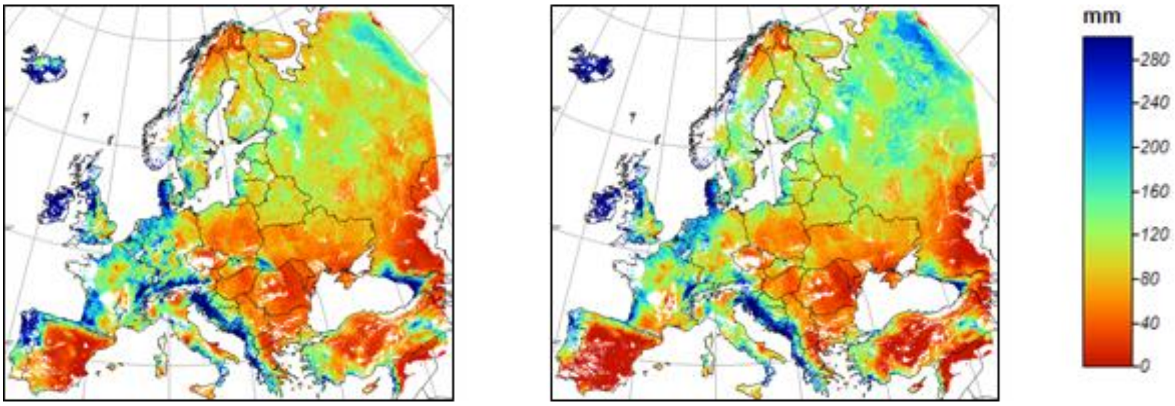


Figure 5.4. Mean annual groundwater recharge estimation for time periods 1971 – 2000 (left) and 2041 – 2060 (right).

In order to verify the rather speculative approach to compute groundwater recharge used in this study, groundwater recharge was calculated using WorldClim 1.4 data with the above described groundwater recharge factor for the climatic normal period 1961 – 1990, and compared to groundwater recharge derived from a baseflow regression model presented in the "Hydrogeological Atlas of Germany" (HAD, Neumann & Wycisk 2003) covering the same period for Germany (Fig. 5.5). It can be observed that though there is some general agreement in recharge patterns and magnitudes, many areas show a large mismatch, especially in the Alpine foreland in Bavaria. However, for nearly 50% of the area the comparison shows an absolute mismatch in groundwater recharge of less than 30 mm. The groundwater recharge pattern elaborated in this study shows more bias, mainly due to the comparably low resolution of the input data (Fig. 5.5 B)

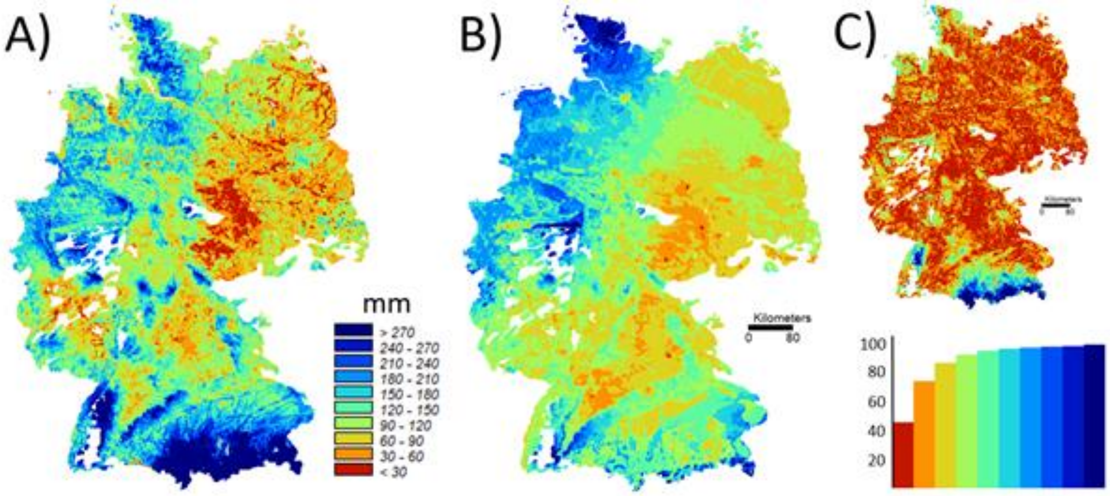


Figure 5.5. Comparison of data-driven / speculative mean annual groundwater recharge rates (GWR) for Germany covering the climatic normal period 1961 – 1990. A) GWR from

“Hydrogeological Atlas of Germany”, HAD, B) GWR from this study, C) Absolute difference with cumulative histogram

In Fig. 5.6, Groundwater recharge difference of the periods 1971 – 2000 and 2041 – 2060 is shown together with the classified index of groundwater vulnerability to climate change. For the classification of the vulnerability index, a natural breaks algorithm was applied. From Fig. 5.6, it can be deduced that larger areas of very high vulnerability are mostly situated in karstic aquifer terrains in Western Europe (Germany, France, Spain). In general, Southern European areas and Turkey are delineated as having large areas of high vulnerability. In contrast, large terrains of the East European platform show very low vulnerability to climate change, mainly due to positive groundwater recharge differences and porous aquifer flow characteristics.

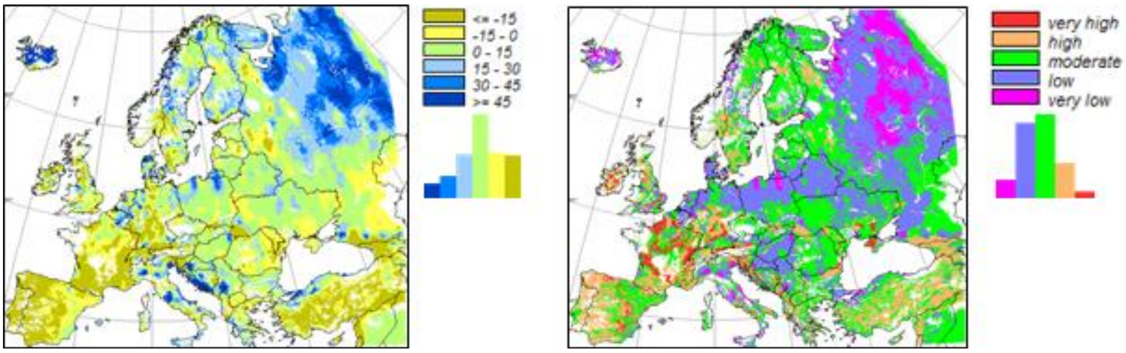


Figure 5.6. Mean annual groundwater recharge difference 1971-2000 / 2044-2060 (left) and climate change vulnerability 1971-2000 / 2041-2060 (right).

The Index-based assessment resembles a purely speculative parameter combination to delineate groundwater vulnerability to climate change that needs to be objectivized in the future. Moreover, the three parameters used are not spatially independent since both “aquifer productivity” and “void type” rely on the same geometry resembling IHME1500 mapping units. Additionally, classification of IHME1500 mapping units for potential aquifer properties according to SLHyM was done by expert knowledge during the long-term production of IHME1500, and is not underlain by data. In this respect, it must also be discussed whether the first-order information of SLHyM-attributed IHME1500 mapping units, that is if they are assigned as “no groundwater” or not, is valid.

The calculation of groundwater recharge difference for the index-based assessment is very simple and was done on an averaged monthly basis. It therefore suffers from comparably low temporal resolution, forcing a rigorous upscaling of the soil texture-specific maximum infiltration rate. More robust groundwater recharge scenarios with higher temporal resolution should be calculated replacing this parameter in the future. With respect to the derivation of future groundwater recharge scenarios based on climate models, it is also important to reconsider the computation of usable groundwater recharge factors (or recharge coefficients) since many environmental information implemented must also be considered to be subject to climate change (e.g., land use / land cover, permafrost, soil cover).

Despite all its limitations, the index-based assessment offers a first synoptic view on potential aquifer vulnerability to climate change over Europe that needs to be enhanced and evaluated in the future. At this stage, it may be used for the spatial identification of first-order “hot spots” at the continental scale not allowing for more detailed interpretations.

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BLOCK IV: SEA AND SALTWATER INTRUSION

6 Assessment of seawater status and vulnerability

6.1 Summary

Seawater intrusion (SWI) status and vulnerability is assessed in TACTIC WP5 at the pilot scale. The pilot scale includes local and regional scale (Fluvia and La Muga rivers delta plain, Hull & East Riding chalk aquifer, Plana de Oropesa-Torreblanca, Ravenna phreatic aquifer, Vrana lake, Liepaja, Campina de Faro and Falster) to small country scale (Malta Mean Sea Level Aquifer). A common method has been applied to summarize seawater intrusion status and vulnerablity in the pilots where the available information allows applying it. The pilots illustrate a large variety of different approaches (e.g., interpolations, sharp interface models, density dependent models) to estimate spatially distributed results.

6.2 Introduction (incl. saltwater intrusion)

The increasing water demand and the scarcity of surface water resources in certain coastal regions lead to the overexploitation of the groundwater bodies. As a result, a great number of coastal aquifers all over the world are affected by seawater intrusion. Moreover, climate change (CC) will exacerbate this problem especially in certain regions in Southern Europe (Benini et al. 2016; Pulido-Velazquez et al. 2018).

Since 2000, after Water Framework Directive (2000) (WFD) came into effect, there has been an increase in the number of groundwater quality assessment studies, and consequently in the development of methodologies to quantify groundwater pollution in an aquifer. Moreover, the protection of groundwater resources is a priority issue to be considered to achieve and maintain the good status of water bodies according to the WFD, which mainly depends on intrinsic vulnerability to contamination.

Many different distributed approaches can be applied to assess spatio-temporal distribution of groundwater quality issues and vulnerability in coastal regions, depending on the aim of the investigation. Distributed hydrological models are useful tools to propagate scenarios to assess impacts on hydrological variables at specific time and location. Nevertheless, they do not allow drawing direct conclusions about the impacts on SWI (status and vulnerability) at aquifer scale. For this purpose, an approach such as an index-based method is a useful tool to analyse this issue. It can also help to summarize SWI problems at aquifer scale in different periods and identify aquifers in risk of not achieving a good chemical status according to the WFD.

6.3 Methodology

In this section the proposed common method to summarize the SWI status and vulnerability is briefly explained (Baena-Ruiz et al. 2018; Baena-Ruiz et al. 2020).

The method based on indices and variables summarize SWI status and vulnerability at aquifer scale. Information on the aquifer volume affected by sea water intrusion at different spatial scales is generated, moving from areal maps to representative conceptual cross section and lumped indices. The maps can be generated by applying different tools, such as numerical groundwater flow and transport models, conceptual models and spatial interpolation techniques using observed chloride concentrations. The resilience and trend of the system to SWI can be deduced from the time series of the proposed indices. Impacts of potential global change (GC) scenarios (CC and Land Use and Land cover Change scenarios) can be also analysed. The proposed method has been applied in different pilots (Plana de Oropesa-Torreblanca aquifer and Fluvia and la Muga Delta river Plain in Spain and Liepaja in Latvia).

Specific methodologies based on index methods, groundwater numerical models, time series analysis, etc. have been applied to the other pilots, which are detailed for each pilot (see Table 6.4).

6.4 Case studies/Examples

Table 6.4 lists examples where the assessment of SWI has been analysed. The common method has been applied in the following pilots: Plana de Oropesa-Torreblanca aquifer, Fluvia and la Muga Delta river Plain and Liepaja aquifer. The method (common or other) used for the assessment as well as the general issue related to CC addressed in the examples are noted. The full assessment report for each example is also linked in the table, where the full detail of the modelling tool, available data and CC implications, are documented.

Table 6.4 SWI assessment and pilot location

Pilot Name	**Method to assess SWI**	**Main CC issues**	**Hyperlink**	**Pilot scale**
Fluvia and La Muga rivers delta plain	Common Other (NBL)	Groundwater overexploitation, frequent storms	link	Local
Hull and East Riding	Other (index methodologies)	Groundwater flooding	link	Local
Malta MSLA	Other (groundwater modelling)	Sea-level rise	link	Country
Plana de Oropesa-Torreblanca	Common Other (groundwater modelling)	Groundwater overexploitation	link	Local
Ravenna phreatic aquifer	Other (groundwater modelling)	Drought, sea-level rise	link	Local
Vrana lake	Other (time series analysis, lumped models)	Droughts, pumping	link	Local
Liepaja	Common	Future overexploitation	link	Local

	Other (NBL)			
Campina de Faro	Other (chemical indicators, time series analysis, lumped indices)	Overexploitation	link	Local
Falster	Other (Geophysical measurements, groundwater modelling, NBL)	Sea-level rise, floods	link	Local

6.5 Conclusion: Pitfalls, pros and cons

Different methods to assess SWI have been applied in nine pilots. A common method has been proposed to summarize SWI at aquifer scale, which has been applied in three of these pilots. The main CC issues are addressed by the different methods in order to analyse the future SWI status in the pilots.

The proposed methodology summarizes the impacts of potential CC scenarios in terms of SWI status and vulnerability at the aquifer scale through steady pictures (maps and conceptual 2D cross sections for specific dates or statistics of a period) and time series for lumped indices. This method allows us to obtain general conclusions about the global status and vulnerability and to assess the effects of CC and adaptation strategies. This method shows a high sensitivity to the chloride threshold to define the affected and non-affected area, so a proper assessment of the natural background level is important to achieve realistic results.

7 Estimation of National Background Level (NBL)

7.1 Summary

In this section an assessment of natural background level (NBL) for chloride concentration (Cl) is proposed to analyze the human impacts on salt-water intrusion. The proposed method is based on different previous statistical approaches for the derivation of NBL for Cl from available measurements, which allows identifying a feasible range of NBL in a consistent way. The method has been applied in five coastal aquifers across Europe.

7.2 Introduction

A correct assessment of the natural background level (NBL) of inorganic compounds is required to determine the chemical status of the groundwater bodies according to the WFD. In the SWI issue, the NBL is mainly focused on chloride concentration (Custodio 2010; García-Menéndez et al. 2016).

During the last decade different EU research projects have been focused on the development and testing of pre-selection methods (PS) to assess NBL and threshold value (TV), for example the EU BaSeLiNe or the BRIDGE projects (Müller et al., 2006). They intended to give response to the necessity of scientific approaches for a rational definition of the quality standards and assessment of potential program of measures. BRIDGE project (Dahlstrom and Müller, 2006) proposed a methodology to identify groundwater TVs, based on both NBLs and environmental quality standards (Müller et al., 2006). Next to that, different NBL approaches based on probability plots (PP) and sample distribution analysis exist (Walter et al., 2012; Griffioen et al., 2008). Both types of methods (PS and PP) aim to identify and individualize uncontaminated samples in a mixed population that includes samples with abnormally high concentrations of certain elements attributable to anthropogenic processes. These methodologies have a degree of subjectivity, so the integration of the two methods is recommended to reinforce the validity of the assessment (Preziosi, E., et al., 2014).

7.3 Methodology

Different statistical approaches for derivation of chloride NBLs from the available measurements are applied in five pilots across Europe: the PS based BRIDGE method (Coetsiers and Walraevens, 2006), the PP based approach (Walter, 2011), and the solution used in Portugal (PT method), which is based on PS and PP.

A detailed sensitivity analysis of the results to different Cl constraints applied to remove samples affected by anthropogenic impacts is performed. Based on the sensitivity analysis results, a novel approach that combines results from different statistical methods is proposed. When the Cl thresholds diminished, the corresponding NBL values would tend to converge or reduce their distance. Taking this into account, a regression curve (linear or logarithmic) is fitted for each method. The intersection of the curve fitted to the BRIDGE approach with the other two approaches (PP and PT methods) define a range of NBLs in each aquifer, whose amplitude will depend on the pilot.

It allows identifying a feasible range of values for the chloride NBL. Its applicability has been demonstrated in coastal aquifers across Europe with significantly different concentration distributions.

7.4 Case studies/Examples

The proposed method has been applied in five coastal aquifers: Plana de Oropesa-Torreblanca and the aquifers of the Fluvia and la Muga rivers delta plain in Spain (Mediterranean pilots); Campina de Faro in Portugal (Atlantic Ocean); Liepaja in Latvia (Baltic sea); Tønder in Denmark (North sea).

Table 7.4 shows the range of the natural chloride concentrations considered feasible in each pilot in accordance with previous studies and/or expert criteria within the aquifer.

Table 7.4. range of the natural chloride concentrations

Pilot	**Range of Cl natural concentrations** (mg/L)
Plana de Oropesa-Torreblanca	30 - 90
Fluvia and La Muga Delta Plain	35 - 80
Tønder	5 - 60
Liepaja	10 - 20
Campina de Faro	100 - 200

7.5 Conclusion: Pitfalls, pros and cons

In order to make a reliable NBL assessment, it is recommended to apply different methods instead of relying on only one method, and to perform sensitivity analyses to the Cl constraints. If we identify methods with low sensitivity to the Cl constraints, we will have a higher confidence on the estimated NBLs. Therefore, the range of the NBL might be based on their results.

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BLOCK V: ADAPTATION

8 Adaptation Strategies

8.1 Summary of Adaptation Strategies

In order to assess adaptation strategies, in addition to having models that simulate/propagate specific impacts, we need to identify and assess potential adaptation measures (Iglesias et al., 2015). In this project we have generated an organized list of potential adaptation strategies, emphasizing those related with Groundwater adaptation strategies. On the other hand, we also reviewed and applied within the pilots different approaches to assess adaptation strategies: top-down, which are focused on the analyses of the physical vulnerability; and bottom-up, which try to assess social vulnerability, and even a mixed of both approaches. Against the classical "top-down" approach where scenarios guide adaptation, bottom-up approaches can be used to identify potential adaptation measures, system performance indicators and acceptable thresholds. They can be also simulated in the modeling framework (“share vision models”) for evaluating and selecting resilient measures. The top-down approach is commonly used and will be applied in most TACTIC pilots, while the bottom up and a mixed Top-Down and Bottom-up approach to co-design adaptation strategies with involvement of different stakeholders has been explored in the Upper Guadiana Basin.

8.2 Introduction

Despite uncertainties in climate projections, global warming is unequivocal (IPCC 2013) and its impact is an important topic in many fields. Climate change influences water resource management, and the assessment of adaptive strategies becomes essential. In Europe, European Union (EU) water and climate policies require water management to consider adaptation to climate change, which entails many policy and scientific challenges (Escriva-Bou et al. 2017). Scientific research is essential for ensuring that new river basin management plans will be “climate proof” (Quevauviller et al. 2012), which requires the development of adequate methods, planning, and governance processes for integrating climate change into water management (EC 2012).

In the literature we find systematic Top-Down approaches focused on identifying potential general adaptation strategies, including actions both, on water demand, and on water supply (Pulido-Velazquez et al., 2011). The assessment of the impacts under specific adaptation measures can be performed by applying top-down approaches based on an analysis of the physical vulnerability of the system (Escriva-Bou et al., 2017). Other works are focused on the identification and assessment of adaptation scenarios by applying bottom-up approaches (Zorrilla et al., 2020). They intend to analyze the social vulnerability, based on participatory processes developed through workshops where stakeholders from the main sectors are involved.

8.3 Methodology

In order to help in the assessment of potential adaptation strategies a review of methods that can be applied has been performed and discussed within the partner involved in work Package 6 (Groundwater adaptation strategies). The assessment of adaptation strategies can be performed by applying two different groups of approaches: top-down, which are focused on the analyses of the physical vulnerability; and bottom-up, which try to assess social vulnerability, and even a mixed of both approaches. The bottom-up approach allows to define plausible socioeconomic scenarios and to assess adaptation measures through participatory processes and workshops with the main actors. The top-down approach intends to identify optimal measurement programs for the different climatic and socio-economic scenarios by using model simulations. The top-down approach is commonly used and will be applied in most TACTIC pilots, while the bottom up and a mixed Top-Down and Bottom-up approach to co-design adaptation strategies with involvement of different stakeholders has been explored in the Upper Guadiana Basin.

On the other hand, a list of potential adaptation strategies has been identified based on the review of the scientific literature about this issue. This list may help to identify potential adaptation measurements in the pilots. Note that we have not only included measures that are directly related with groundwater management (highlighted in red in the list), but also other measures that could have an indirect impact on groundwater status.

Finally, we have also simulated in different pilots, potential impacts of climate change scenarios under different potential adaptation strategies (See WP6 pilot assessment report), by propagating the generated local climate scenarios with different models adapted to the problem studies in each pilot.

8.4 Results. Case studies/Examples

The list of potential adaptation strategies identified from the literature review have been classified in three groups: Measures on the demand, on the offer and mixed (demand and offer). The measures on the demand are those that intend to reduce water requirements for the different water uses. The target of the measures on the demand is to obtain additional resources or to improve the regulation of the water resources systems. There are also some measures that affect to both levels, (i) demand and (ii) offer.

Table 8.4. Demand and offer of adaptation strategies

DEMAND
CHANGES IN LAND USE
Transformation of irrigated area in urban areas
Relocation of industry

Changing/Introducing new irrigation areas
Soil conservation and reduction of floods (E.g. Reforestation and flood plain conservation)
CHANGE IN CROPS AND CROPPING PATTERNS
Re-negotiation of allocation agreements (water concessions)
Set clear water use priorities
Improve crop diversification
Increase short life cycle (horticultural) crops
Promote woody crops
Change to rainfed crop
I+D+i in Crops. Develop climate change resilient crops
WATER USE EFFICIENCY
Modernization of irrigation systems
Irrigation good practices
Improve soil moisture retention capacity
Improve nitrogen fertilization efficiency
ECONOMIC INSTRUMENTS
Prices. Set block rate tariff (agricultural demands); regulatory fees and taxes
Subsidies (CAP) to low water requirement crops
Water **markets**
OFFER
INCREASE REGULATION & CONTROL
Small-scale water reservoirs on farmland
Improve the reservoir capacity
Conjunctive use management (including artificial recharge)
New technologies in aquifer control
Increase rainfall interception capacity
Hard defenses against floods and erosion
Improve drainage systems
COMPLEMENTARY RESOURCES
Water reutilization
Water transfer
Increase groundwater pumping
Desalination plants
MIXED (improving resilience)
Improve planning, control and resources allocation

More participative and transparent management
Management decision by farmer organizations
Improved monitoring and early warning
Innovation and technology
Integrate water demands in conjunctive systems
Insurance to floods or drought
REDUCING ENVIRONMENTAL IMPACTS (environmental demand/improve resources quality)
Phytoremediation
Increase/optimization water allocation for ecosystems
Maintain ecological corridors. Restore rivers and wetlands

The WP6 ‘pilot descriptions and assessment report for adaptation’ (Pulido-Velazquez et al. (2020), D6.3), describes the assessment and analyses of adaptation strategies for pilots focused on the assessments of impacts on groundwater and associated surface water conditions (WP3), including local and regional scale case studies (Avre, Storåen-Sunds, Segura, Upper Guadiana) and also coastal aquifer pilots related with sea water intrusion (Plana de Oropesa-Torreblanca and Marecchia).

8.5 Conclusion: Pitfalls, pros and cons

An integrated Bottom-Up and Top-Down approach is proposed to co-design adaptation strategies based on the analyses of their influence on CC impacts under some emissions and socio-economic scenarios. It allows us to analyze adaptation strategies considering both, physical and socio-economic vulnerabilities and local priorities with high uncertainty. Against the classical "top-down" approach where scenarios guide adaptation, we propose to include also a bottom-up approach to identify potential adaptation measures, system performance indicators and acceptable thresholds. They will be simulated in the modeling framework (“share vision models”) for evaluating and selecting resilient measures.

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ANNEX: UPLOAD DATA TO GIP

9 Upload data to GIP

9.1 Summary of Upload data

The EGDI platform has the purpose to make data from the GeoERA scientific projects available and easy to use. This provides the opportunity to deliver the GeoERA TACTIC project outputs to the scientific community and the wider public audience.

TACTIC project has involved the analysis of groundwater related processes such as the groundwater / surface water interaction, infiltration recharge, saline intrusion, and the analysis of groundwater fluctuations under historical and future climate data for the assessment of aquifer vulnerability and for adaptation. The analysis outputs are presented in the form of reports in PDF format, maps showing spatially distributed information, figures and plots, etc. All these outputs are uploaded to the EGDI. More specifically, the TACTIC preview map of the EGDI contains the following layers:

- Online sensor data
- Assessment of seawater intrusion status and vulnerability
- Groundwater time series
- Groundwater change
- Aquifer group France
- National scale recharge (Spain, The Netherlands, Ireland, France, Great Britain)
- Pan-European recharge estimation including: Effective precipitation, potential recharge, runoff, and runoff coefficient values
- Pilot studies reports
- Point calculation, including recharge, recharge uncertainty, future recharge values.

9.2 Introduction

This section discusses the upload of data to the EGDI. The EGDI platform has the purpose to make data from the GeoERA scientific projects available and easy to use. The GeoERA TACTIC project has produced a range of model outputs including climate data, recharge values, groundwater heads, groundwater flows, in addition to their corresponding documentation. These data are visually displayed with different means such as using maps, time series plots, bar plots, etc., and then converted into a format that is accepted by the EGDI platform. TACTIC project includes six work packages, which all produced one or more outputs that are uploaded on the GIP. In this Section we show the approach followed to upload these data.

Licencing: GeoERA TACTIC project products are delivered to the GIP to be accessible by the public. However, we believe that these data will be used by the groundwater research community as a reference for comparison or for future development. All the data provided are based on conceptual models that are simplifications of real processes. The tools used to produce these data include a number of approximations that need to be taken into consideration when interpreting the data. The data are delivered, therefore, as best estimates at the time of writing this report; however, no guarantees are given to their validity considering the limitations of the conceptual models.

We anticipate that the data will be used to enhance knowledge in groundwater processes. We encourage the users to access the data and inform their research. For this reason, and for most of the data, we grant users the CC BY 4.0 Creative Commons Licence where they can. This license allows re-users to distribute, remix, adapt, and build upon the material in any medium or format for non-commercial purposes only, and only so long as attribution is given to the creator. For further details please refer to the GeoERA Licencing Data report (Luton and Tulstrup, 2020).

9.3 Methodology

A comprehensive methodology to upload data on the EGDI platform is provided by a report (Hanse, 2020, Introduction (geus.dk)) produced under WP6 and WP7 of the project "Information Platform" dedicated to address the development of a common geoscience information platform to integrate up-to-date data, interpretations and models from the three main geoscientific themes of GeoERA (Information platform – GeoERA). While we follow this methodology to upload TACTIC data on the EGDI, we are not going to describe it here, rather we will focus on the high-level approach followed to upload the data together with the important information regarding the preparation of data according to their visualisation type.

Before uploading data in the EGDI, a metadata describing the data set must be added in the EGDI Metadata Catalogue (MIcKA). The methodology used to create metadata is described in a report (Kramolisova et al., 2020, https://czechgeologicalsurvey.github.io/MICKA-Docs/) and the user is advised to refer to this report for the creation of a metadata. Here we give a brief description of the main items that are mandatory to include in the metadata. It must be noted, however, that not all the layers uploaded on the EGDI need a comprehensive metadata to be filled similar to that described in the report. For uploading pdf documents or figures for example, the EGDI will require the user to fill in a short metadata that includes a brief abstract, the name of the layer, the creation date, and author's name. For a layer that represents a map or any other spatial information, having the form of a GeoTiff or a GeoPackage, a full comprehensive metadata has to be created. Of the many items included in this comprehensive metadata, the following are the main entries:

- Resource title
- Resource abstract
- Topic category
- Keywords
- Geographic location
- Reference date
- Lineage
- Condition to access Responsible party
- coordinate reference

- Metadata point of contact
- etc.

Once the metadata is created and saved, the user needs to copy the hyperlink which will be used later to link the layer to be uploaded to its corresponding metadata. It must be noted that the metadata status needs to be set as “Public” for it to be accessible by the EGDI platform to link to the corresponding layer.

The procedure to upload a layer into the EGDI platform is as follows:

- At the front page of the EGDI platform
    - there is a link with text: “Upload documents/ images/ data/ doi” for documents and images
    - there is a link with text “Upload GeoPackage / GeoTIFF file” for uploading spatial data
- Click to open file explorer to select the required layer to upload
- Select the file name and hit upload.
- Add the link to the metadata and upload.

9.3.1 Times-series

This section includes the times series analysis at the scale of France. In order to represent the results of the analysis in the EGDI platform, four shapefiles have been created showing the locations of the selected boreholes in two reference periods 1976-2019 and 1996-2019. The shapefiles are then converted into a GeoPackage format as this is the only format accepted by the EGDI. In the TACTIC platform, there are:

- The layer of the aquifer group of France (grouping of major aquifers in France with different lithologies)
- Two layers showing the locations of all boreholes where trends have been calculated for monthly groundwater levels and cumulative effective precipitation for two reference periods 1976-2019 and 1996- 2019.
- Two other layers that represent the same values for the filtered data of groundwater levels and effective precipitation on the two periods.

The maps show comparison between groundwater (sticks in red) and effective precipitation (sticks in blue) trends magnitude and direction calculated with the Sen’s slope for each period (1996-2019 and 1976-2019). A downward stick indicates a negative Sen’s slope, and an upward stick indicates a positive Sen’s slope, while the stick length indicates the magnitude of trends. The small black line to the right of the sticks indicates the reference for positive or negative values of trends.

The significance of detected monotonic trends was determined with a modified Mann-Kendall trend test for autocorrelated data (Hamed and Ramachandra Rao, 1998). The statistical significance threshold was set at 5%. Indeed, the Sen’s slope (Sen, 1968) is defined as the median of the set of slopes calculated between each pair of points.

The geographic coordinate system used in QGIS is the EPSG4326 - WGS 1984. Once metadata are prepared and links are available, the same procedure mentioned in Section 10.3 is followed to upload these layers.

9.3.2 Pan-European scale and national scale models

TACTIC WP4 includes the estimation of recharge values on a Pan-European scale. In this study, recharge estimates from seven European countries are used in combination with remote sensing data and a machine learning approach to produce a harmonised Pan-European scale long-term average potential recharge map. Long-term average maps of actual evaporation and effective precipitation values are also produced as a bi-product of the model application. The data produced from this task are available in gridded ascii format. These are imported into a geographical information system where the spatial reference properties are set. The geographic coordinate system used in is the WGS 1984 which was accepted by the EGDI platform. Gridded files cannot be uploaded to the EGDI platform except in the GeoTIFF format. The adjusted grids are converted, therefore, into GeoTIFFs and then the procedure described in Section 10.3 is followed to upload this layer into the EGDI.

Five of the seven national scale long-term average recharge maps are also uploaded to the EGDI. These layers are included to highlight differences in recharge values when different methods are used to estimate these values. Care should be also taken when recharge values are compared at the same location as the different layers could be showing different types of recharge values. For example, the Pan-European recharge map is showing potential recharge values while other maps could be showing actual recharge values. Finally, the recharge rates shown in these maps are presented in mm/year.

9.3.3 Lumped models

A number of lumped models were applied in WP4 to estimate recharge values at selected boreholes. These models produce time-series of recharge values at point locations. A spreadsheet was created to read the model outputs for each borehole and to produce the four plots showing the long-term average values, the time-series over selected periods of times, estimated recharge values under future climate scenarios, and uncertainty in the estimated recharge values. This resulted in over 150 plots, which are converted into (.png) figure format, to upload to the EGDI. The procedure mentioned in this section 9 is followed to upload these figures; however, no detailed metadata is required for these figures, instead a short metadata form is filled straight after hitting the upload button for each figure. Once the figure is successfully uploaded, the hyperlink shown in the web browser is saved to be used in the next step.

In order to clearly present the data on the EGDI platform, four shapefiles showing the locations of all boreholes were created. These shapefiles are identical except that their attribute tables differ in one column where the hyperlinks are defined to show figures from one of the four category plots mentioned above. For example, one shapefile includes hyperlinks to figures displaying long-term average recharge values, another includes hyperlinks to figures displaying time series of recharge values etc.

The EGDI platform requires that these shapefiles are converted to GeoPackages. The simplest approach was to use the QGIS (https://qgis.org/en/site/) to convert the shapefiles to GeoPackages. The geographic coordinate system used in QGIS is the EPSG4326 - WGS 1984. Unlike figures, these GeoPackages represent spatial information and they require the preparation of detailed metadata before uploading them on the EGDI. Once metadata are prepared and links are available, the same procedure mentioned in Section 10.3 is followed to upload these layers.

9.3.4 Integrated models

Table 9.1 lists relevant outputs/data from integrated hydrological models and groundwater for storing at EGDI. The order of the records is not in prioritized order because model objectives can be very different.

Table 9.1 List of model outputs and data from integrated hydrogeological models stored at the EGDI

Decription	**data**	**Period**	**Condition**	**Unit**	**Comments ***
Groundwater head for the phreatic surface, reference	Areal	Reference period (1981-2010)	Mean of period	m.a.sl. or below surface	Most upper unconfined GW level, the GW table
Groundwater head for the phreatic surface, future	Areal	Future period/scenario (e.g. 2071-2100 or a + 1 og 3 degree C)	Mean of period	m.a.sl. or below surface	Most upper unconfined GW level, the GW table
Change for Groundwater head for the phreatic surface (future - reference)	Areal	Future - reference period	Based on mean of periods	m	Most upper unconfined GW level, the GW table
Groundwater head for primary aquifer used for abstraction, reference	Areal	Reference period (1981-2010)	Mean of period	m.a.sl.	Primary aquifer defined as the one most important for GW abstraction
Groundwater head for primary aquifer used for abstraction, future	Areal	Future period/scenario (e.g. 2071-2100 or a + 1 og 3 degree C)	Mean of period	m.a.sl.	Primary aquifer defined as the one most important for GW abstraction. Often also deep aquifer

Change for Groundwater head for primary aquifer used for abstraction (Future - reference)	Areal	Future - reference period	Based on mean of periods	m	Primary aquifer defined as the one most important for GW abstraction. Often also deep aquifer
Recharge map	Areal	Reference period (1981-2010)	Mean of period	mm/yr	
Recharge map	Areal	Future period/scenario (e.g. 2071-2100 or a + 1 og 3 degree C)	Mean of period	mm/yr	
Actual Evapotranspiration	Areal	Reference period (1981-2010)	Mean of period	mm/yr	
Interaction groundwater surface water (outflow /inflow to rivers, drains, etc.)	Areal and point	Reference period (1981-2010)	Mean of period	mm/yr or volumetric	
Water balance, reference	Areal and point	Reference period (1981-2010)	Mean of period	mm/yr or volumetric	
Water balance, future	Areal and point	Future period/scenario (e.g. 2071-2100 or a + 1 og 3 degree C)	Mean of period	mm/yr or volumetric	

* If the model is dynamic, transient, outputs from average winter, summer, or other seasons can be uploaded. Areal means spatially distributed data covering the analyzed area with data formats such as GeoTiff (tif), NetCDF and point data in data format of shapefile or GeoPackage.

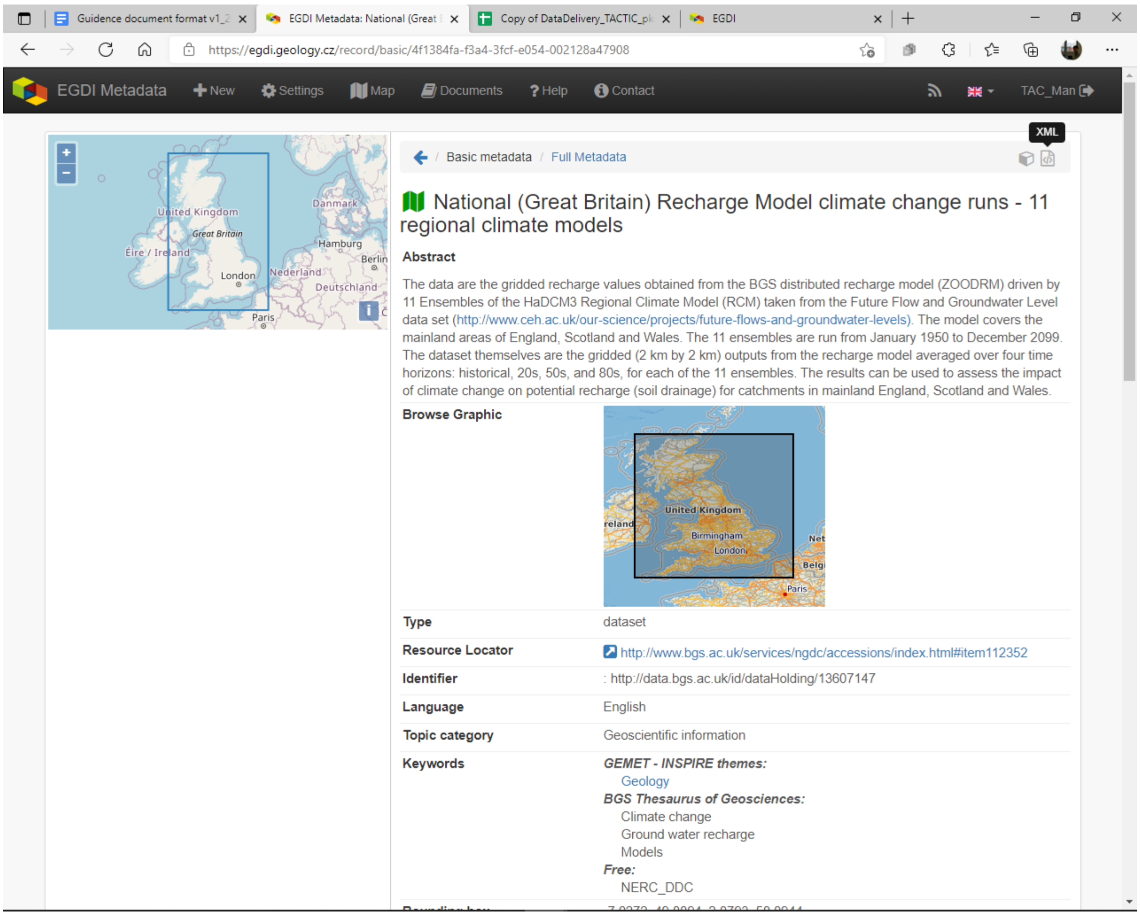
The integrated models most often produce spatially distributed grid or raster data of groundwater elevation for specific aquifers, e.g. phreatic surface in the top of the model, intermediate or deeper aquifers.

9.4 Case studies/Examples on how to upload to GIP

TACTIC project produced a range of hydrogeological information, such as groundwater heads, recharge, and effective precipitation in a gridded format. In this section we demonstrate the uploading of two layers, the first is showing gridded distributed information and the second is showing data at point locations. The upload of these layers must be preceded by the creation of detailed metadata that describes the type of the data and includes other information related to them. To create metadata, the following steps are followed:

- the user must have login credentials to use when accessing the metadata website using the link "https://egdi.geology.cz". Once logged in, a new record can be created by pressing the "New" tab at the top of the webpage.
- This will lead to a new webpage where the user defines the "Standard" (selected Iso19115), chooses a username for editing and the main language of the metadata. Press the "Create" tab to create a metadata.
- A new webpage will be displayed showing a metadata form. There are edit boxes in this form that are mandatory to fill in. These include: Resource title, abstract, type, etc. The web form provides a button next to each box title that if pressed displays help about the edit box. In addition, the user is referred to the cookbook accompanying this form and available at (https://egdi.geology.cz/catalog/micka/cookbook) for a detailed assistance to fill in the form.
- When the form is completed, the user can validate the entries by clicking the "Validate" tab located at the top right of the screen. Items with red colour indicate that they need further attention from the user.
- The user can stop and save the filled form once all the items in the validate list are green.
- Before stopping and saving the form, make sure the drop list next to the "Status" tab is set to "Public" otherwise it won't be possible to use metadata when uploading the layer.
- Finally, the webpage link provided at the top of the webpage must be copied to be used with the actual layer upload process.

An example of part of the metadata prepared for uploading the potential recharge values estimated over the British mainland is shown in Figure 9.1.



National (Great Britain) Recharge Model climate change runs - 11 regional climate models

Abstract

The data are the gridded recharge values obtained from the BGS distributed recharge model (ZOODRM) driven by 11 Ensembles of the HaDCM3 Regional Climate Model (RCM) taken from the Future Flow and Groundwater Level data set (http://www.ceh.ac.uk/our-science/projects/future-flows-and-groundwater-levels). The model covers the mainland areas of England, Scotland and Wales. The 11 ensembles are run from January 1950 to December 2099. The dataset themselves are the gridded (2 km by 2 km) outputs from the recharge model averaged over four time horizons: historical, 20s, 50s, and 80s, for each of the 11 ensembles. The results can be used to assess the impact of climate change on potential recharge (soil drainage) for catchments in mainland England, Scotland and Wales.

Browse Graphic	
Type	dataset
Resource Locator	http://www.bgs.ac.uk/services/ngdc/accessions/index.html#item112352
Identifier	: http://data.bgs.ac.uk/id/dataHolding/13607147
Language	English
Topic category	Geoscientific information
Keywords	***GEMET - INSPIRE themes:*** Geology ***BGS Thesaurus of Geosciences:*** Climate change Ground water recharge Models ***Free:*** NERC_DDC

Figure 9.1: An example showing the top part of the metadata prepared to upload the long-term average potential recharge values calculated over the British mainland.

9.4.1 Uploading a GeoTIFF showing gridded spatial information

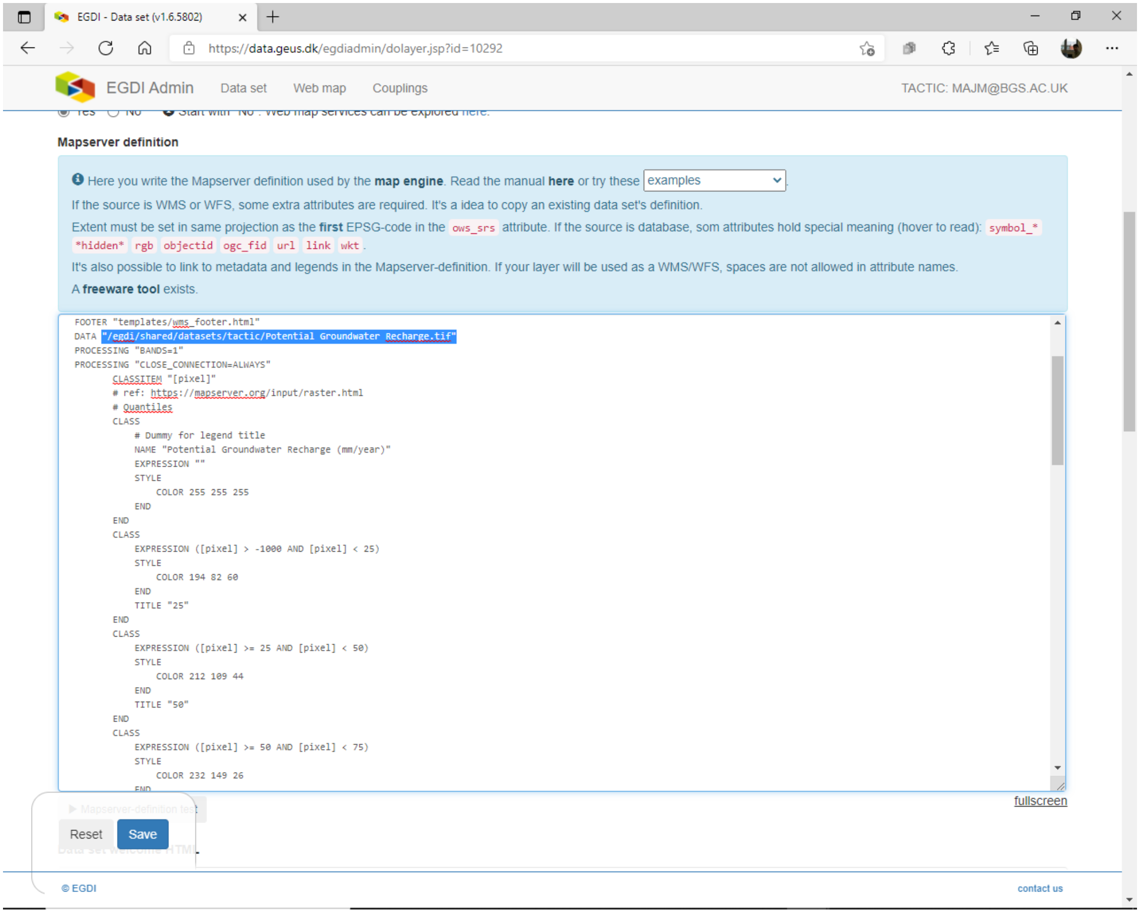
As mentioned earlier, the best format to upload gridded spatial data to the EGDI is the GeoTIFF format. one approach to create a layer in this format is to import the gridded ascii information into a geographical information system (GIS) and then export the layer using the GeoTIFF extension after setting the correct geographic coordinate system. In this section we use the layer related to the calculation of potential recharge across Europe to demonstrate the upload of a GeoTIFF layer to the EGDI.

The process of uploading a GeoTIFF layer to the EGDI platform consists of the following steps:

- Access the EGDI production platform using the link "https://data.geus.dk/egdiadmin/login.jsp" and use credentials to login into the system.
- Use the "Upload GeoPackage / GeoTIFF" tab to upload the layer
- Enter the metadata URL related to the layer being uploaded.
- Click and select the GeoTIFF layer from the computer.

- Specify the name of the layer
- Select the map “TACTIC_preview” in this case to add the layer to the map.

The layer will be displayed in the map using a grey scale. The user needs to update the displaying properties through accessing the dataset of the uploaded layer. The user can access the data set by clicking the “EDDI Admin” at the top of the webpage to go to the main webpage and then select the “Data set” tab at the top of the webpage. This will open a new webpage where the user can search for a dataset. Use the keyword “TACTIC” to display the datasets related to the project TACTIC (Assuming that the word TACTIC has been used when the metadata is created). Click on the name of the dataset to get into a new page displaying details related to the dataset. Here, we are interested in the “Mapserver definition” box. The details in this box are used by the map engine to display the layer. To define a new colour map, the user needs to edit this box to specify a colour that is related to a range of recharge values. Figure 9.2 shows an example where the recharge values of the layer "/egdi/shared/datasets/tactic/Potential Groundwater Recharge.tif" are displayed using the colours specified in the shown code.



Mapserver definition

Here you write the Mapserver definition used by the **map engine**. Read the manual **here** or try these examples.

If the source is WMS or WFS, some extra attributes are required. It's a idea to copy an existing data set's definition.

Extent must be set in same projection as the **first** EPSG-code in the `ows_srs` attribute. If the source is database, som attributes hold special meaning (hover to read): `symbol_*` `*hidden*` `rgb` `objectid` `ogc_fid` `url` `link` `wkt`.

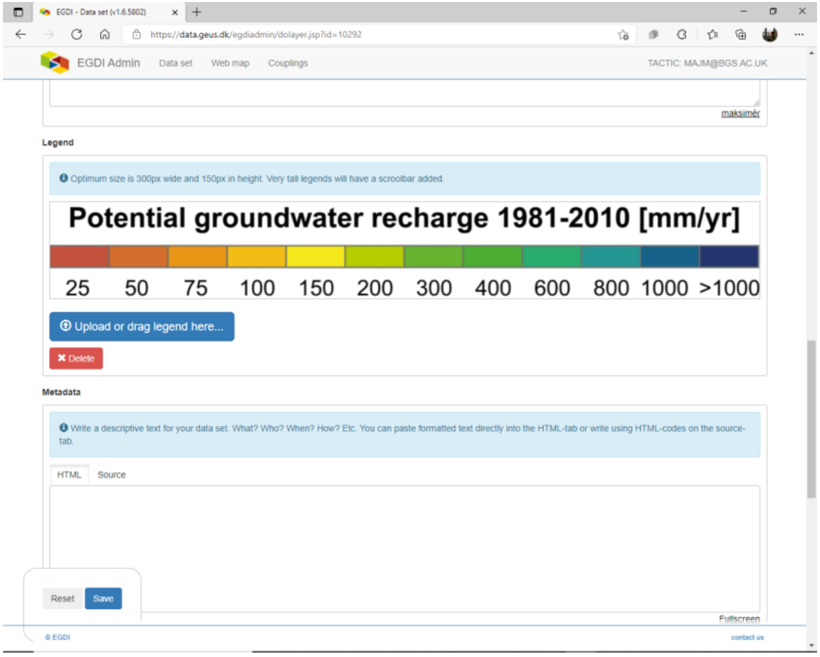
It's also possible to link to metadata and legends in the Mapserver-definition. If your layer will be used as a WMS/WFS, spaces are not allowed in attribute names.

A **freeware tool** exists.

```
FOOTER "templates/wms_footer.html"
DATA "/egdi/shared/datasets/tactic/Potential Groundwater Recharge.tif"
PROCESSING "BANDS=1"
PROCESSING "CLOSE_CONNECTION=ALWAYS"
       CLASSITEM "[pixel]"
       # ref: https://mapserver.org/input/raster.html
       # Quantiles
       CLASS
           # Dummy for legend title
           NAME "Potential Groundwater Recharge (mm/year)"
           EXPRESSION ""
           STYLE
               COLOR 255 255 255
           END
       END
       CLASS
           EXPRESSION ([pixel] > -1000 AND [pixel] < 25)
           STYLE
               COLOR 194 82 60
           END
           TITLE "25"
       END
       CLASS
           EXPRESSION ([pixel] >= 25 AND [pixel] < 50)
           STYLE
               COLOR 212 109 44
           END
           TITLE "50"
       END
       CLASS
           EXPRESSION ([pixel] >= 50 AND [pixel] < 75)
           STYLE
               COLOR 232 149 26
           END
```

Figure 9.2 Example of modifying the Mapserver definition box to change the characteristics of colour map of the displayed grid

A legend can be added to the map displaying the layer. However, this legend has to be prepared outside the EGDI platform and provided to it in the form of a figure that has a jpg or png extension. Figure 9.3 shows an example legend that is related to the uploaded layer and added in the box dedicated to the legend within the layer data set.

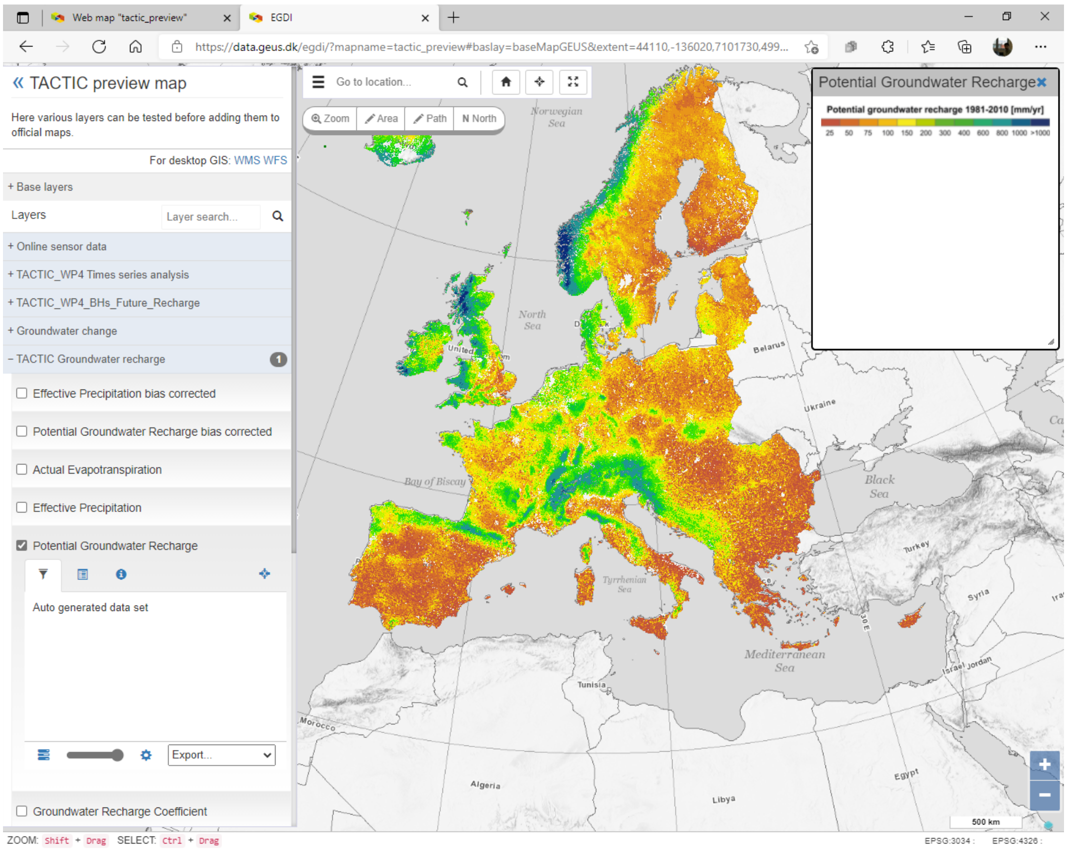


Optimum size is 300px wide and 150px in height. Very tall legends will have a scroolbar added.

Write a descriptive text for your data set. What? Who? When? How? Etc. You can paste formatted text directly into the HTML-tab or write using HTML-codes on the source-tab.

Figure 9.3 Example of a legend imported into the dataset definition as a picture.

An example of the potential groundwater recharge estimated at a pan-European scale is shown in Figure 9.4.



Here various layers can be tested before adding them to official maps.

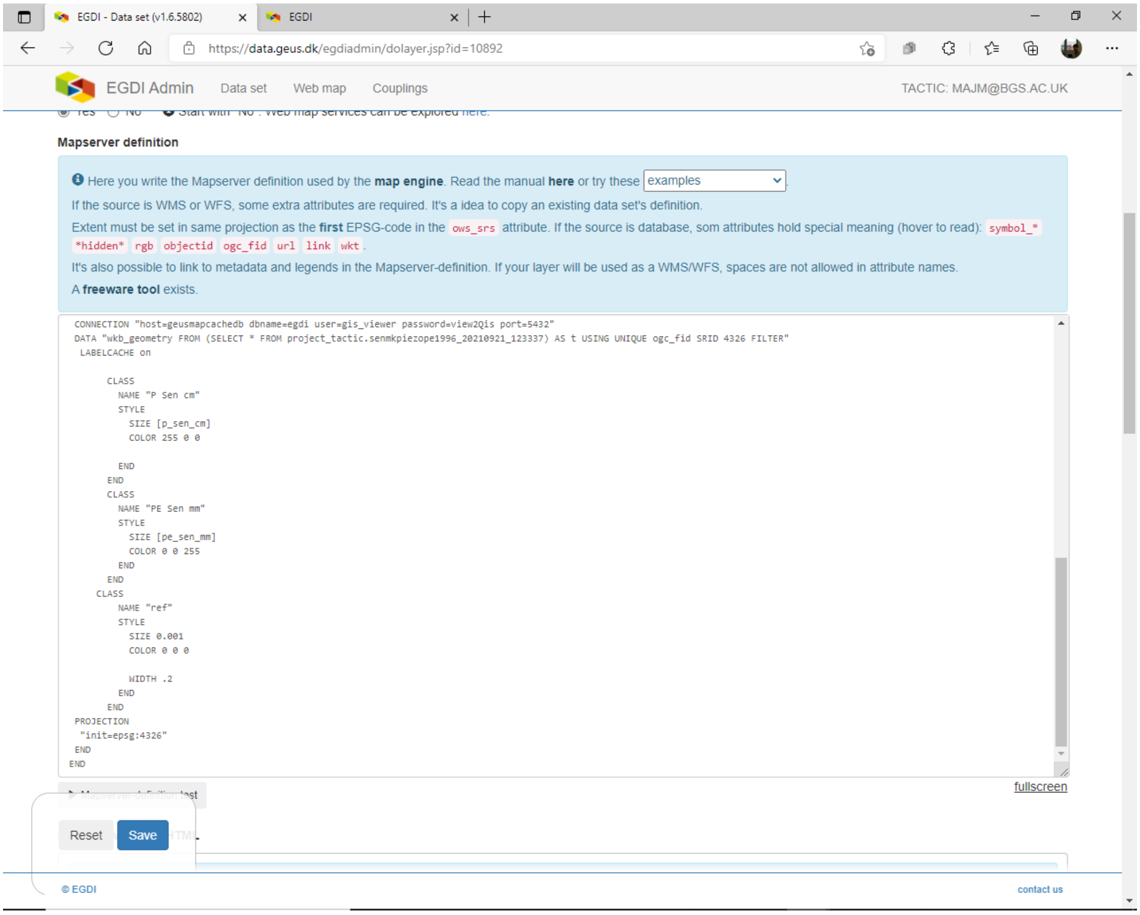
Auto generated data set

Figure 9.4 The pan-European scale potential groundwater recharge values uploaded to the EGDI.

9.4.2 Uploading a GeoPackage showing point information

TACTIC project provided output at selected boreholes. The information includes recharge values, groundwater levels, etc. To display this information in a map, a shapefile is created to show the locations of these boreholes. The shapefile is then converted into a GeoPackage format as this is the only format accepted by the EGDI platform alongside the GeoTIFF format. In this section we use the analysis of time series of groundwater levels and effective precipitation at boreholes with France as an example to demonstrate how to display point information on the EGDI platform. The layer shows the trends of groundwater levels and effective precipitation calculated over the period 1996 to 2019.

The process of uploading the GeoPackage layer is as described in Section 9.4.1. The locations of the boreholes will be represented by points with a colour selected automatically by the system. In a similar manner to changing the colours of the map legend discussed in Section 9.4.1, the same approach can be used to update the shape, size, and colour of the displayed points. To achieve this, the user needs to access the data set of the layer by clicking the “EGDI Admin” at the top of the webpage after uploading the layer. This to go to the main webpage and then select the “Data set” tab at the top of the webpage. This will open a new webpage where the user can search for a dataset. Use the keyword “TACTIC” to display the datasets related to the project TACTIC (Assuming that the word TACTIC has been used when the metadata is created). Click on the name of the dataset to get into a new page displaying details related to the dataset. The code in the “MapServer definition” box is updated to reflect the desired shape, size and colour of the point feature. An example of the modified entries in the MapServer definition box is shown in Figure 9.5.



Mapserver definition

Here you write the Mapserver definition used by the **map engine**. Read the manual **here** or try these examples.

If the source is WMS or WFS, some extra attributes are required. It's a idea to copy an existing data set's definition.

Extent must be set in same projection as the **first** EPSG-code in the `ows_srs` attribute. If the source is database, som attributes hold special meaning (hover to read): `symbol_*` `*hidden*` `rgb` `objectid` `ogc_fid` `url` `link` `wkt`.

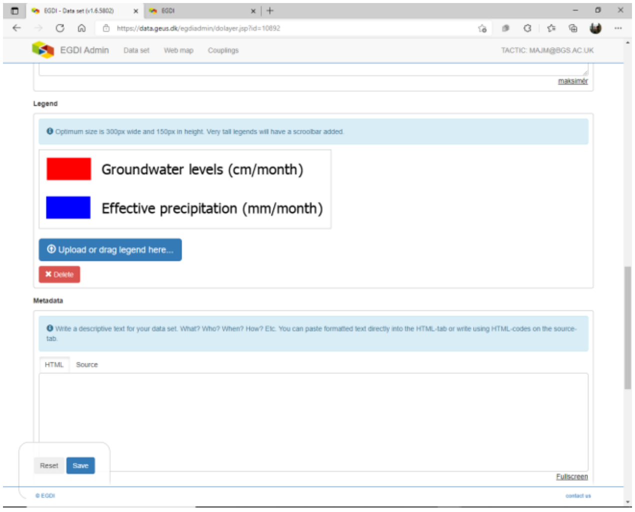
It's also possible to link to metadata and legends in the Mapserver-definition. If your layer will be used as a WMS/WFS, spaces are not allowed in attribute names.

A **freeware tool** exists.

```
CONNECTION "host=geusmapcachedb dbname=egdi user=gis_viewer password=view2Qis port=5432"
DATA "wkb_geometry FROM (SELECT * FROM project_tactic.senmkpiezope1996_20210921_123337) AS t USING UNIQUE ogc_fid SRID 4326 FILTER"
 LABELCACHE on

      CLASS
        NAME "P Sen cm"
        STYLE
          SIZE [p_sen_cm]
          COLOR 255 0 0

        END
      END
      CLASS
        NAME "PE Sen mm"
        STYLE
          SIZE [pe_sen_mm]
          COLOR 0 0 255
        END
      END
    CLASS
        NAME "ref"
        STYLE
          SIZE 0.001
          COLOR 0 0 0

          WIDTH .2
        END
      END
 PROJECTION
  "init=epsg:4326"
 END
END
```

Figure 9.5 Example of modifying the Mapserver definition box to change the characteristics of the displayed point feature

A legend can be added to the displayed map. As explained in Section 9.4.1, this legend has to be prepared outside the EGDI platform and uploaded to EGDI as a figure that has a jpg or png extension. Figure 9.6 shows an example legend that is related to the uploaded point feature layer and added in the box dedicated to the legend within the layer data set.



Legend

Optimum size is 300px wide and 150px in height. Very tall legends will have a scroolbar added.

🟥 Groundwater levels (cm/month)

🟦 Effective precipitation (mm/month)

Metadata

Write a descriptive text for your data set. What? Who? When? How? Etc. You can paste formatted text directly into the HTML-tab or write using HTML-codes on the source-tab.

Figure 9.6 Example of a legend imported into the dataset definition as a picture.

An example of a point feature showing specific information, the trends of groundwater levels and effective precipitation values in this case, is shown in Figure 9.7.

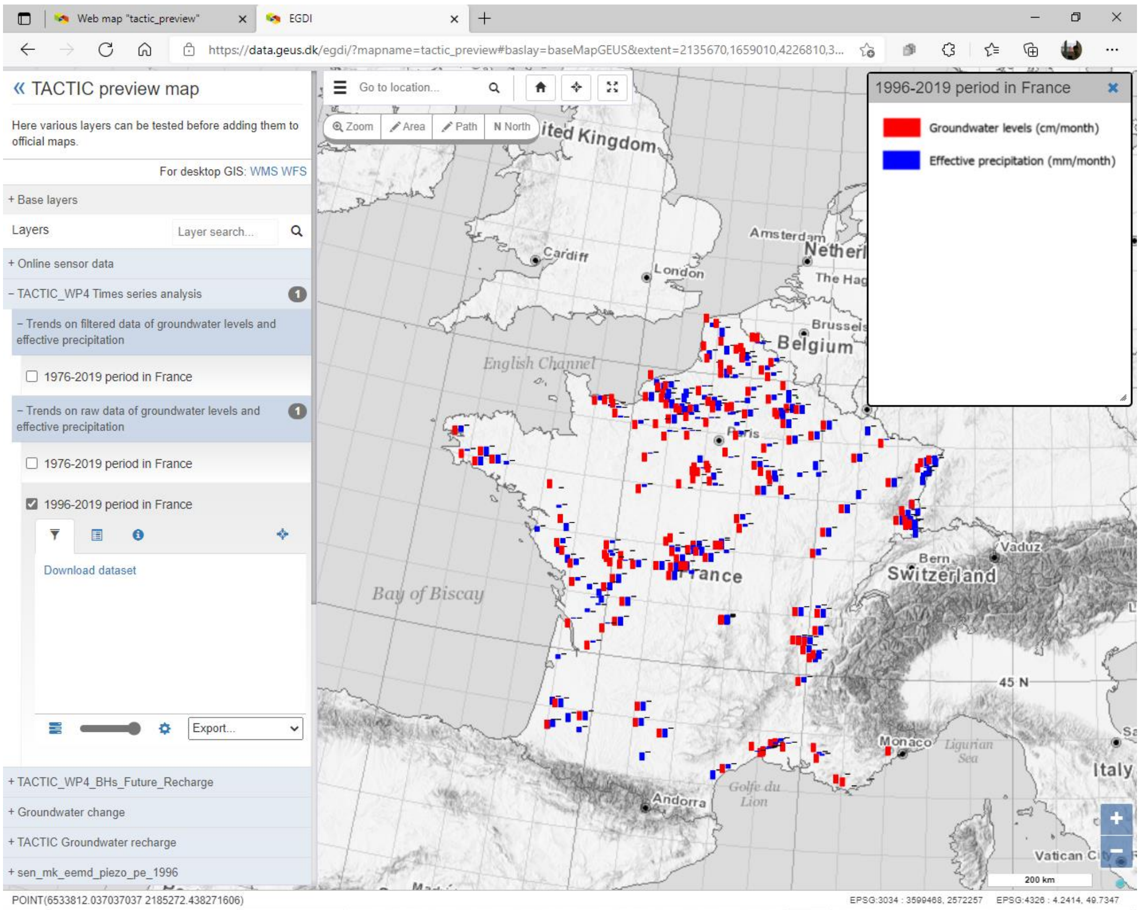


Figure 9.7 Trend values of groundwater level and effective precipitation calculated over the period 1996 to 2019 uploaded to the EGDI.

9.5 Conclusion: Pitfalls, pros and cons

The EGDI platform provides a flexible medium to disseminate data for the scientific community and for the public. There are enough resources prepared by the EGDI working group to guide the user through the process of uploading data to the platform in an easy and straight forward approach. Minimum interaction was needed with the EGDI developers to be able to complete the task as the process is clearly detailed in the supporting documents. The detailed metadata were easily prepared once the first metadata was created as the system allowed cloning and modifying the metadata. However, the preparation of metadata for documents and figures was found to be time consuming and repetitive as no automatic procedure to fill in these metadata was provided. It must be noted that the metadata of these documents and figures are not exhaustive to fill in; however, the problem stems from the need to fill forms for hundreds of items.

The EGDI platform allows the upload of spatially distributed data in the form of GeoTIFF grids or point GeoPackage information. The selection of the geographic coordinate system for the data originating from the different countries was not a straightforward task. In addition, the platform allows the upload of the GeoTIFF layer but it does not allow for querying information from the layers. This is a functionality that is highly desired to have in such an application. The point GeoPackage data, on the other hand, are clickable to provide information from the corresponding attribute table. This is a useful functionality that allows the user to include a link to a figure to display. It would be also desirable, however, to have the possibility to display the figure by clicking on the point directly without resorting to the link provided in the table.

The EGDI platform is a powerful tool that can be used to display both gridded and point information. It is flexible as it links to figures showing plots and to reports. The display is clear and allows for zooming in for detailed information and zooming out for large scale displays. The system also allows for an organised display of layers in a hierarchical form and from where the user can select layers to display.

References and further reading to ANNEX

Luton, C. and Tulstrup, J. 2020. GeoERA - Licencing Data and other material. A report for a project that has received funding by the European Union’s Horizon 2020 research and innovation programme under grant agreement number 731166.

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