DRIN CORDA

Enabling Transboundary Cooperation & Integrated Water Resources Management in the extended DRIN RIVER BASIN

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Guidelines for Monitoring Strategies in Transboundary Aquifers: Goals, Methods and Tools. The Case of the DRIN project (ALB-MTN)

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The Coordinated Action for the implementation of the Memorandum of Understanding for the management of the Drin basin (Drin CORDA) is supported by the GEF Drin Project. Thus, the latter constitutes an institutional project implemented by the United Nations Development Programme (UNDP) and executed by the Global Water Partnership (GWP) through GWP-Mediterranean (GWP-Med), in cooperation with the United Nations Economic Commission for Europe (UNECE). The Drin Core Group (DCG), being the multilateral body responsible for the implementation of the Memorandum of Understanding serves as the Steering Committee of the Project. GWP-Med serves as the Secretariat of the DCG.

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1 Introduction and scope

Monitoring is, beyond any doubt, the key aspect to support decision-making processes and for a successful implementation of water management strategies. Gathering field data, on one hand, permits obtaining information and creating knowledge (Figure 1).

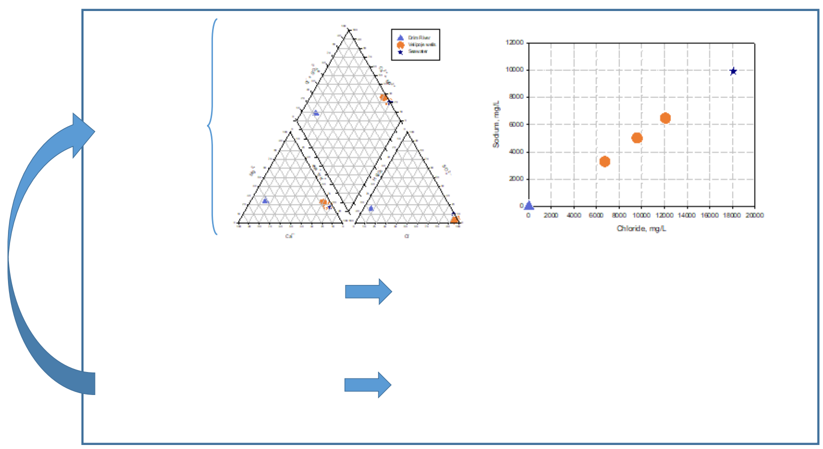

Figure 1.- Process from data – information – knowledge

On the other, this knowledge is then used to create initiatives that will be included in water resources planning in order to meet human demand, as well as the environmental goals inherent to any natural resources exploitation development.

In particular, transboundary aquifers are specific cases where the continuous path from gathering data, acquiring information, and creating knowledge is more delicate as it has to meet the licit interests of two distinct countries, each one of them with its own needs, interests and idiosyncrasy; yet both of them must agree on protecting their common resources and preventing environmental degradation while satisfying their water demand. It is indeed a negotiation process that must end up with a political agreement based on respect to each site interests and a common goal of environmental protection, meaning that overexploitation must be avoided at all costs. Therefore, field data regarding the characterization of the shared groundwater bodies must be gathered based on a common strategy, so decisions can be made on equal grounds of knowledge and commitment.

Based on previous reports[1], the scope of this webinar is to develop technical guidelines that set a knowledge baseline about groundwater monitoring in transboundary aquifers among stakeholders with different backgrounds (geologist, lawyers, economists, engineers, …), and organizations (administration, research institutions, operators, …). Effort has been made to summarize suitable monitoring methods and approaches to develop a monitoring network and to attain groundwater management and environmental goals in transboundary aquifers based on the EU Water Framework Directive (WFD) regulations for operation in the two hydrogeology context chosen in the project (coastal area and inland alluvial aquifer).

The webinar that presents such guidelines is structured in several sessions that cover distinct aspects from the legal EU setting defined by the Water Framework Directive (WFD) and some conceptual issues on aquifer characterization to practical monitoring methods and tools to gather quantity (hydraulic head) and quality data (hydrochemistry, pollutants, …) from groundwater bodies. Through the content of these sessions, we insist on the fact that data must be interpreted on the context of a conceptual model that comprehensively describe groundwater dynamics (recharge areas, flow paths, interaction with streams, rivers and groundwater dependent ecosystems, exploitation rates, and finally, discharge areas).

The content of this webinar is addressed to administration officials in charge of water resources management, professionals and technicians involved in monitoring plans, and environmental professionals and stakeholders concerned with the management of transboundary aquifers and/or the implementation of the EU WFD (or similar regulations) in the frame. Therefore, its content look forward a didactic exposition that will enable the addressees to be aware of the goals, methods and tools that are finally involved in a monitoring network design and data gathering program.

[1] "*Hydrogeological conceptual model of the Skadar/Shkoder – Buna/Bojana Transboundary Aquifer System situated between Albania and Montenegro*" authored by L. del Val Alonso (2019), and "*Design and development of a groundwater-monitoring network and program for the transboundary aquifer between Albania and Montenegro*" authored by J. Mas-Pla (2019), both in the context of the UNESCO project "Design and testing of a multipurpose transboundary groundwater monitoring network in the Extended Drin River Basin" (DRIN).

2 Motivation for groundwater monitoring in the European context: the Water Framework Directive

Groundwater monitoring is a basic effort to achieve a sustainable water resources management. Defining sustainability in the context of water resources is quite difficult, since many variables are involved in its use and exploitation: environmental, economic and social issues must be included to insure ecological preservation and human well-being. Indeed, one of the most well-known definition for a sustainable use of water resources was stated by the Australian National Groundwater Committee, in 2002, which declares a sustainable exploitation as "*The groundwater extraction regime measured over a specified planning time frame that allows acceptable levels of stress and protects dependent economic, social and environmental values*". The definition was released subject to the proviso that it should be read in conjunction with a series of qualifications that occupies two pages. The qualifications recognised that the total extraction volume is not necessarily the most important part of a groundwater management regime, that some level of stress on the aquifer will occur, that there may be some storage depletion, and highlighted the need for trade-offs between these aspects[2].

Back to the legal frame, the Water Framework Directive (WFD; 2000/60/EC) is a comprehensive piece of legislation that sets out "good status" objectives for all waters in Europe. The WFD looks forward the integration of different decision-making levels that influence water resources, be local, or national, for an effective management of all waters. This integration is actually more relevant for transboundary aquifers.

Later on, on 2006, the EU Groundwater Directive (GWD; 2006/118/EC) was issued with the aim of preventing and combating groundwater pollution in the European Union. It includes

[2] For a deeper discussion on the sustainability concept: Kalf, F.R.P., Woolley, D.R. Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeol J* 13, 295–312 (2005). https://doi.org/10.1007/s10040-004-0401-x

procedures for assessing the chemical status of groundwater and measures to reduce levels of pollutants.

Under the WFD, the framework for groundwater protection imposes on Member States to:

i. delineate groundwater bodies within River Basin Districts and characterise them through an analysis of pressures and impacts of human activity on the status of groundwater in order to identify groundwater bodies presenting a risk of not achieving WFD environmental objectives,
ii. establish registers of protected areas within each river basin districts for those groundwater areas or habitats and species directly depending on water, including all bodies of water presently used for the abstraction of water intended for human consumption and those intended for such future use,
iii. establish a groundwater monitoring network providing a comprehensive overview of the groundwater chemical and quantitative statuses,
iv. Set up a river basin management plan (RBMP), and establish a programme of measures for achieving WFD environmental objectives (e.g. abstraction control, measures to prevent or control pollution). In particular, a river basin where use of water *may have transboundary effects*, the requirements for the achievement of the environmental should be coordinated for the whole of the river basin district, producing a single international RBMP. Moreover, the GWD state that Member States sharing bodies of groundwater should coordinate their activities in respect of monitoring (set in Annex V, point2, of the WFD), the setting of threshold values, and the identification of relevant hazardous substances.

As mentioned, the Groundwater Directive is to be seen as part of the framework provided by the WFD, defining groundwater management as an integrated part of river basin management. It establishes specific measures in order to prevent and control groundwater pollution, specifically,

a. Criteria for the assessment of good groundwater chemical status,
b. Criteria for the assessment of a good qualitative status,

c. Criteria for the identification of significant trends of groundwater pollution, with special emphasis to stop upward concentration trends.

Pressures and Impacts

According to the WFD, a review of the effects of human activity on the status of surface waters and groundwater must be conducted. Human activity (as *drivers*) produces pressures that influences negatively the characteristics and operations cause a malfunctioning of the hydrological system or water bodies, resulting in impacts that deteriorate water resources in quantity and quality (*states*). Management actions must be based on the knowledge of the water bodies, the identification of the existing *pressures* and the assessment of the resulting *impacts*. Actions should thus be devoted to alleviate the effect of and subsequently decrease correct such pressures so their impacts are minimized (*response*), and good statuses is are finally attained. The vulnerability analysis provides a contextual framework for this task.

Monitoring network and program

The monitoring program provides is a means to analyse the effects of human activity upon a groundwater body (Figure 2). Assessing the likely impacts arising from each of the pressures will produce a list that can be used to identify points where monitoring is necessary to better understand whether the water body is at risk of failing to achieve good status.

Monitoring goals

The establishment of high quality long-term monitoring programs is essential to achieve the WFD goals. It is recognized that monitoring can be expensive, so the guidance presented here aims to establish cost-effective, risk-based and targeted groundwater monitoring across Europe that enables WFD objectives to be met. A monitoring program always is *objective-driven*; in our case, to fulfil the goals defined by the WFD.

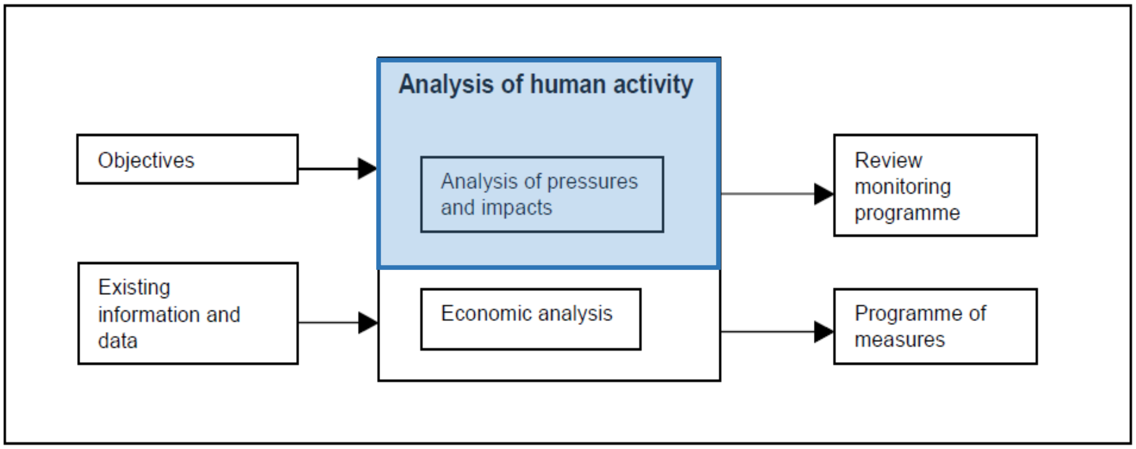

Figure 2 Monitoring programs, within the water management planning process, permits characterizing the water body and detect alterations.

Always recall that m*onitoring programs create knowledge!*

What is a monitoring network?

Groundwater monitoring networks can serve many different purposes and be constructed on varying scales and extents. Groundwater monitoring networks are generally designed to answer one or more of the following questions[3]:

- In what direction is groundwater flowing?
- Is groundwater abstraction sustainable?
- How do seasonal and climatic variations in recharge affect water use in a basin?
- Where is recharge coming from in a basin?
- What are the contributing sources of diffuse groundwater contamination?
- Where is point-source contamination going and how quickly?
- What are the long-term trends in groundwater quality?
- What is the status of water quality in a basin?

Therefore, *monitoring networks* are devoted to fulfil data to build up a conceptual model and to assess pressures and impacts so management actions can be taken. Data come out monitoring programs, which establish the location of the sampling points, data acquisition

[3] Rosen MR (2009). Groundwater monitoring networks. UNESCO-EOLSS.

frequency, and analytical parameters to be considered to answer one, or many, of the stated questions.

Groundwater monitoring and groundwater data acquisition are pre-requisites for any effective management of groundwater resources, in terms of both the groundwater quality and the availability of the groundwater resource itself. Because of the complexities of groundwater systems, the design and operation of an effective groundwater monitoring is far from simple. Yet well-designed monitoring systems are capable of providing vital aquifer information at a reasonable cost.

Article 8 of the WFD requires the establishment of programmes for the monitoring of groundwater. WFD groundwater monitoring is focussed primarily on the groundwater body as a whole, but it also supports the overall management of the river basin district and the achievement of its environmental objectives. Monitoring networks should focus on specific areas where WFD objectives are at risk, as well as to depict the heterogeneity of aquifer and its variable behaviour resulting from one or several simultaneous pressures.

The establishment of high quality long-term monitoring programmes is essential if the implementation of the WFD and the daughter Groundwater Directive is to be effective. It is recognised that monitoring can be very expensive and so the guidance presented here aims to establish cost-effective, risk-based and targeted groundwater monitoring across Europe that enables WFD objectives to be met. However, inadequate investment in monitoring, including network infrastructure and data quality and management will result in a significant risk of failure to meet the WFD’s environmental objectives.

A monitoring network shall be designed so as to provide a coherent and comprehensive overview of groundwater qualitative and quantitative statuses within each river basin and to detect potential impacts and the presence of long-term anthropogenically induced upward trends in the effects of resulting impacts; i.e., hydraulic head declines and, more specifically, the increase of pollutant concentration.

A monitoring program always is *objective-driven*; in our case, to fulfil the WFD goals. A monitoring cycle involves defining this goals, considering the monitoring network and program, analyse data, program actions, evaluate responses and, if necessary, redefine the monitoring network and program again (Figure 2).

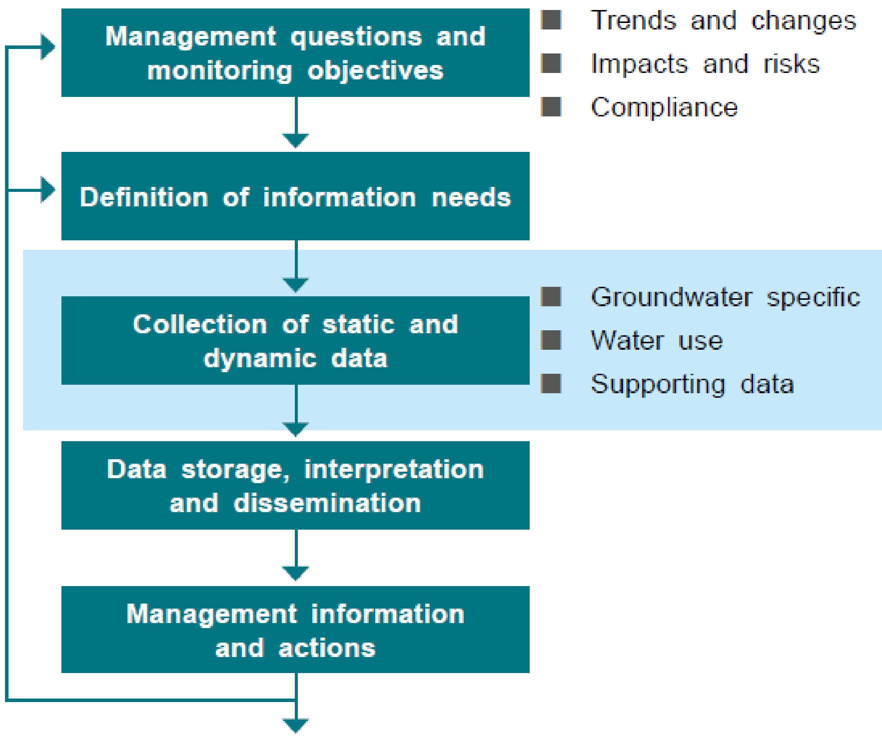

Figure 3 Monitoring cycle: objectives > monitoring > data > actions > monitoring

3 Guidelines - Content of the webinar sessions

As mentioned, the scope of this webinar is to develop technical guidelines that set a knowledge baseline about groundwater monitoring in transboundary aquifers among stakeholders with different backgrounds (geologist, lawyers, economists, engineers, …), and organizations (administration, research institutions, operators, …). It is addressed to administration officials in charge of water resources management, professionals and technicians involved in monitoring plans, and environmental professionals and stakeholders concerned with the management of transboundary aquifers and/or the implementation of the EU WFD (or similar regulations) in the frame.

The outline of each session of the webinar is hereafter described and complemented by the presentations that will be shown during the webinar celebration. Each section in this guidelines develops the presentation and includes all the concepts presented in the webinar. We finally suggest some additional readings that may be useful to complement the content of this Guidance document.

3.1 Session 1.- Monitoring for management

Why monitoring is paramount to address appropriate groundwater resources management and to attain EU WFD environmental goals? The specific case of transboundary aquifers

According to the WFD, the environmental objectives for groundwater bodies consist on (WFD; Article 4),

i. implementing the measures necessary to prevent or limit the input of pollutants into groundwater,
ii. protecting, enhancing and restoring all bodies of groundwater, ensuring a balance between abstraction and recharge of groundwater, with the aim of achieving good groundwater status, and
iii. implementing the measures necessary to reverse any significant and sustained upward trend in the concentration of any pollutant resulting from the impact of human activity.

Previous knowledge of a GWB must include:

a) Geological features of the hydrogeological system,
b) Hydrogeological characteristics of the flow system: recharge and discharge areas, regional vs local flow systems, interaction between surface water and groundwater bodies, …,
c) Potentiometric maps under non-influenced conditions, where possible,
d) Natural (background) hydrochemical composition of the aquifer (quality),
e) Human pressures affecting quantitative and qualitative status of the GWBs (Table 1). Concept of over-exploitation,
f) Impacts derived from the identified pressures.

Monitoring must be organized so points c), d) and f) are properly characterized considering spatial and temporal variability. In particular, temporal changes are paramount to identify pollutant concentration trends necessary to determine the need of actions to attain the environmental goals.

Indeed, by acquiring hydrogeological knowledge and gathering field data, we look for creating a conceptual model of the aquifer system that comprehensibly includes all its known physical properties and define the overall flow system. In particular, we seek to define a potentiometric map that reveals the flow paths, and its seasonal variability, as well as the extent of the groundwater quality parameters, mainly those related to pollution.

Therefore, monitoring must address the following issues:

1. Characterize background head levels and concentration levels, where possible, so future impacts can be clearly detected,
2. Identify the type, magnitude and extent of the impact, whether quantitative (as enlarging depression cones) or qualitative (upward trend of a pollutant concentration),
3. Inform about the effect of applied measures on the hydrogeological dynamics, given by a reverse of declining head levels or an upward concentration trend.

Transboundary aquifers are specific cases where the continuous path from gathering data, acquiring information, and creating knowledge is more delicate as it has to meet the licit interests of two distinct countries, each one of them with its own needs, interests and idiosyncrasy; yet both of them must agree on protecting their common resources and preventing environmental degradation while satisfying their water demand. It is indeed a negotiation process that must end up with a political agreement based on respect to each site interests and a common goal of environmental protection, meaning that overexploitation must be avoid at all costs. Therefore, field data regarding the characterization of the shared groundwater bodies must be gathered based on a common strategy so decisions can be made on equal grounds of knowledge and commitment.

Area	Point source pollution	Diffuse pollution	Change in water levels due to abstraction
Skadar Lake area:			
Zeta Plain (MTN)	✓ Aluminium production facility. ✓ Food-processing and plastic industries as potential pollution focuses. ✓ Gravel mining along Morača River.	✓ Fertilization (nutrients and pesticides) in cereal and forage crops using slurries and manures (not in vineyards). ✓ Stream recharge due to well capture zones, depending on the Morača River quality potentially affected by wastewater dumping (urban drainage) and leaking septic systems.	✓ Water abstraction in Podgorica urban area (MTN). ✓ Water abstraction due to agricultural activity (MTN).
Koplik-Shkodër Plain (ALB)		✓ Fertilization in cereal and forage crops using slurries and manures	
Buna/Bojana River area:			
Trush – Zadrima Basin (ALB, MTN)	✓ Landfill near Shkjezë (ALB). ✓ Saski Lake has been reported to show high heavy metal concentrations. ✓ Gravel mining along the Drin River left-bank, near Ashtë (ALB). ✓ Pollution from septic systems and network (where existing).	✓ Fertilization in cereal and forage crops using slurries and manures (ALB, MTN).	✓ Well field near Fshati i Ri for urban supply (ALB). ✓ Overpumping for agricultural demand (ALB).
Buna/Bojana delta area (ALB, MTN)	✓ Leakage from salt production ponds (ALB, MTN).	✓ Fertilization (nutrients, especially P, and pesticides) in cereal and forage crops using slurries and manures (ALB, MTN). ✓ Stream recharge due to well capture zones affected by wastewater dumping (urban drainage). ✓ Non-farmed stock breading (ALB).	✓ Domestic and agriculture wells near the coastline in Velipojë (ALB) and Doni Štoj (MTN): effects on wetlands and lagoons due to head level decline, and drivers of seawater intrusion. ✓ Saline water in karstic springs (Gac spring). ✓ River salinization.

Table 1 Identified pressures on groundwater resources (ALB: Albania, MTN: Montenegro).

- ***Further reading***

Water Framework Directive (WFD).- Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy
https://www.eea.europa.eu/policy-documents/directive-2000-60-ec-of

Groundwater Directive (GWD).- Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration.
https://www.eea.europa.eu/policy-documents/groundwater-directive-gwd-2006-118-ec

WFD Guidance Documents.- Guidance Documents are intended to provide an overall methodological approach, but will need to be tailored to the specific circumstances of each EU Member State.
https://ec.europa.eu/environment/water/water-framework/facts_figures/guidance_docs_en.htm

EU-WFD Guidelines Document 3 - *Analysis of Pressures and Impacts*.
https://circabc.europa.eu/sd/a/7e01a7e0-9ccb-4f3d-8cec-aeef1335c2f7/Guidance%20No%203%20-%20pressures%20and%20impacts%20-%20IMPRESS%20(WG%202.1).pdf

EU-WFD Technical Report 1 - *The EU Water Framework Directive: statistical aspects of the identification of groundwater pollution trends, and aggregation of monitoring results*.
https://circabc.europa.eu/sd/a/a1f194ce-8684-436c-a130-ec88ee781bd2/Groundwater%20trend%20report.pdf

ACSAD-BGR Technical Cooperation Project, 2004. Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region - Volume 7 - Guideline for Groundwater Monitoring

Lapham et al., 1995. *Ground-water data-collection protocols and procedures for the national water-quality assessment program: Selection, installation, and documentation of wells, and collection of related data*. U.S. Geological Survey Open-File Report 95-398.

3.2 Session 2.- Hydrogeological conceptual model

The hydrogeological conceptual model as an initial step towards design of a monitoring network. Data requirements, basic issues (including pressures, impacts, vulnerability and risks) to be considered

The EU WFD states that the design of a monitoring network should be based on the “characterization, assessment of risk and building of a conceptual model of the groundwater system, in which the general scheme ‘recharge-pathway-discharge’ is known”. Therefore, the first step in the design of a groundwater-monitoring programme is to generate a hydrogeological conceptual model of the transboundary aquifer system, as required by the EU WFD. Additionally ,and in the context of the EU WFD the definition of groundwater bodies, as the management unit, is also identify as one the first steps.

- ***What is a hydrogeological conceptual model?***

A conceptual model is a simplified representation, or working description, of a hydrogeological system. It describes and quantifies the relevant geological characteristics, flow conditions, hydrogeochemical and hydrobiological processes, anthropogenic activities and their interactions[4]. Under the European Water Framework Directive (EU-WFD), the conceptual model is stablished as one of the steps in the water management cycle (Figure 4). It is actually the basis of the initial characterization required for all EU-member states and a requirement for the design of the monitoring network. Moreover, it serves as reference along the management process and should be updated in each management cycle.

[4] EU-WFD Guidelines Document 26 on “Risk assessment and the use of Conceptual models for Groundwater”

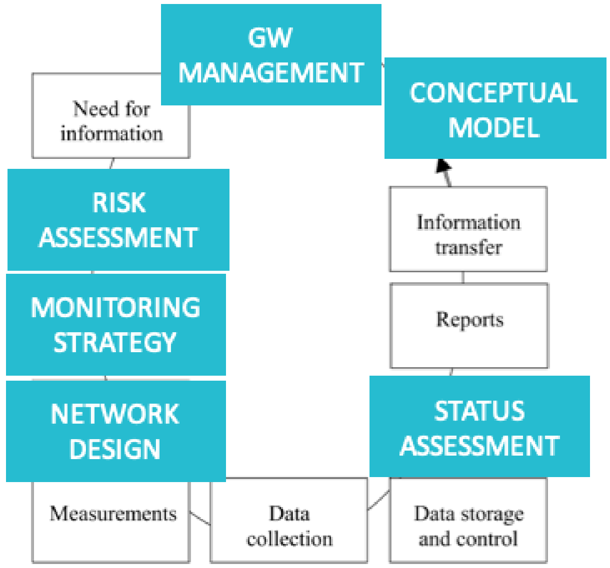

Figure 4.- Groundwater management cycle. Highlighted the steps were the conceptual model should be considered[5]

- ***Steps towards the construction of a hydrogeological conceptual model***

The conceptual model should present an integrated overview of the state of the groundwater resource, including information about hydrologic, environmental and socioeconomic aspects. Moreover, this characterization should be based on the most up-to-date available information, where data gaps should be highlighted in order to be tackled through the monitoring network design. Figure 5 presents an overview of the steps followed in the construction of a conceptual model. Notice that some steps are specific of a transboundary context. These are the harmonization of data and the definition of transboundary features.

[5] EU-WFD Guidelines Document 26 on "Risk assessment and the use of Conceptual models for Groundwater"

I. Data Collection

- Be representative of the overall state of the groundwater body
- Consider 3D nature of groundwater system
- Consider spatial and temporal variability
- Considered all existing information

II. Harmonization of data

- Harmonization of geological formations nomenclature
- Harmonization of units
- Harmonization of geografical coordinate systems

III. Multidimensional assessment

- **Hydrogeological aspects**
  - Geology
  - Hydrogeology
  - Water balance
- **Environmental aspects**
  - Hydrochemistry and groundwater quality
  - Groundwater Dependent ecosystems
  - Landscape and protected areas
- **Socio-economical aspects**
  - Groundwater use
  - Sources of pollution
  - Pressures and Impacts analysis

IV. Definition of Groundwater Bodies

V. Definition of transboundary features

Figure 5.- Steps in the construction of a transboundary hydrogeological model under the EU-WFD guidelines

- ***I. Data collection: What information should it include?***

The EU-WFD Guidelines Document 26 on "Risk assessment and the use of Conceptual models for Groundwater" provides a detailed methodology for the construction of a conceptual model. Figure 6 summarizes the methodology described in the mentioned EU-WFD guiding document, emphasizing the required information for the different scales of complexity of a hydrogeological conceptual model. Additionally, Annex I. Strategy for the generation of a hydrogeological conceptual model) details the information required to build a conceptual model from lower to higher complexity.

Since a conceptual model should consider all existing information of all aspects affecting groundwater management. This approach is relatively broad, and includes a wide variety of information, from more technical data – e.g. groundwater levels - to more qualitative information – e.g. natural protection areas-. Therefore, we will prioritize as a first step the biophysical characterization of the transboundary aquifer, thus the geological context, delineation, identification of permeable units, as well as the analysis of quantitative data like groundwater level or geochemical data, which will allow us to stablish spatial and temporal trends in the quantitative and qualitative status of the groundwater resource. Later on, we can start to add layer of complexity, like the analysis of anthropogenic impacts.

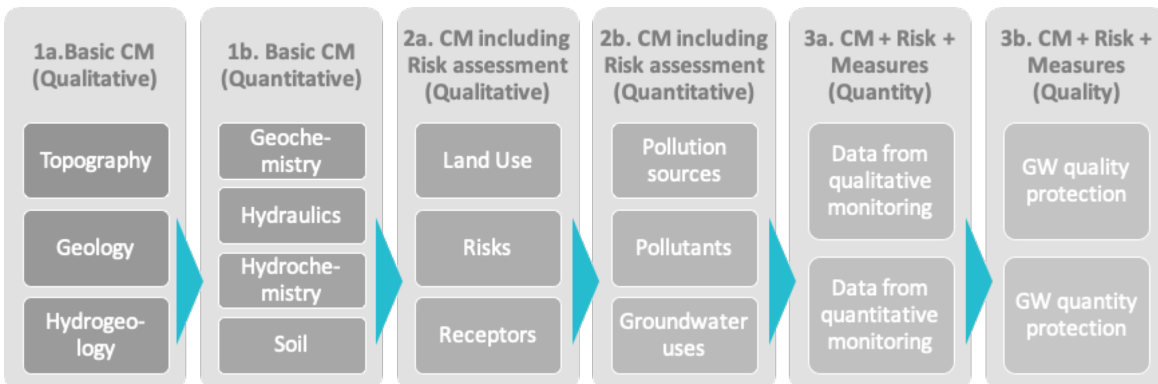

Figure 6 Evolving complexity of an hydrogeological conceptual model

- ***I. Data collection: What specific data should we collect?***

From all the information that could be useful for the construction of the hydrogeological conceptual model, we made a selection of specific information that would be useful to elaborate each of the aspects of your conceptual model. The flowing list might be extended to account of the characteristics of each case study.

	Data Needed for the elaboration of hydrogeological conceptual model	Priority (based on EU-WFD requirements)
Topography	Detailed and georeferenced topographic maps as raster files or vector files (1:100.000, 1:50.000 or 1:25.000).	*ESSENTIAL*
	Detailed Digital Elevation Model (cell around 10 m if available).	
	Surface waters (updated maps with the natural rivers flow with the indication of the area where the river feed the aquifer and where the aquifer feed the river).	*ADVISABLE*
	Surface water catchment (updated maps with the artificial catching and discharges area done for hydropower stations or agricultural purpose or water supply).	*OPTIONAL*
Geology	Geology/Lithology Map (1:100.000 or better at 1:50000 or 1:25000).	*ESSENTIAL*
	Tectonics (Faults, anticlinal and synclinal axis)	*ESSENTIAL*
	Stratigraphy descriptions (borehole description and well drilling reports for construction vertical cross-sections).	*ESSENTIAL*
	GeophysSical data	*OPTIONAL*
Hydrogeology	Hydrogeological units, Aquifer type, geometry (to defined groundwater bodies)	*ESSENTIAL*
	Basic geochemistry (for water types definition, sea water intrusion delineation and conceptual model verification (ej. Recharge zones).)	*ADVISABLE*
	Permeability	*ADVISABLE*
	Wells inventory including location, use, total depth and depth of screened interval.	*ESSENTIAL*
	Groundwater levels time series (for groundwater flow direction, spatial variability and fluxes and time series analysis in order to select optimum sampling frequency).	*ESSENTIAL*
	Local uses of groundwater.	*ADVISABLE*
Climatic	Rainfall distribution Atmospheric temperature Radiation (To calculate effective recharge and spatial distribution).	*ADVISABLE*

	Data Needed for the elaboration of hydrogeological conceptual model	Priority (based on EU-WFD requirements)
Pollution sources	Inventory of diffuse sources (with indication of the kind of sources and the presence of risk preventer). Inventory of point sources (with indication of the kind of sources and the presence of risk preventer).	*ADVISABLE*
	Map of flood prone areas and map of the areas that in the past were flooded.	*OPTIONAL*
Target of pollution	Shape files and database containing polygons, lines or points that mark aquifer areas have to be safeguarded like recharge areas of the aquifer, extractions sites of drinking water, water reservoirs, natural protected areas, karst features: sinkholes, caves etc.	*ADVISABLE*

Table 2 List of information to collect in order to construct the hydrogeological conceptual model. Information is prioritized from "Optional" to "Essential".

- ***II. Data harmonization***

This is a particular step in the process of building a transboundary conceptual model and the subsequent transboundary monitoring network. This is the first moment in the process when riparian states have to work together to find a common language to report all data and resulting information. This means that nation-specific nomenclatures of, for example, geological units, lithological descriptions, metric units or pollution limits need to be harmonized. The UN/ECE Task Force on Monitoring and Assessment Guidelines on Monitoring and Assessment of Transboundary Groundwaters propose to agree on a data dictionary. A document where the equivalence for nomenclatures, units, geographic coordinate systems, methods and standards is defined and agreed.

- ***III. Multidimensional assessment: Questions that should be answered***

✓ ***Hydrogeological aspects***

The first step in the multidimensional assessment aims for an hydrogeological characterization. The hydrogeological characterization should summarize the geomorphological context in which the aquifer formation occurs, defining the main tectonic movements and orogenic processes as well as describing the major geological formations and its characteristics. Bases on this geological description the permeable units should be identified and delineated. Horizontal delineation of the aquifer formation as well as the vertical extension of the permeable unit/s should be included in the assessment. Additionally, description of the hydraulic properties of the aquifer materials should be provided. Once the extension of the aquifer formation is clear, groundwater levels should be analysed in order to find major recharge discharge pathways. Finally, climatic data can be used to calculate effective recharge to the aquifer, which in combination with the analysis of groundwater level trends can give us an idea about the temporal variability and quantitative status of the groundwater resource.

Outputs of this part may be:

- maps with the harmonized geological formations, delineation of the permeable formations, groundwater heads and flow directions;
- vertical cross sections depicting vertical extension of the aquifer formations and recharge- discharge pathways, and
- groundwater level time series and water balance yearly plots.

✓ ***Environmental aspects***

Environmental aspects include the assessment of the background water groundwater quality as well as the identification of hot-spots and negative trends in groundwater quality. Groundwater chemical analysis should be gathered for a representative amount of wells in each aquifer formation. General geochemistry of the groundwater can be assessed by defining the groundwater chemical facies. Correlations between major ions is also useful to identify possible reactions and geochemical processes taking place. Additionally, spatial visualization of concentrations for certain compounds could be extremely useful to detect possible pollution hot spots and its effects on drinking water supply systems or surface water related bodies. In this line, the identification of groundwater dependent ecosystems is important to assess the environmental impact of any existing negative trend down flow.

Outputs of this part may be:

- piper diagrams showing hydro chemical facies, types of groundwaters and hydro chemical processes;
- XY plots of major ions to identify geochemical processes like dissolutions, adsorption, cations exchange or redox reactions;
- maps showing spatial distribution of major ions where hot-spots and spatial trends can be identified;
- time series showing temporal trends of relevant ions; and
- maps showing location of groundwater dependent ecosystems.

✓ ***Socio-economical aspects***

We consider socio-economical aspects all those human activities that may directly or indirectly interact with the groundwater. These includes the assessment of groundwater abstraction volumes and locations, groundwater artificial recharge and sources of diffuse and point pollution. These anthropogenic interaction can be summarize in a "pressures and impacts assessment".

Outputs of this part could be:

- table enumerating sources of diffuse and point pollution as well as groundwater abstraction actives in each groundwater body or aquifer unit;
- map location abstraction wells, and
- map depicting location of major industrial activities, solid waste dump sites, water treatment plants, and land uses.

- ***IV. Scale of the conceptual model and definition of groundwater bodies***

The scale of the conceptual model will adapt to the management units used in each case, the objective for which it was built and to the information available. For example, in a situation where scarce data is available a regional model might be preferred. While the increasing data availability in time will allow to narrow down the scale of a conceptual model.

The scale of the conceptual model will also depend on its purpose. For example, for the design of a monitoring network, a regional scale conceptual model is required for all identified groundwater bodies.

Finally, each legislative and governing tool, like the EU-WFD, might have their own management unit to which the conceptual model should adapt. That is the case of the groundwater bodies of the EU-WFD.

- ✓ ***Aquifer*** *means "a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater"*
- ✓ ***Groundwater body*** *is a "distinct volume of groundwater within an aquifer or aquifers"*

In the case of a transboundary aquifer in the context of the EU-WFD guiding principles we will go from larger to smaller scale, thus from defining a overall regional model, then defining the groundwater bodies and finally identifying the main transboundary features in each (Figure 7).

Figure 7.- Scales of the hydrogeological conceptual model

- ***V. Definition of transboundary features***

We mean by "transboundary features" all those aspects of a transboundary aquifer or groundwater body, which could require shared management between riparian countries. The detection of these features requires the definition of the hydrogeological model including groundwater identification of groundwater flow barriers, flow directions, intense abstraction areas and identification of pollution sources between others. Rivera et al. (2015)[6] presents a synthesis of the most frequent configurations of transboundary aquifer systems, and associated transboundary features (Figure 8). The position of the country border with respect to the regional groundwater flow, and this to the main abstraction locations and pollution sources will reveal areas where shared management might be required. Identification of these areas and the processes that have a transboundary implication will help to prioritize monitoring, measures and cooperation actions between riparian states.

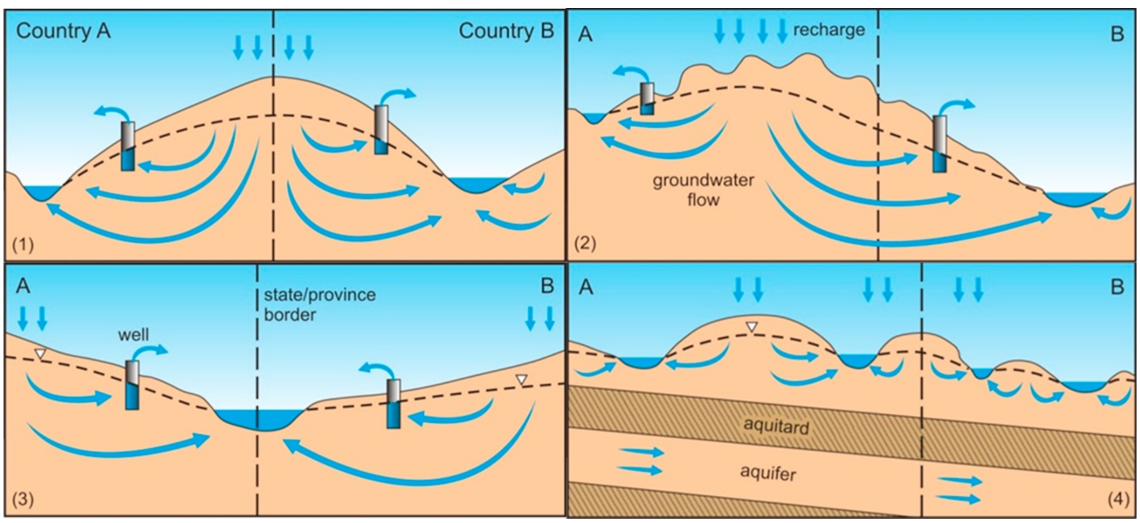

Figure 8.- Example of transboundary aquifer configurations[7]

- ***Reporting of the conceptual model***

Results of the hydrogeological model should be synthesized in the form of simplified representations, cross-sections, block diagrams and maps. While designing these

[6] Rivera, A. Journal of Hydrology : Regional Studies Transboundary aquifers along the Canada – USA border : Science , policy and social issues. 4, 623–643 (2015).
[7] Rivera, A. Journal of Hydrology : Regional Studies Transboundary aquifers along the Canada – USA border : Science , policy and social issues. 4, 623–643 (2015).

visualization items we need to keep in mind that these representations are aimed to be used as instruments for expert discussion, communicating with the general public and stake holders, understanding of the aquifer dynamics, assessing risks, planning of monitoring and measures, setting up numerical models and identifying failures in meeting any of the EU-WFD status objectives[8].

The following are some examples of the most frequent aquifer conceptual model representations and the information present in each of them:

- ✓ **Cross-sections**
  - Vertical extension of the aquifer
  - Vertical component of groundwater flow directions
  - Groundwater flow barriers
  - Relation between recharge and discharge areas
  - Location of water bodies and groundwater dependent ecosystems
  - Location of overlaying anthropogenic activities that might result in impact to the groundwater

- ✓ **Map view**
  - Delineation of aquifer and groundwater bodies
  - Horizontal component of groundwater flow directions
  - Location of surface water bodies and groundwater dependent ecosystems
  - Location of urban areas
  - Location of pollution sources
  - Location of protected areas
  - Location of abstraction wells

- ***When is it ready?***

The straight answer is “never”. The conceptual model is part of the groundwater management cycle, and as such, it will be periodically revised. The conceptual model will adapt to existing information, and evolve while more information is gathered (Figure 9).

[8] EU-WFD Guidelines Document 26 on “Risk assessment and the use of Conceptual models for Groundwater”

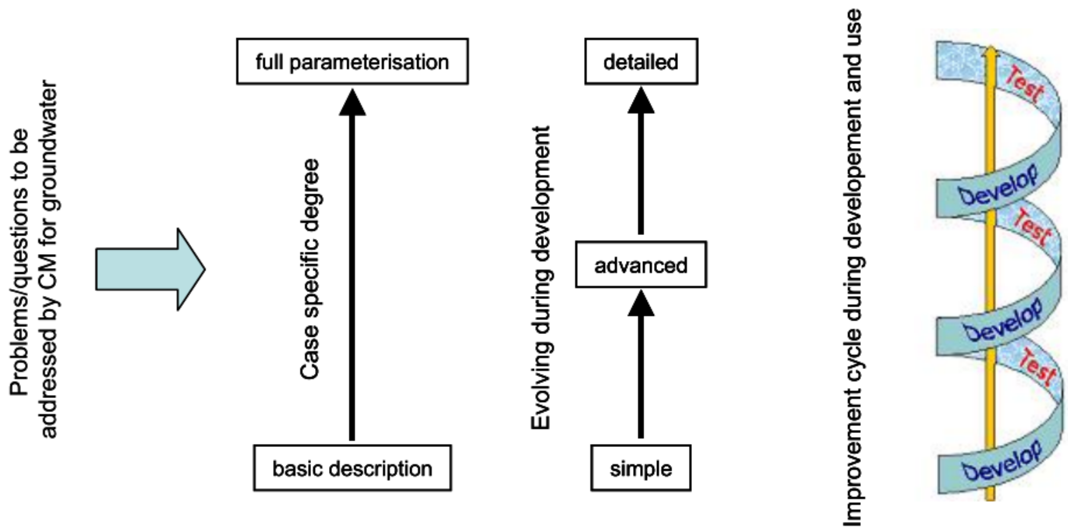

Figure 9.- Evolving complexity of an hydrogeological conceptual model[1]

In this approach, we will always work with the following premise:

- ✓ ***"Better** a simple conceptual model than no model"*

The exercise of constructing a hydrogeological conceptual model is one of the most basic, complex and abstract tasks that a hydrogeologist should do prior to anything else. It stablish the basics for hypothesis that will be tested during the management plan, including the design of the monitoring network.

- ***Further reading***

EU_WFD guidance documents:

- European Commission. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). **Groundwater body characterisation**. Framework 9, (2004). https://circabc.europa.eu/sd/a/157c2240-b988-417b-9137-a14e89db41d8/Groundwater%20characterisation%20report.pdf
- European Commission. Common Implementation Strategy for the Water Framework Directive. Guidance document No. 26. **GUIDANCE ON RISK ASSESSMENT AND THE USE OF CONCEPTUAL MODELS FOR GROUNDWATER**. (2003). https://circabc.europa.eu/sd/a/8564a357-0e17-4619-bd76-a54a23fa7885/Guidance%20No%2026%20-%20GW%20risk%20assessment%20and%20conceptual%20models.pdf

Other documents:

- Enemark, T., Peeters, L.J.M., Mallants, D., Batelaan, O., Hydrogeological conceptual model building and testing: A review, *Journal of Hydrology* (2018), doi: https://doi.org/10.1016/j.jhydrol.2018.12.007
- UN/ECE Task Force on Monitoring & Assessment. *Guidelines on Monitoring and Assessment of Transboundary Groundwaters*. (2000). https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjbnoH6k7zsAhXMAGMBHU_SCIEQFjAAegQIAxAC&url=https%3A%2F%2Fwww.unece.org%2Ffileadmin%2FDAM%2Fenv%2Fdocuments%2F2018%2FWAT%2F05May_28-30_IWRM_WGMA%2FTransboudary_Groundwaters.pdf&usg=AOvVaw2a1VSE6KFcHekWgnGxvXTc
- Mas-Pla, J. et al, 2006. *La Directiva marc de l'Aigua a Catalunya*. CADS – Generalitat de Catalunya.

3.3 Session 3.- Monitoring locations

Where must be monitoring wells located and how often must they be sampled? Identifying and selecting the most representative spots in coastal and inland aquifers

This section deals with the hydrogeological aspects of coastal aquifers and inland aquifers, as they will determine, jointly with the existing pressures, where the monitoring wells must be distributed in each area. This must consider the location as well as which aquifer levels in depth are to be considered whether to quantify the extent of the impact or to prevent it from happening.

For coastal aquifers (Figure 10), it is necessary to identify their geology, the magnitude of the groundwater withdrawal flow regimes, the occurrence of streams and other types of boundaries, …, in order to detect the advance of seawater intrusion.

For inland aquifers, their geological nature, whether consolidated or unconsolidated, is paramount. For consolidated rocks, their tectonic structure, stratigraphic and geomorphological features needs to be known to identify the recharge and discharge areas of the system. Karstic areas, so abundant in the region, are a specific case of consolidated aquifers in limestone rocks.

Unconsolidated deposits along stream valleys and fluvio-deltaic areas consist chiefly of silt, sand and gravel layers that form productive aquifers (Figure 11). The thickness of the deposits may vary and the occurrence of aquifers, aquitards and aquicludes must be identified to assess the proper structure of the hydrogeological system.

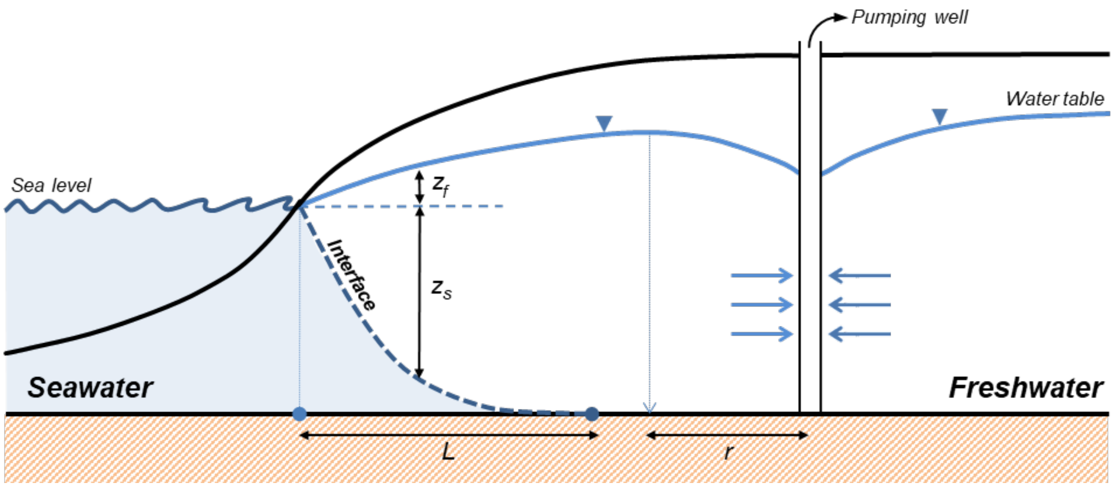

Figure 10.- Scheme showing seawater intrusion phenomena, with the location of the salinity wedge (interface) below the coastline (after Mas-Pla et al., 2014)9.

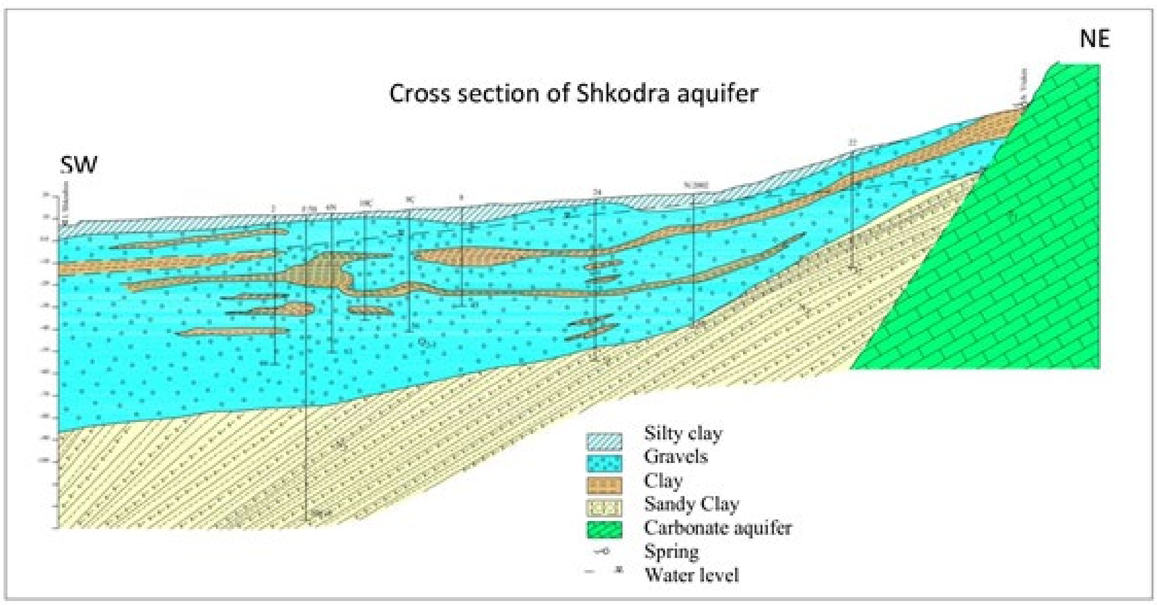

Figure 11.- Cross-section of the Koplik-Skhodër plain as an example of unconsolidated heterogeneous alluvial fan deposits. Source:

[9] *Explanation*: The cross-section indicatestwo distinct hydraulic conditions: left, a natural scenario, and right, the effects of a pumping well. Variables Zf and Zs correspond to the water table elevation and the interface depth, respectively. L indicates the location of the wedge toe (see text for explanation). On the right side, a pumping well produces a cone of depression that still does not generate seawater intrusion. If the cone radius (r) reaches the wedge toe, seawater will flow into the well and salinize both its discharge and the coastal side of the capture area. After Mas-Pla, J., G. Ghiglieri i G. Uras (2014). Seawater intrusion and coastal water resources management. Examples from two Mediterranean regions: Catalonia and Sardinia. *Contributions to Science*, 10:171-184. DOI:10.2436/20.7010.01.201

According to the WFD, monitoring networks can be distinguished by its goal to track the quantitative or qualitative status of the aquifer.

Quantitative monitoring network.- Characterization and risk assessment procedure with respect to risks of failing to achieve *good groundwater quantitative status* in all groundwater bodies.

Good quantitative status. - A groundwater body with good quantitative status will:

- ✓ have stable groundwater levels with average annual abstraction which does not reduce the available groundwater resource / the average annual recharge,
- ✓ have no negative impact on surface waters and groundwater dependent terrestrial ecosystems,
- ✓ have reduced risk of saline and other intrusions.

Qualitative monitoring network.- The evaluation of the qualitative status of a groundwater body, that its hydrochemistry and pollutant occurrence, is conducted by *surveillance and operational monitoring network* and program.

Good qualitative status. - A groundwater body with good quantitative status will:

- ✓ comply with quality standards of the WFD and the GWD and associated directives,
- ✓ have no negative impact on surface waters and linked terrestrial ecosystems,
- ✓ have no indications or effects of saline or other intrusions.

Surveillance** monitoring network.-** It is intended to:

(a) The characterisation and *risk assessment* procedure with respect to the risks of failing to achieve good groundwater chemical status;
(b) Gather information for use in the assessment of *long-term trends* in natural conditions and in pollutant concentrations resulting from human activity and;
(c) Establish, jointly with the risk assessment, the need for *operational monitoring*.

***Operational** monitoring network*. – It is intended to:

(a) establish the status of all groundwater bodies, or groups of bodies, *determined as being 'at risk'*,

(b) establish the presence of significant and *sustained upward trends* in the concentration of pollutants,

(c) it can also be used to *assess the effectiveness of measures* implemented to restore a body to good status or reverse upwards trends.

	EU WFD				Project
Type of monitoring network	**Quantitative**	**Surveillance**	**Operational**	**Drinking Water Protected Areas**	**Pilot test**
GWB-01 Cijevna	X	X	X		
GWB-01 Morača River	X	X	X		X (*)
GWB-01 Podgorica	X	X		X	X (*)
GWB-01 Seepage to lake	X	X			
GWB-06 GDEs	X	X			
GWB-06 Seawater intrusion	X	X	X		X

Table 3 Types of monitoring networks and proposed monitoring zones (either one or both).*

Discussion.- Implementing the types of monitoring networks (surveillance vs. operational) can be a tough issue when adapting existing monitoring networks to the EU directives. The key point here is to adapt existing sampling sites to the WFD and GWD requirements. In other words, it is not the density of the network or the existence of huge databases what will be evaluated, but *how the network is used to fulfil de directives' goals*.

The monitoring program set in the 2019 report *does not differentiate between surveillance and operational monitoring*. Indeed, it considers the available information and the proposal sets which areas should be monitored. The report considers that *all such zones must be monitored as operational sampling sites*, while the rest of the database can be maintained as surveillance sampling sites. Local technicians/experts have the final decision about it.

Selection of monitoring sites.- Based on the EU WFD, the "groundwater monitoring network shall include sufficient representative monitoring points to estimate groundwater level and quality parameters in each groundwater body". *WFD CIS Guidance Document No. 15 - Monitoring Guidance for Groundwater* provides a set of criteria for the selection of adequate monitoring locations and facilities.

Surveillance monitoring locations should be close to locations where changes are expected to occur, thus, where impact might occur and along flow paths. In groundwater bodies, which could be at risk, the surveillance monitoring provides the basics for operational monitoring. Operational monitoring locations consider these sampling points within the surveillance network that are more relevant and therefore need a more detailed sampling and monitoring. As just mentioned, our proposal of sampling sites does not differentiate between surveillance and operational monitoring. The report considers that all such zones must be monitored as operational sampling sites, while the rest of the database can be maintained as surveillance sampling sites.

Type of sampling point	Character of discharge	Discrete vertical sampling points	Quantitative measurements	Hydraulic testing	Inert materials	Costs			Notes
						Drilling	Materials	Sampling	
Existing groundwater sampling points									
Public supply borehole	Usually high and continuous	Integrates over screen interval	Usually disturbed by pumping	Data may exist	No	None	None	Very low	
Private supply borehole	Often low and intermittent	Integrates over screen interval, but may be shallow	Sometimes disturbed by pumping	Data may exist	No	None	None	Low	Purging may be problematic/time consuming for irregularly used boreholes
Irrigation borehole	High but may be intermittent or seasonal	Integrates over screen interval	Possible in non-pumping seasons	Data may exist	No	None	None	Low	Purging may be time consuming when boreholes not used
Dug well	Usually intermittent	No	Yes, usually	Unlikely	No	None	None	Low	Large storage in well, difficult to purge with sampling pump
Large springs	High and continuous	No	Yes, discharge	No	No materials	None	None	Low	May have large catchments and good in karst areas
Small springs	May be low and seasonal or irregular	No	Yes, discharge	No	No	None	None	None	May have shallow, vulnerable flow paths
Purpose-constructed observation or monitoring boreholes									
Single piezometer	Low and needs portable pump	One, usually a short screen near bottom	Yes	Yes	Yes	Moderate	Low	Moderate, but needs pump	
Cluster of single piezometers	Low and needs portable pump	Several distinct depths	Yes	Yes	Yes	Very high	High	High, needs pump	
Nest of piezometers in single borehole	Very low, needs portable pump	Two to five	Yes	Yes	Yes	High	High	High	
Multi-port sampling systems	Very low, needs specialist pump	Many	Some types	Some types	Yes	Moderate	High	High	Requires specialist techniques and expertise for installation and operations

Table 4 Types of monitoring sites (Source: EU-WFD Guidance document on Groundwater monitoring

Sampling site density.- Site density is related to the chances of the groundwater body to be "at risk". If chances are low, density can be also low meanwhile it is representative of the groundwater body characteristics. For those to be already "at risk", *monitoring sites provide the basis for the operational monitoring*. Consequently, the monitoring network must be increased with more, strategically located sampling wells. Nevertheless, cost-efficiency stands, as usual, as a limitation.

Sampling frequency.- The selection of appropriate sampling frequency will be based on the conceptual model and existing groundwater monitoring data. Where there is adequate knowledge of the groundwater system and a long-term monitoring program is already established, this should be used to determine an appropriate frequency for monitoring.

According to the WFD Guidance documents, sampling frequencies are determined in the next two tables:

Table 2: Proposed monitoring frequencies for surveillance monitoring (where understanding of aquifer systems is inadequate).

Note: This table proposes monitoring frequencies that can be used as a guide where the conceptual understanding is limited and existing data are not available. Where there is a good understanding of groundwater quality and the behaviour of the hydrogeological system, alternative monitoring frequencies can be adopted as necessary.

		Aquifer Flow Type				
		Confined	Unconfined			
			Intergranular flow significant		Fracture flow only	Karst flow
			Significant deep flows common	Shallow flow		
Initial frequency – core & additional parameters		Twice per year	Quarterly	Quarterly	Quarterly	Quarterly
Long term frequency – core parameters	Generally high-mod transmissivity	Every 2 years	Annual	Twice per year	Twice per year	Twice per year
	Generally low transmissivity	Every 6 years	Annual	Annual	Annual	Twice per year
Additional parameters (on-going validation)		Every 6 years	Every 6 years	Every 6 years	Every 6 years	-

Table 5 Proposed monitoring frequencies (Source: EU-WFD Guidance document on groundwater monitoring

Table 3: Proposed frequencies for operational monitoring.

		Aquifer Flow Type				
		Confined	Unconfined			
			Intergranular flow significant		Fracture flow only	Karst flow
			Significant deep flows common	Shallow flow		
Higher vulnerability groundwater	Continuous pressures	Annual	Twice per year	Twice per year	Quarterly	Quarterly
	Seasonal / intermittent pressures	Annual	Annual	As appropriate	As appropriate	As appropriate
Lower vulnerability groundwater	Continuous pressures	Annual	Annual	Twice per year	Twice per year	Quarterly
	Seasonal / intermittent pressures	Annual	Annual	As appropriate	As appropriate	As appropriate
Trend assessments		Annual	Twice per year	Twice per year	Twice per year	-

Table 6 Proposed frequencies (Source: EU_WFD Guidance document on Groundwater monitoring)

Monitoring parameters in qualitative monitoring.-

- For the surveillance network (quality) Dissolved Oxygen, pH, Conductivity, Nitrate and Ammonium are the core parameters that need to be monitored. Additionally, Eh (redox potential) and turbidity can also be monitored, as well as major anions and cations. The last are extremely important, especially during the first years of operation in order to confirm the conceptual model and interpret the core geochemical parameters. Moreover, the norm indicates that major constituent analysis is highly recommended in transboundary water bodies, which are relevant for the protection of all of the uses supported by the groundwater flow. Do not forget that monitoring programs create knowledge!

- The operational monitoring network is specific of the pollutants affecting the aquifer. In general terms, we can say that in areas that could be affected by heavy industry metals should be sampled, while in areas where sewage might represent a risk, fecal bacterial can be also object of sampling. The *final list of compounds to be monitored is site-specific*, and must be determined according to the goals of the directive.
- In Drinking Protected Areas is important to have a full range of parameters, those specified by the international and local regulations, as water is use for human consumption.

- ***Further reading***

EU-WFD Guidelines Document 15 on "Monitoring under the Water Framework Directive" (only refers to surface water bodies!).
https://circabc.europa.eu/sd/a/63f7715f-0f45-4955-b7cb-58ca305e42a8/Guidance%20No%207%20-%20Monitoring%20(WG%202.7).pdf

EU-WFD Guidelines Document 15 on "Groundwater monitoring".
https://circabc.europa.eu/sd/a/e409710d-f1c1-4672-9480-e2b9e93f30ad/Groundwater%20Monitoring%20Guidance%20Nov-2006_FINAL-2.pdf

Textbooks:

- Brassington R, 2007. *Field Hydrology*. Wiley.

- Dassargues A, 2019. *Hydrogeology*. *Groundwater Science and Engineering*. Taylor&Francis.
- Fetter CW, 200. *Applied Hydrogeology*. 4th ed. Prentice Hall.
- Fitts CR, 2013. *Groundwater Science*. 2nd ed. Academic Press.
- Freeze A, Cherry J, 1979. Groundwater. Prentice Hall.
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3.4 Session 4.- Monitoring of quantitative status

How to monitor groundwater levels? Instrumentation and practical considerations.

Quantitative monitoring of a transboundary aquifer should answer three main questions:

- Evaluate if the available groundwater resource is not exceeded by the long-term annual average rate of abstraction. This implies the calculation of the groundwater balance of the aquifer, having to know inputs (natural and artificial recharge, inputs from other aquifer units, if any) and outputs (discharge to surface water bodies, abstraction).
- Evaluate of groundwater levels and flows are sufficient to meet environmental objectives for associate surface and groundwater dependent ecosystem (GDEs). In which case, information about the groundwater balance is need in combination for environmental indicators of the status of the GDEs.
- Evaluate if the anthropogenic alterations to flow direction resulting from level change cause saline or any intrusion.
- And in transboundary aquifer, evaluate if the groundwater flow along riparian countries has change in direction or rate.

The most important variable that defines the quantitative status of the groundwater resource is the groundwater level variation. Therefore, to evaluate all this questions over time, a quantitative monitoring groundwater network needs to be implemented, so that groundwater levels can be monitored over time.

- ***Groundwater heads***

  Groundwater-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect ground- water recharge, storage, and discharge[10]. Groundwater heads represent the potential energy stored in groundwater. This energy is the combination of several forces: the matrix potential, described as the energy required to remove the water bound to the soil matrix; the gravitational potential; expressed as the energy required to move water between different heights; the pressure potential, energy exerted by the column of water; loading potential, the effect of an external weight on the water column; and the osmotic potential, expressed as the energy required to move water from a hypotonic solution to a hypertonic solution. Typically the groundwater head is expressed as:

$$h = z + \frac{P_i}{\rho_i g} \qquad \text{Eq. 1}$$

where, h is the groundwater head (m), z is the elevation, P is the pressure of groundwater at the measuring point ($Kg/m \cdot s^2$) (point A and B in Figure 12), ρ is the groundwater density (kg/m) and g is the gravitational acceleration (m/s^2). The last term is also known as the pressure head.

Changes in groundwater potential energy field are directly related to the velocity of water flowing through the porous media through a proportionality constant, the hydraulic conductivity. This relation is the Darcy´s Experimental Law, the basic of groundwater hydraulics.

$$q = -\mathrm{K}\ \frac{dh}{dx} \qquad \text{Eq. 2}$$

Where q Is the unitary groundwater flux rate (m/s), K is the hydraulic conductivity (m/s) and $\frac{dh}{dx}$ is the hydraulic gradient in the x direction.

From this equation the only parameter that changes in time is the groundwater gradient, at least in most cases. This is the reason why variation in heads are the

[10] Taylor, C. J., & Alley, W. M. (2001). Ground-water-level monitoring and the importance of long-term water-level data. *Geological Survey Circular*, 1–76.

most important information to record from an aquifer. It will allow us to compute the evolution of the groundwater volume, groundwater velocities, direction of the flow, groundwater fluxes, hydraulic properties, and to calibrate groundwater-flow models.

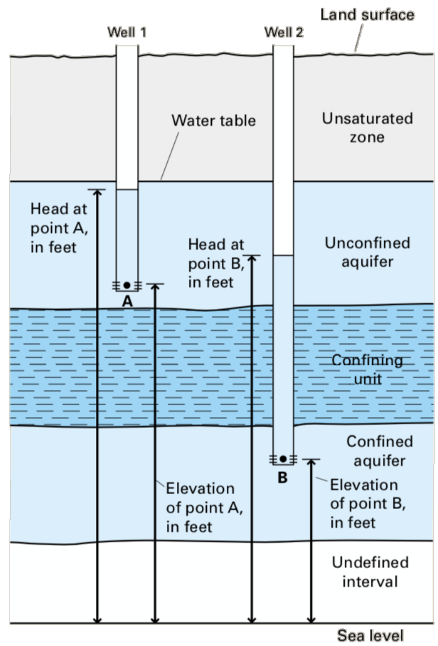

Figure 12 Sketch showing the relation between hydraulic heads and water levels in two observation well. Notice screened interval from well 1 is open in an unconfined aquifer, while the screen of well 2 is open in a confined aquifer (Figure source: Taylor, C. J., & Alley, W. M. (2001). Ground-water-level monitoring and the importance of long-term water-level data. Geological Survey Circular, 1–76.)

- ***Field measurement of groundwater heads***

Groundwater head measurements are typically done in two ways: manually or automatically.

Manual measurements usually really in lowering a measuring tape along the piezometer, and measuring the distance between the well rim and the water table inside the piezometer, thus the depth to the groundwater in the well. The most used instrument for this purpose are the electric probe attached to a graduated measurement tape, also referred as a water-level meter, a dipmeter or a dipper (Figure 13)[11] . To translate from depth of the groundwater table to elevation of the groundwater table (groundwater head), it is necessary to measure the elevation of the rim with respect to a common datum and to know the depth to the well screen (a in Figure 14). Thus, apart from measuring the depth to the groundwater table, the elevation of the borehole rim is necessary to be known. This is the reason why a GPS or equivalent (Figure 14c) is always necessary in the field.

Figure 13 Field equipment for measuring groundwater heads. a) water-level meter, b) pressure sensors, and c) instruments for measuring xyz coordinates (GPS, level meter, altimeter)

On the other hand, automatic measurements are usually done by hanging a pressure sensor (Figure 13) in the piezometer, which will measure continuously the pressure at an specific depth (“k” in b in Figure 14). In this case, apart from the mentioned measurements necessary for interpreting manual measurements, it is also necessary to know the depth at which the pressure sensor is hanging and the atmospheric pressure.

Most pressure sensors record the total pressure at the measuring point. This includes the pressure due to the column of water, but also the pressure due to the weight of the atmosphere. In order to remove the oscillations in atmospheric pressure, it is necessary to subtract it from the recorded data. Thus, a atmospheric pressure sensor is necessary to be installed in parallel to the downhole pressure sensor.

[11] Post, V.E.A., von Asmuth, J.R. Review: Hydraulic head measurements—new technologies, classic pitfalls. Hydrogeol J 21, 737–750 (2013). https://doi.org/10.1007/s10040-013-0969-0

To calculate the depth at which the sensor is located manual measurements of the groundwater depth need to be always done. Knowing the depth to the water table (Figure 14 w) and the pressure recorded at that moment by the sensor (Figure 14 k), one can easily subtract the length of the cable used to hang the sensor. This process needs to be repeated periodically in order to correct for changes in the cable length, due to manipulations, nodes or tensions that may affect its length in time.

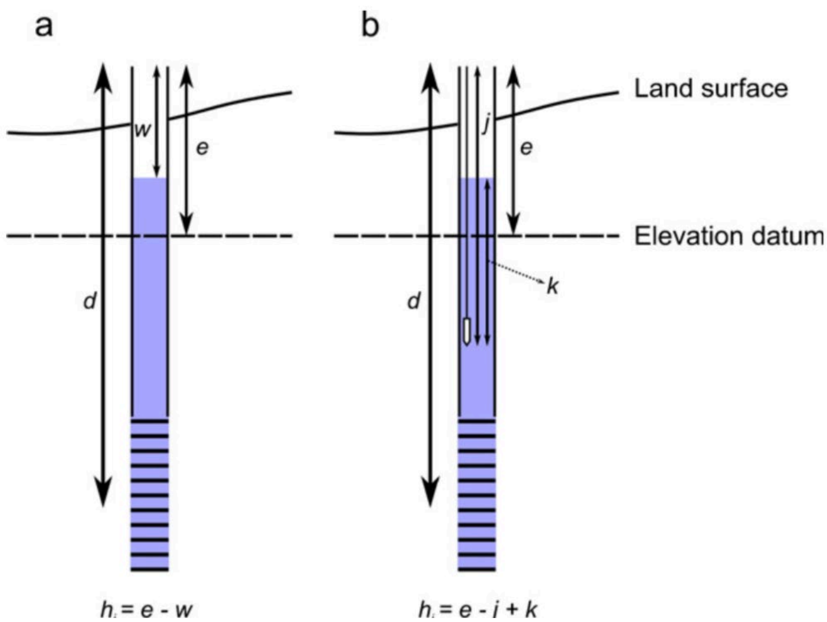

Figure 14.- Measurements involved in determining the hydraulic head, where d is the depth of the well screen, w is the depth to the groundwater in the well, e is the elevation of the well rim, j is the depth to the pressure sensor and k is the water column above the pressure sensor. a) Manual measurement. b) Measurement with pressure sensor (Source: Post, V.E.A., von Asmuth, J.R. Review: Hydraulic head measurements—new technologies, classic pitfalls. Hydrogeol J 21, 737–750 (2013). https://doi.org/10.1007/s10040-013-0969-0)

While manual measurements are simple and easy to perform, while requiring very cheap instrumentation. However, temporal coverage is difficult, human errors frequent, and the cost for transport and personnel hours may well increase the costs.

On the other hand, automatic measurement provide a good even temporal coverage, reduction in human errors and less amount of personnel hours and transport to reach far away locations. However, sensors are costly, they need maintenance, and still some manual measurements need to be performed.

In conclusion, the selection of one mechanism over the other will depend on budget, spatial distribution and accessibility of the monitoring locations, personnel availability and monitoring frequency required. In many cases, a mixed monitoring system is implemented, where manual measurements allow to cover a large area, and the installation of sensors allow high frequency monitoring of key spots or far away locations.

- ***Groundwater heads measurements in coastal aquifers***

Coastal aquifers main difference with inland aquifers is the presence of variable density groundwater, due to the intrusion of saline groundwater coming from the sea. The varying density affects to the groundwater heads measured in a coastal aquifer. In order to compare groundwater heads between different x, y and z locations, it is necessary to introduce in Eq. 1 a common reference density, the fresh water density (Figure 15 b), which transforms Eq 1 into the equivalent fresh water head[12]:

$$h_{f,i} = \frac{\rho_i}{\rho_f} h_i - \frac{\rho_i - \rho_f}{\rho_f} z \quad \text{Eq.3}$$

This equation adds a very important variable that needs to be measured in the field, the density at the measuring point (i). Unfortunately, this is neither obvious nor easy. Manual measurements could be done by tacking a sample of the borehole each time a manual measurement of the groundwater depth is done. With automatic measurements this is slightly simplified by the addition of an electrical conductivity sensor to the already mentioned pressure sensors which allows to have simultaneously measured both pressure and solutes content. However, not even this is enough in some cases. Even equivalent fresh water heads rely on the assumption that the density of the water in the well tube is homogeneous. If this is not the case then correction of the measured pressure head becomes impossible. Therefore, here we advise to first purge the borehole when de

[12] Jiao and Post (2019). Coastal Hydrogeology. Ed Cambridge. 10.1017/9781139344142

pressure sensor is installed, and second perform periodic electrical conductivity profiles along the borehole to detect and correct changes in the density of the water column.

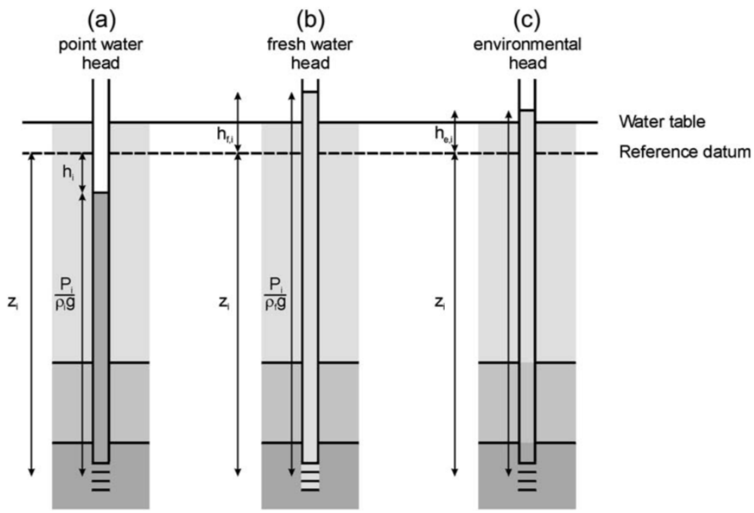

Figure 15.- Groundwater head in the presence of varying groundwater density[13].

Because of the presence of varying density the design of the monitoring wells and position and length of the screened interval are crucial in a coastal setting. Short screen intervals are preferred over long ones, as measurements of density will less mixed and closer to the actual density in the aquifer at the monitoring point. In fact, in coastal monitoring networks, grouping of several monitoring wells in a small location opened at different depths are common in order to capture oscillations in the position of the saline intrusion. Alternatively, multilevel wells, or multiport wells, provide better alternative, but imply larger costs and advance knowledge for the operation making the installation.

- ***Information to collect in the field***

Before performing any field measurements, a form with the necessary information to collect on the field per monitoring location should be designed. The list bellow included some of the most important items:

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[13] Post, Kooi and Simmons (2007) Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses. Groundwater, Vol. 45, No. 6, 664–671), 10.1111/j.1745-6584.2007.00339.x

Information about monitoring point:

- Site name
- Date and time
- Coordinates of the well
- Contact information
- Measuring-point elevation
- Access to location

Construction details:

- Drilling method
- Lithology description (if available)
- Materials of casing and annulus
- Type of cap
- Total depth
- Measuring point
- Diameter of borehole
- Height/depth of the borehole rim
- Screen interval
- Status/maintenance

Hydrological information

- Aquifer monitored
- Groundwater body
- Type of monitoring point
- Operating interval
- Pump status
- Pump status time
- *Depth to groundwater*
- Depth to sensor (if any)

For coastal aquifers:

- *EC profile or equivalent*

- ***Additional quantitative information***

Groundwater heads are the basic information to answer some of the most basic questions to manage an aquifer, however not the only. Additional information, such as:

Groundwater related:

- Spring flows
- Groundwater abstraction (and artificial recharge)

Surface water related:

- Stage levels of surface water courses
- Stage levels in significant groundwater dependent wetlands and lakes

Recharge related:

- Rainfall and the components required to calculate evapo-transpiration

One of the most important questions is to quantify the renewable resource available in a specific aquifer over time. For this, one needs to calculate a, more or less complicated, water balance. Groundwater levels in combination with estimated hydraulic parameters and knowledge about the geology (information collected during the construction of the conceptual model), will help us estimate the total resource. However, oscillation in the effective recharge, is necessary to calculate inputs versus outputs. Therefore, the groundwater monitoring network should always be complemented with a meteorological network and surface water network. In this case, a simple water balance can be calculated in order to estimate the abstracted water, and derive control measures if necessary in order to prevent overexploitation, and protect groundwater dependent ecosystems.

In coastal aquifer, availability of continuous sea level measurements are also extremely useful to interpret the causes of any change in the groundwater heads and saline intrusion movement.

- ***Further reading***

EU-WFD guidance documents:

- European Commission (2007). Guidance Document No. 15. Guidance on Groundwater Monitoring. Common Implementation Strategy for the water framework directive (2000/60/EC). ISBN 92-79-04558-X https://circabc.europa.eu/sd/a/e409710d-f1c1-4672-9480-e2b9e93f30ad/Groundwater%20Monitoring%20Guidance%20Nov-2006_FINAL-2.pdf

Other relevant documents:

- Taylor, C. J., & Alley, W. M. (2001). Ground-water-level monitoring and the importance of long-term water-level data. Geological Survey Circular, 1–76.
- Post, V.E.A., von Asmuth, J.R. (2013) Review: Hydraulic head measurements—new technologies, classic pitfalls. Hydrogeol J 21, 737–750. https://doi.org/10.1007/s10040-013-0969-0
- ISO (2005) Manual methods for the measurement of a groundwater level in a well. ISO 21413:2005, ISO, Geneva
- USGS. A National Framework for Ground-Water Monitoring in the United States. (2013).

3.5 Session 5.- Monitoring of qualitative status

How to monitor groundwater quality? Groundwater sampling techniques and practical considerations. Interpretation and reporting hydrochemical data

Groundwater quality issues stand as a major aspect that puts in danger the achievement of the WFD environmental goals. In consequence, their monitoring network and programme must ensure gathering data based on well-established methods and protocols, adequate data treatment and analysis and, finally, a transparent way to communicate data to other agents and to the public as well. In the case of transboundary aquifers, the licit interests of two countries looks for a good and common management strategy that preserves water resources from deterioration and pollution. This effort must be supported by complete and open datasets that has been obtained using appropriate methods and techniques that permit working together with data taken by any of the parts. In this context, the procedures dictated by the WFD offer a common ground for agreement.

Therefore, monitoring quality parameters must consider,

1. fulfilling the legal requirements that defines thresholds and limits of specific compounds in the environment,
2. using the highest field work and analytical standards that reduce uncertainty on the datasets,
3. Proceeding with an adequate treatment and plotting of the data, and using appropriate modelling approaches when necessary, and
4. Interpreting the results according to the problem needs and looking forward to addressing the achievement of the set environmental goals.

Monitoring quality requirements.- Along these guidelines, we insist that monitoring and data gathering must create knowledge. Nevertheless, the amount of data and the number analysed parameters must be in agreement with the objectives of the monitoring network, and conducted on the basis of cost-efficiency. In this sense, surveillance and operational monitoring differ on their requirements since their goals, as mentioned, are notably distinct.

For surveillance monitoring, the "core suite" will comprise dissolved oxygen (DO), pH, electrical conductivity (EC), nitrate, ammonium, temperature, and a suite of major and trace ions plus, where appropriate, selected indicators. Include redox potential (Eh) as well. The suite of "major ions" must include HCO_3^-, SO_4^{2-}, Cl^-. NO_3^-,Ca^{2+}, Mg^{2+}, Na^+, and K^+, which are necessary to calculate the ionic balance and, with it, identify potential analytical errors. Trace ions will depend on the aquifer lithology, as they can be clues to depict flow path, recharge areas, and so on. Moreover, trace ions may be directly related to some identified pressure and, therefore, they become indicatives of the risks to and impacts on groundwater from identified pressures. In such case, they must included in the analytical list as key parameters to identify the magnitude of the impact and represent its evolution or trend.

Nevertheless, a priori, it is not necessary to monitor each of the priority substances including in the WFD and subsequent legislation.

Surveillance monitoring should also consider the analysis of other parameters that may help to understand the aquifer dynamics and recharge processes. In particular, the water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) are actually helpful on hydrogeological investigations, and they must be highly considered as parameters of interest. Other isotopes, as radioactive elements as tritium and radiocarbon, and those elements that support groundwater dating methods can be eventually selected for specific cases, yet they are not entirely necessary to build up the conceptual model of the hydrogeological system.

Conversely, the requirements for operational monitoring add those selective elements/compounds necessary to categorize the pressure and its impact at selected locations where groundwater bodies can be "at risk". Then, parameter selection will be made on a case-by-case basis, and be influenced by other information including existing water quality data and local knowledge. In such case, groundwater threshold values must be taken as references for quality status. Given the relevance of a successful tracing of a pollution event, and assuming the fact that hydrogeological dynamics may vary seasonally or annually, whether by natural or human factors, chemical monitoring suites must be reviewed on a regular basis to ensure that they provide representative information.

Gathering quality field data.- Quality field data are indicators of the environmental health and determines which actions must be conducted to preserve water resources quality. It must be based on proper field work, data treatment and plotting and their interpretation based on a sound understanding of the hydrogeological and geochemical processes that control the fate of the solutes and, especially, those that are considered pollutants.

Field sample collection can be summarized in the following hints,

a) Collecting samples is an easy, … but a tricky task!
b) Empty the borehole volume three times at least, and wait for constant EC and T values.
c) Select the right type of bottle (material, color, sterilized, acid rinse, …), the necessary water volume, check whether additives are needed, … Avoid air-bubbles before closing the bottle! Filter the sample! Store it cold at 4^{o}C! Bring it to the lab as soon as possible, avoid long storage periods even under refrigerated conditions
d) Check procedures at "Standard Methods" books
e) Ask the lab, ask colleagues, … on how to conduct the field work. Define a common set of procedures, find (technical and scientific) agreement about them, and communicate it to all partners involved in the data gathering process.
f) When sampling distinct parameters, samples may require several flasks depending on the necessary analytical pretreatment procedures. Logistics is important for a successful campaign. So, … take a large car (or van) to the field!!!

Besides bottles, flasks and vials, several apparatus are necessary for in situ measurements; namely, EC-meter, pH-meter (with a redox potential probe), and DO-meter. Other apparatus and probes may also be of interest. When possible a flow-cell should be used to avoid the contact of the pumped water sample with the atmosphere so dissolved gases (DO, CO_2) are not lost, or some parameters (pH, Eh) ill-measured (Figure 16).

Figure 16 Flow cell and measuring devices on a field campaign

Instrumentation must be calibrated before going to the field. Occasionally, it can be necessary to recalibrate them in situ, especially when measurements do not agree with the expected values at that given spot. This doesn't mean that the measurement is wrong; it just means that, being distinct from the expected result, we check whether there is an instrumental error or not. It is worth double-checking unexpected results once in the field.

The calibration procedures for most conductivity meters are quite similar. The procedures typically involve using a conductivity standard to determine the meter's accuracy. The meter reading is then adjusted to meet the value provided for the standard. Usual calibration solution for conductivity meter is a 0.01 M KCl solution that has an EC of 1411 µS at 25°C. Distinct solutions might be recommended for different EC range values or by the commercial brand.

pH-meter calibration.- To calibrate a pH meter you need two types of buffer solutions: pH7 and pH4. These buffer solutions help you with displaying the right pH values, because when you use a pH meter you want to be sure that the pH meter displays the right measurement. You use the buffer solutions with known pH, so you can adjust the meter. First start with pH7 buffer solution and then pH4 buffer solution. However, make sure to use fresh buffer solution for each pH meter calibration. Nevertheless, some meters, or in some cases, you will be asked to calibrate it using a basic standard at pH10 or higher. Just follow the meter manual. This solutions are also sold in sealed, single-use small envelops which are actually useful to take to the field. Do not reuse used standard solutions!

The frequency of calibrating a pH meter depends on usage and possible contamination. The higher the usage and the amount of contamination, the more often you need to calibrate your pH-meter. Ensure a pH meter calibration twice a month to avoid measuring errors.

The most popular method for dissolved oxygen measurements is with a dissolved oxygen meter and sensor. While the general categories of dissolved oxygen sensors are optical and electrochemical, electrochemical sensors. Calibration and operating procedures can vary between models and manufacturers. An instruction manual should be referenced during the measurement and calibration processes. However, most of them are easily calibrated by using a non-ionized water that has been exposed to air for oxygen saturation, making it quite simple even in the field.

Depending on the measurement conditions, dissolved oxygen meters, similar to redox potential meters, may take time to equilibrate. It is always recommended to use a cell-flow. However, even within a cell-flow it may take time to get a stable lecture of both parameters.

Data treatment and plotting.- Solutes in groundwater mainly depend on the following processes:

- Water-rock interaction: mineral equilibria
- Ion exchange / sorption
- Mixing between different sources
- Seawater intrusion
- Groundwater pollution: non-natural introduced chemicals

For most of these processes, we assume that the governing reactions are in equilibrium; that means, the ratio between products (solutes) and reactants (minerals) depend on the equilibrium constant. Therefore, all interpretation of chemical data must be scrupulously based on geochemical terms. For instance, the electroneutrality principle must be checked through the electrical (or ionic) balance as the accuracy of the analysis of the major ions can be estimated from the electrical balance since the sum of positive and negative charges in the water should be equal,

$$Error\ (\%) = 100\ \frac{\sum cations - \sum anions}{\sum cations + \sum anions}$$

Accepted errors depend on the anion concentration. For low salinity samples, (<10 meq/L) an error of 2% is accepted; for larger salinities, a maximum error of 5% is consented.

Plotting must also be conducted on the basis of stoichiometric relationships, so the dissolution of the main mineral-forming rocks can be studied. Binary plots must include lines that represent geochemical ratios between the two variables, or those expected geochemical trends as the dissolution paths of the $CaCO_3$-CO_2-H_2O system, where the open and closed system are plotted in the diagram pH-HCO3, as well as the equilibrium with calcite (Figure 17). Plotting data in such graphics permit a quick understanding of the geochemical processes that act in the aquifer.

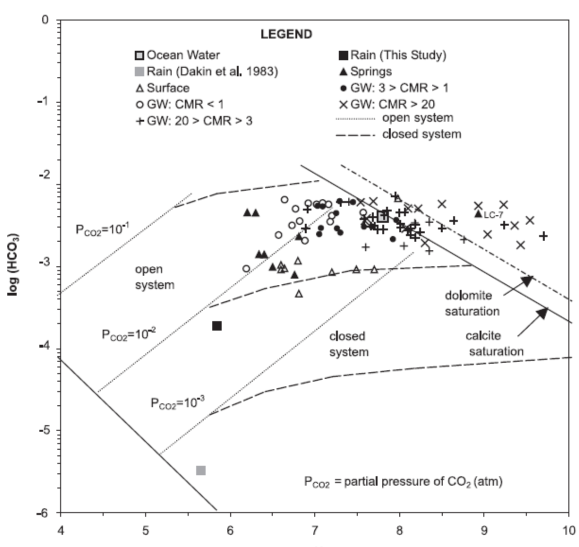

Figure 17 Diagram pH-HCO3 with the dissolution path for distinct CO2 partial pressures,

Diagrams as those of Stiff, Schoeller-Berkaloff and Piper-Hill are effective graphic procedures for presenting water chemistry data to help in understanding the sources of the dissolved constituents in water. Stiff and Schoeller-Berkaloff plots compare the chemical composition of several samples, while Piper-Hill diagram integrate all samples within two ternary plots (one for anions, other for cations) that are then projected onto a central diamond plot. This procedure is based on the premise that cations and anions in water are generally in chemical equilibrium.

All these plots permit identifying hydrochemical facies, mixing relationship and their end-members, and other geochemical processes that may affect the groundwater chemical composition. *Hydrochemical facies* denotes the diagnostic of the composition categories of ground-water solutions occurring in hydrologic systems. The facies reflect the response of chemical processes operating within the lithological framework and the pattern of flow of the water. All of them are clearly explained in the main hydrogeology and geochemistry textbooks.

Finally, geochemical modelling can be a useful tool to build up knowledge. Even though geochemical codes (WATEQF, PHREEQC, MINTEQ, …) are complex and difficult to use to non-skilled researchers, their simple functions as the estimation CO_2 partial pressure or saturation indexes; that is, performing speciation[14]; can be relatively easy and their results highly interesting to understand the system dynamics from geochemical data.

Fourteen tips about data treatment, plotting and reporting

1. Always present all data in an understandable form (tables, plots) so the receptor of the document can also work with the data. Restrict or stick to partial information only when required by contract or law.
2. Add field and laboratory methodologies, and the uncertainty limits of the analysis.

[14] For instance, Appelo and Postma (2005) Geochemistry, Groundwater And Pollution. 2nd Edition. Balkema.

3. Act consistently with the <LOQ / <LOD values; LOQ: Limit of Quantification / LOD: Limit of Detection[15].
4. When possible, refer to previous historical data to put the new data into context. Plot them versus time.
5. Provide simple statistics of each variable: mean, median, standard deviation, error (as standard deviation divided by the square root of the number of data), coefficient of variation, and max and min values. For large datasets, this simple statistics give a quick understanding of the data set. Percentile estimation can also be of the greatest interest. Be careful, the "mean", as a commonly used statistic, can be highly misleading!
6. Plotting hydraulic head data, report whether the monitoring frequency has enough detail to capture maximum and minimum drawdown levels. When wells are near streams, report the head data in relation to stream stage to provide information about the stream-aquifer relationship.
7. When dealing with hydrochemical data, estimate the ionic balance and report the mass-balance error. Be sure that errors are acceptable (<5%); if not, treat data with caution!
8. When dealing with hydrochemical data, use Piper-Hill, Schoeller-Berkaloff, Stiff diagrams, … Avoid fancy diagrams that are seldom used and are hard to understand (e.g., Durov diagrams). Be careful on diagrams based on % of each component, as they may be misleading about geochemical processes.
9. Plot also binary graphs to look for geochemical evolution, mainly: water-rock interaction (mineral dissolution/precipitation), ionic exchange, mixing and seawater intrusion (as a particular case of mixing), and groundwater pollution noticed by the occurrence of non-natural introduced chemicals. Contrast hydrochemical data with geological evidences.
10. Avoid plotting, and above all reporting, unnecessary, meaningless graphs!
11. Interpret spatial occurrence considering sources/sinks, transport processes (advection, dispersion, reactions, …), and other hydrogeological-based concepts.

[15] EC (2001). *The EU Water Framework Directive: statistical aspects of the identification of groundwater pollution trends, and aggregation of monitoring results.* Technical Report, n. 1. Final Report, 65 pp

12. Estimations from geochemical models, as CO_2 partial pressure and saturation indexes are easy to obtain (e.g., using PHREEQC, or other open codes), and they may provide a very interesting complementary information.
13. Avoid unnecessary regression analysis unless you are really sure that the relationship between variables is linear, exponential, …, or any other kind of equation. Relationship between variables are governed by geochemical laws that do not usually follow simple regression models.
14. Avoid linear regression to show upward or downward trends, or the lack of a trend, with time. If done, recall that the statistics (i.e., r2 values) can sometimes be meaningless. As a substitute, use weighted smoothed curves. For instance, the LOESS method, which smoothers the data by applying the linear regression method only locally, is much more flexible with regard to the shape of trend.

- ***Further reading***

EU-WFD Guidelines Document 15 on “Groundwater monitoring”. https://circabc.europa.eu/sd/a/e409710d-f1c1-4672-9480-e2b9e93f30ad/Groundwater%20Monitoring%20Guidance%20Nov-2006_FINAL-2.pdf

U.S. Geological Survey, 1997 to present, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9. Handbooks for Water-Resources Investigations. file:///C:/B-Biblioteca%20PMP/13%20-%20UC%20Davis/USGS/Field%20Manual%20--%20Index.htm

Textbooks:

- Appelo C, Postma D, 2005. *Geochemistry, Groundwater and Pollution*. 2nd ed, Balkema
- Brassington R, 2007. *Field Hydrology*. Wiley.
- Edmund WM, Shand P, 2008. *Natural Groundwater Quality*. Blackwell Pub.
- Stumm W, Morgan J, 1996. *Aquatic Chemistry*, 3rd ed. Wiley.
- Weight WD, Sonderegger JL, 2000. *Manual of Applied Field Hydrogeology*. McGraw-Hill.

3.6 Session 6.- Data management and quality assurance

Considerations on data processing, storage, quality assurance and reporting. Sharing databases in transboundary aquifer monitoring programs

- **Dataflow**

For a monitoring programme to be successful, data needs to be collected, stored, interpreted and translated into useful information. In the case of the transboundary monitoring programmes this process present another level of complexity as all these steps should be agreed between riparian countries. Figure 18 aims to represent the different steps and elements involve in the functioning of a monitoring programme. While until know we have focussed in the description of the criteria to collect the data (location of monitoring points or methods to collect data), in this section we will discuss the other steps for data to be properly and effectively collected and transformed into information. Thus, a data management strategy needs to be designed between riparian countries.

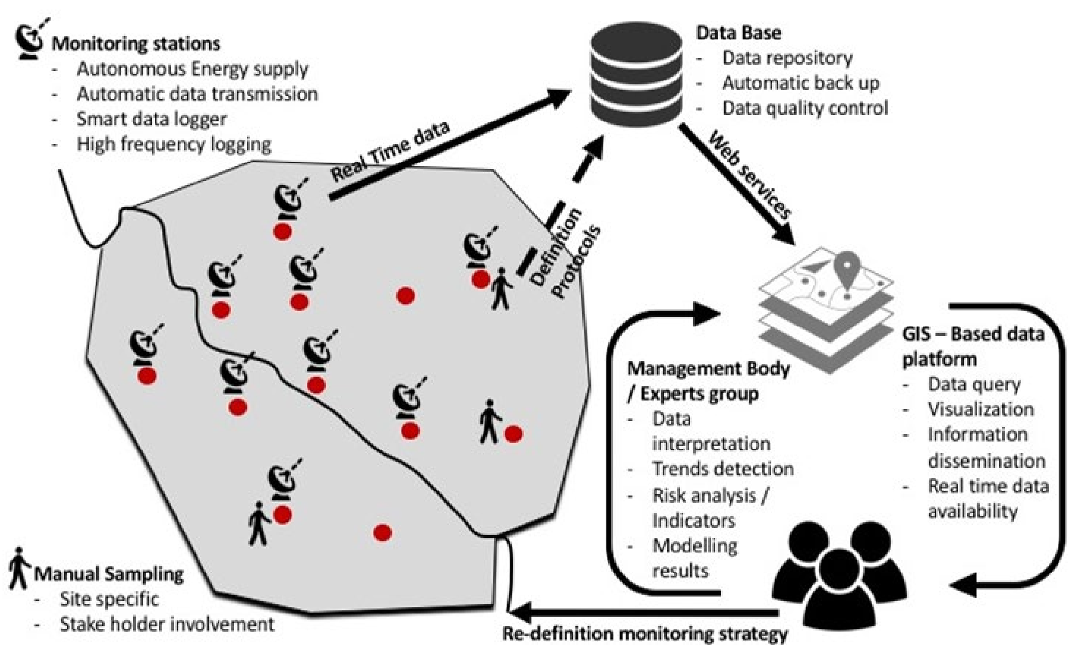

Figure 18 Dataflow in a transboundary groundwater monitoring network

- **Data management**

Based on Guidelines on Monitoring and Assessment of Transboundary Groundwaters from UN/ECE, a management strategy should go through the following steps before releasing any data or information[16]:

I. Data should be analyzed, interpreted and converted into defined forms of information using appropriate data analysis techniques;
II. Collected data should be validated or approved by a joint commission/body before they are made accessible to any user or entered into a data archive;
III. Information should be reported to those who need to use it for decision-making, model validation, management evaluation or in- depth investigation;
IV. Data and information necessary for future use should be stored, and the data exchange should be facilitated not only at the level of the monitoring body itself, but also at all other appropriate levels (international, ECE regionwide, aquifer, etc.).

All these steps should be address jointly with the quality control strategy (explain below), as they require the definition of protocols and standards that facilitate smooth cooperation between riparian countries.

The data management process has two specially time consuming and difficult steps: data gathering and data storage and exchange. Nowadays, tools are available that facilitate both.

Data gathering concerns to the process of collecting the data on the field, transcribe it into a digital format and enter it into a database. This process can be facilitated when using automatic sensors, if a telemetric station is installed. These type of stations allow data to be sent from the sensor located in the field to an online database, using telephone or satellite signal. The cost of such devises is large, between 1500 to 10000 Eur. depending on the manufacturer, sensors and services included. However, for some

[16] UN/ECE Task Force on Monitoring and Assessment (2000). Guidelines on Monitoring and Assessment of Transboundary Groundwaters. ISBN 9036953154

circumstances, where the number of monitored locations is reduced, the location is difficult to reach, personnel costs are large and/or a regular and frequent monitoring is required, these devises may provide an effective solution. Moreover, some additional benefits are involved, like the reduction of human errors or the instantaneous availability of the data. The last is especially interesting for the design of real-time alerts, for example should the groundwater levels oscillate from a pre-determined value.

Data storage and exchange is one of the most delicate matters in designing a transboundary monitoring programme. The storage and exchange strategy should ensure equal access from all riparian states to each other's data once it passes all quality requirements. There is no one unique solution for this, however the mediation of some international impartial organizations may be of use in this specific step. Common databases and exchange platforms have been implemented by IGRAC (GGIS) and UNESCO-IHP (WINS) in the past years. This platforms facilities riparian states to automatically connect parts of their datasets using standards from the OGC (Open Geospatial Consortium), and allowing to interact between them to review and release data at different levels. Moreover, the fact that these are GIS-based online platforms facilitates the accessibility and visualization of the data. The information system developed for the Ramotswa Aquifer (Southern Africa) by IGRAC using their GGIS, is a great example of the type of tool that addresses data management, exchange, quality assurance, visualization and dissemination in one platform.

- **Quality management**

A quality policy should be draft by a joint body where all riparian countries are represented. The body should define the level of quality and the control protocols to ensure produces and shared data from the transboundary monitoring network satisfies all riparian states and serves for the purpose of taking informed decisions about the transboundary aquifer. Quality requirements may change in strength and nature depending on the type of data and its purpose.

For example, based on the conceptual model, quality requirements may be defined in terms of the acceptable deviations of the measured variable from predicted properties. This can be done by formulating questions to be answered by the data. For example, a considerable deviation from the dominant groundwater flow direction, or a decrease in recharge of more than 10% annually. This may trigger a red flag a proms the responsible working team to review a specific set of data.

Quality requirements for groundwater head measurements may be formulated based on the error in the measurement in comparison with the targeted trends. In the case of geochemical data, a traditional quality check is to calculate the ionic balance and set a maximum error. Thus, confidence intervals should be defined for each variable entering the database that help to identify outlier or anomalous values automatically.

Quality policy should also include reporting mechanisms. Elements like the formatting of periodic reports, peer-review process or the validating protocols for data to be published should be agreed by all riparian states.

Therefore, one of the first steps in implementing a monitoring network would be to generate a quality policy report addressing all the mentioned aspects and defining responsible organisms for each task. Therefore, the generation of protocols is part of this task. This includes: sampling, sample transport, sample storage, laboratory analysis, data validation, data storage, data analysis, and data presentation[17]. These protocols are the operational steps in a process where insufficient quality control may lead to unreliable data. By following protocols, mistakes are minimized, and any mistakes can be traced and undone[13]. Especially in field data collection and chemical analysis, international standards and methods should be used upon agreement between all riparian states to ensure comparability and reduce postprocessing.

[17] UN/ECE Task Force on Monitoring and Assessment (2000). Guidelines on Monitoring and Assessment of Transboundary Groundwaters. ISBN 9036953154

Therefore, based on the Guideline for groundwater monitoring of the EU commission the minimum elements to be covered by quality assurance procedures are:

- Identification and records for samples, devices and operators
- Sampling methods, sampling plan and sampling field reports
- Sample transportation, receipt, storage and preservation
- Validation of methods, including uncertainty estimation
- Analytical measurement procedures
- Internal quality control of methods
- Participation in external QC schemes (proficiency testing schemes etc)
- Expression of results
- Traceability of documents
- Traceability of measurements

- ***Further reading***

- UN/ECE Task Force on Monitoring and Assessment (2000). Guidelines on Monitoring and Assessment of Transboundary Groundwaters. ISBN 9036953154

- Wickert, Sandell, Schulz, Crystal (2019). Open-source Arduino-compatible data loggers designed for field research. Hydrol. Earth Syst. Sci., 23, 2065–2076, 2019. https://doi.org/10.5194/hess-23-2065-2019

<u>Textbooks:</u>

- Jakeman et al. 2016. Integrated Groundwater Management. Springer.

4 The case of the Skadar/Shkoder – Buna/Bojana transboundary aquifer system

The Skadar/Shkoder - Buna/Bojana transboundary aquifer system is an unconsolidated aquifer situated between Albania and Montenegro (Figure 19). These groundwater resource is of great importance for both countries. It provides fresh water to highly populated areas like Podgorica or Shkoder cities. It is affected by intense human activities, like agriculture and industry. Additionally, it is located in the Mediterranean coastal region, an area highly vulnerable to climate change variability, thus increasing frequency of extreme flooding and droughts. Moreover, several initiatives took place in the area: DIKTAS project (GEF/UNDP/UNESCO), Integrative Management Framework (IMF) for Bojana/Buna Area – MedPartnership (GEF/UNEP/MAP), Development of Hydrological and Hydraulic Study of Regulation of Skadar Lake and Bojana River Water Regime and Initial Characterization of Lakes Prespa, Ohrid and Shkodra/Skadar projects funded by the GEF (UNDP, World Bank).

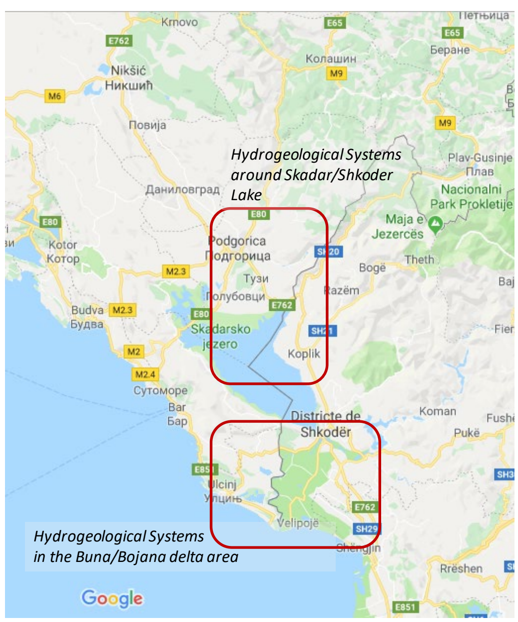

Figure 19.- General map of the studied area, locating the hydrogeological systems around the Skadar/Shkodër Lake and those in the Buna/Bojana delta area. Source: Google Maps.

The reports entitled "Hydrogeological conceptual model of the Skadar/Shkoder – Buna/Bojana Transboundary Aquifer System situated between Albania and Montenegro" authored by L. del Val Alonso, and "Design and development of a groundwater-monitoring network and program for the transboundary aquifer between Albania and Montenegro" authored by J. Mas-Pla, both in the context of the UNESCO project "*Design and testing of a multipurpose transboundary groundwater monitoring network in the Extended Drin River Basin*" (DRIN) under the supervision of Dr. Alexandro K. Makarigakis, issued in December 2019, describe the hydrogeological characteristics of the area and proposed a monitoring program based on the EU-WFD guidance documents. Both reports were carried out following the methodology described along these guidelines document. Therefore, this case study serves as example of their application.

Following the content of both reports, a brief summary of the hydrogeological features of the transboundary aquifer system of the Skadar/Shkoder- Buna/Bojana area, specifically its groundwater bodies, are described in this section.

4.1 Hydrogeological conceptual model

The Skadar/Shkoder Buna/Bojana transboundary aquifer system represents a groundwater resource of great importance for both Montenegro and Albania. Therefore the design of a transboundary groundwater monitoring network was required under the UNESCO project "Design and testing of a multipurpose transboundary groundwater monitoring network in the Extended Drin River Basin" (DRIN). The network should:

- improve transboundary cooperation for the sustainable management of groundwater resources in the area, and
- comply with European Water and Groundwater Framework Directives (EU WFD and EU GFD) requirements.

The EU WFD states that the design of a monitoring network should be based on the "characterization, assessment of risk and building of a conceptual model of the groundwater system, in which the general scheme 'recharge-pathway-discharge' is known". Therefore, the first step is to generate a hydrogeological conceptual model of the transboundary aquifer system, as required by the EU WFD for the preparation of the groundwater-monitoring programme. As states in the guidelines, the characterization, should include the <u>definition of groundwater bodies</u>, which are the main groundwater management units used by the EU WFD. The conceptual model should present an <u>integrated overview of the state of the groundwater resource</u>, including information about hydrologic, environmental and socioeconomic aspects. Moreover, this characterization should be <u>based on the most up-to-date available information</u>, where data gaps should be highlighted in order to be tackled through the monitoring network design.

4.1.1 Data collection

The first step in the construction of the aquifer conceptual model is the collection of data. For this purpose we used Table 1. Data was required from the responsible administrations of both Montenegro and Albania (Table 7).

	Data Needed for the elaboration of hydrogeological conceptual model	Priority (based on EU-WFD requirements)	MNT	ALB
Topography	Topographic maps	*ESSENTIAL*	Yes	Yes
	Detailed Digital Elevation Model		Yes	
	Surface waters	*ADVISABLE*		
	Surface water catchment	*OPTIONAL*		
Geology	Geology/Lithology Map	*ESSENTIAL*	Yes	Yes
	Tectonics	*ESSENTIAL*	Yes	Yes
	Stratigraphy descriptions	*ESSENTIAL*	Yes	Yes
	Geophysical data	*OPTIONAL*		
Hydrogeology	Hydrogeological units	*ESSENTIAL*		Yes
	Basic geochemistry	*ADVISABLE*	Yes	Yes
	Permeability	*ADVISABLE*	Yes	Yes
	Wells inventory	*ESSENTIAL*	Yes	Yes
	Groundwater levels time series	*ESSENTIAL*	Yes	

	Data Needed for the elaboration of hydrogeological conceptual model	Priority (based on EU-WFD requirements)	MNT	ALB
	Local uses of groundwater.	*ADVISABLE*	Yes	Yes
Climatic	Meteorological data	*ADVISABLE*	Yes	
Pollution sources	Inventory of diffuse sources and point sources	*ADVISABLE*	Yes	Yes
	Map of flood prone areas	*OPTIONAL*		Yes

Table 7 Data collected under the DRIN project

Fortunately, a previous effort in the area, the DIKTAS project, already generated part of this information and harmonized it, especially the geological and hydrogeological information.

4.1.2 Multidimensional assessment

First, an hydrogeological assessment was done. A detailed interpretation of the geological data was done, which helped identifying and delineating in greater detail the aquifer units. In this case, the focus was placed on the non-alluvial deposits placed on top of the regional karst system that dominates the area. For this purpose, hydrogeological schematic cross-sections were drawn in order to illustrate the vertical extension of each aquifer unit and geological context (Figure 20 and Figure 21).

Knowing the horizontal and vertical extension of the aquifer, meteorological information and groundwater heads data was used to analyse the recharge-discharge pathways and estimates some figures of the water balance. Figure 22 shows the example of the Zeta Plain in Montenegro. The groundwater heads map tells us about the recharge-discharge pathways. In this case, showing a clear dependence from the groundwater fluxes and recharge coming from the north-eastern part of the catchment.

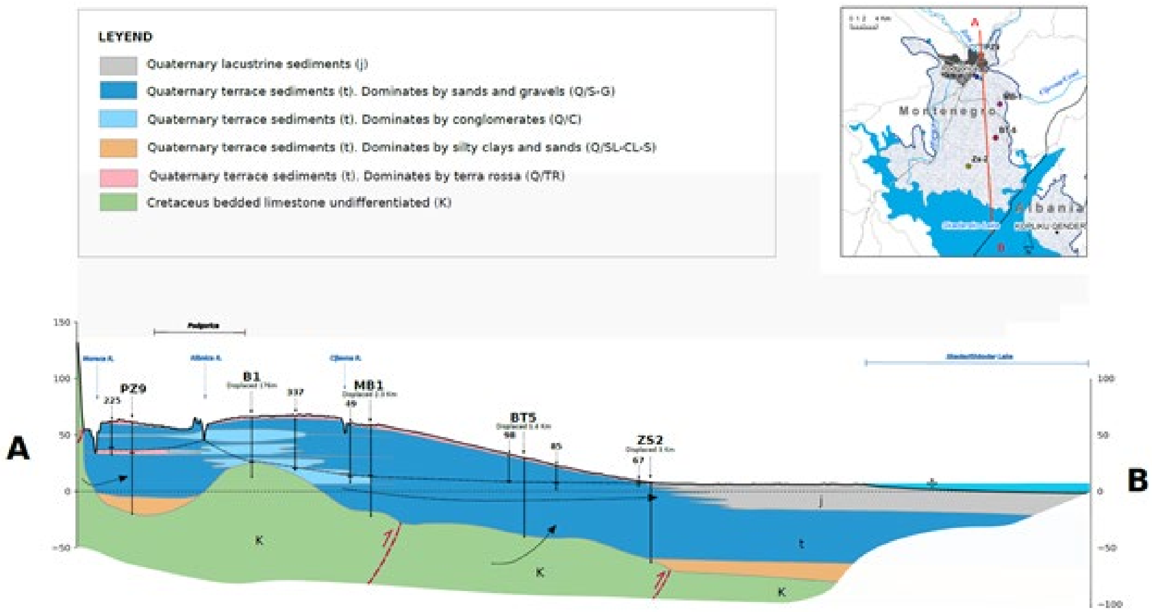

Figure 20 Cross-sections of the Zeta Plain alluvial and fluvio-glacial deposits, according to geological maps and to well logs for the Quaternary deposits thickness. Borehole lithological description based on borehole construction reports provided by Montenegrin authorities.

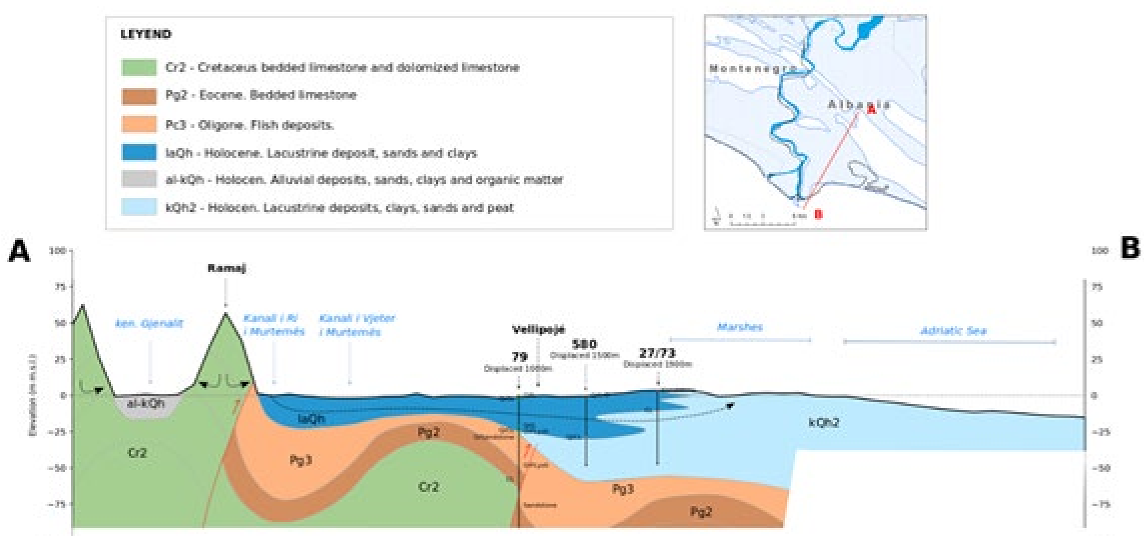

Figure 21 Geological cross-section of the Albanian side of the Buna/Bojana delta.

Additionally, Figure 23 provides information about the available renewable resource, if only recharge from precipitation is considered. Recharge was calculated in 885 mm per year, thus 50% of precipitation approximately. However, most of the recharge occurs in winter, while summer is a season of deficit.

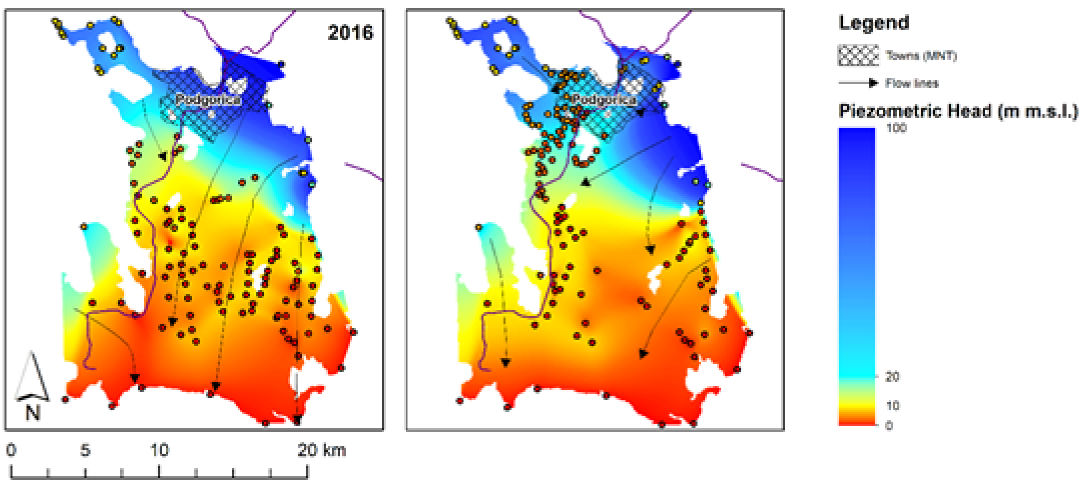

Figure 22 Groundwater heads map of the Zeta plain including flow lines

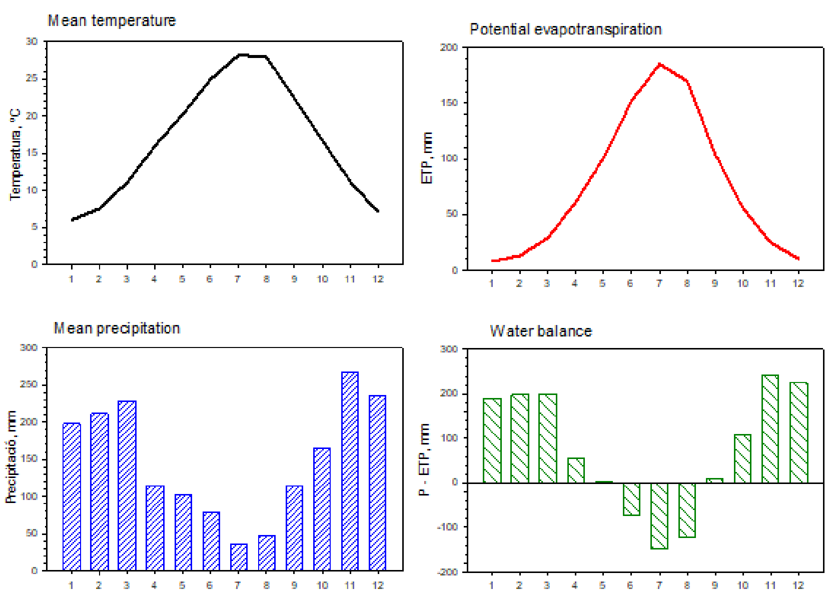

Figure 23 Water balance for the Zeta Plain

Environmental information was collected as well, which allows us to answer questions about the relation between groundwater and surrounding ecosystems and the quality of groundwater.

Main groundwater depend ecosystems were identified:

- Springs:
  - Karstic springs, called “oko”, meaning “eye” in the local tongue, are a source of water supply for the surrounding settlements.
  - Other springs occur at the contact between a permeable and impermeable layer where groundwater is forces upwards towards the surface.
- Wetlands:
  - Shkoder/Skadar Lake and lake marshes
  - Sasko Lake
  - Viluni coastal brackish lagoon
  - Ulcinj Saline

These ecosystems need to be considered in the planification of the monitoring network, as their preservation is a requirement to achieve a good quantitative status of the aquifer. Luckily, most of these environments are already protected by several figures: i) Lake Shkoder/Skadar and River Buna RAMSAR site (ALB), ii) Lake Shkoder/Skadar National Park (ALB), IUCN managed natural reserve of the Lake Shkoder/Skadar and Viluni, Velipoja and Dumi areas (ALB), Lake Shkoder/Skadar National Park (MNT) and Ulcinj Salina EMERALD site (MNT). The existence of these protection figures is determinant for the implementation of the monitoring network, as they provide personnel, resources and save locations to implement the monitoring, plus a set of regulations that can ease the implementation of management actions to solve any negative trend identified through the monitoring network.

Information of the groundwater quality was collected, although too scarce to draw strong conclusions. Still, enough to identify some trends, mainly spatial, in those cases where complete hydro-chemical analysis were available. The Zeta Plain is used in this case as an example, as it was the area from the aquifer from which more data of the geochemistry was received. Based on this data, and the even distribution of the samples in the territory, we could deduce that the hat dominant hydrochemical facies in the Zeta plain is Calcium Bicarbonate (Figure 24), which is clearly driven by the groundwater interaction with dominant limestone regional lithology. Additionally, information on the pH, indicated additional reactions that may indicate the presence of other chemicals, whether natural or artificial.

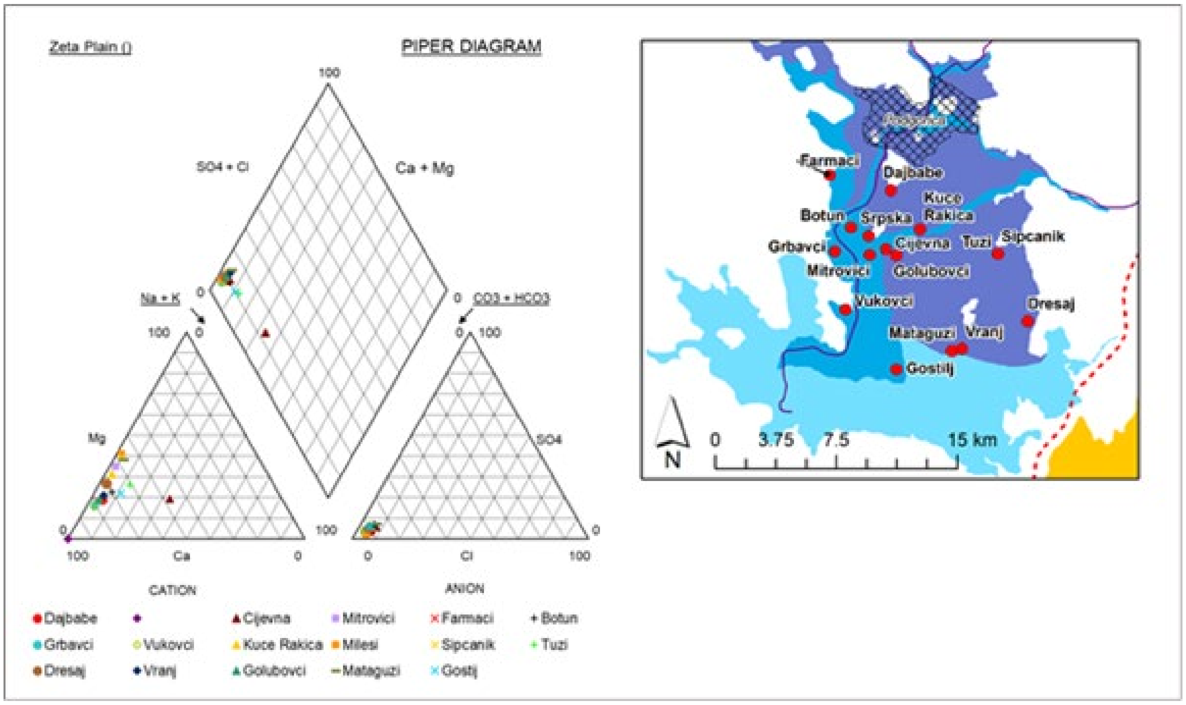

Figure 24 Piper's plot including hydrochemical data from the Zeta Plain. (Data source: Devic & Filipovic (2005) Geochemical Quality Parameters, as tracer of outside influence on water of intergranular aquifer of Zeta plain. In Water Resources and Environmental Problems in Karst.)

Information about possible sources of pollution, abstraction rates and lands uses is used to identify pressures and impacts in the aquifer area (Table 8 Pressures and Impacts) .

	PRESURES			IMPACTS		
Area	**Point source pollution**	**Diffuse pollution**	**Change in water levels due to abstraction**	**Quantitative**	**Qualitative**	**Ecological**
Skadar Lake area:						
Zeta Plain (MTN)	✓ Aluminium production facility. ✓ Food-processing and plastic industries. ✓ Gravel mining along Morača River.	✓ Fertilization ✓ Stream recharge due to well capture zones	✓ Water abstraction in Podgorica urban area (MTN). ✓ Water abstraction due to agricultural activity (MTN).	✓ Reduced available groundwater resource ✓ Decrease contribution of groundwater to surface water bodies	✓ Pollution of supply wells ✓ High concentrations of nutrients and metals	✓ Eutrophication
Koplik-Shkodër Plain (ALB)		✓ Fertilization				
Buna/Bojana River area:						
Trush – Zadrima Basin (ALB, MTN)	✓ Landfill near Shkjezë (ALB). ✓ Heavy metal concentrations in Saski Lake ✓ Gravel mining along the Drin River left-bank, near Ashtë (ALB). ✓ Septic systems and network	✓ Fertilization in cereal and forage crops using slurries and manures (ALB, MTN).	✓ Well field near Fshati i Ri for urban supply (ALB). ✓ Overpumping for agricultural demand (ALB).			
Buna/Bojana delta area (ALB, MTN)	✓ Leakage from salt production ponds (ALB, MTN).	✓ Fertilization ✓ Stream recharge ✓ Non-farmed stock breading (ALB).	✓ Domestic and agriculture wells near the coastline. ✓ Saline water in karstic springs ✓ River salinization.			

Table 8 Pressures and Impacts

4.1.3 Identification of Groundwater bodies and conceptual model

With the scope to adapt the monitoring and management of the studied aquifers to the requirements of the WFD, a first exploratory, working demarcation of the "groundwater bodies" is mandatory. While the aquifer definition for the WFD is the usual one for hydrogeology textbooks (*Aquifer means a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater;* Article 2, 11), the concept of "groundwater body" is singular to the WFD. Indeed, a *body of groundwater means a distinct volume of groundwater within an aquifer or aquifers* (Article 2, 12).

Therefore, groundwater bodies (GWB) are, at the end, principal reporting units; i.e. management units (size, pressures, status issues). Therefore, the aquifer is the "structure" where groundwater is stored, and can be defined on the basis of how much water can flow into them and the ability to extract significant quantities from them. Conversely, groundwater bodies constitute the "basic units" where it is possible to assess the water status. The "groundwater body" should be a coherent sub-unit in the river basin (district) to which the environmental objectives of the directive must apply. Hence, the main purpose of identifying these bodies is to enable the (quantitative and chemical) status to be accurately described, monitored, and compared to environmental objectives (EU, 2003)[18].

The characterization of GWBs is a detailed task that must be carried out by the Member States. Nevertheless, committed to our goal of "developing a proper monitoring program that allows both countries, Albania and Montenegro, to manage their groundwater resources in the context of a transboundary aquifer system", the proposed groundwater bodies must be understood as "working tools" that serve to the goals of this preliminary analysis of the hydrogeological systems in the study area.

[18] EU Commision (2003). R*iver Basin District Management Systems. Approach to Delineation of Groundwater Bodies.* Paper by the Working Group on Groundwater Guidance document no. GW2, 18 pp.

- **GWBs in the Skadar/Shkoder Lake area**

According to the hydrogeological information summarized in the previous section, the following GWBs for the Skadar/Shkoder Lake area are suggested (Figure 25):

1. ***GWB-01 Zeta plain.-*** The GWB formed by alluvial aquifer of the Zeta, Morača and Cijevna rivers that includes all three terraces and the lacustrine sediments in its distal parts, near Skadar/Shkoder Lake. It is a sedimentary unit, with dominant coarse particles and intergranular porosity. Despite that some layers can show some degree of cementation it is considered an excellent aquifer. Flow recharge is due to karst lateral inputs, rainfall and, locally, stream infiltration. Main discharge is towards Skadar/Shkoder Lake, occasionally stream discharge, and groundwater withdrawal for urban (mainly, Podgorica city), industrial and agricultural demand. Main pressures are groundwater abstraction and pollution from urban, industrial and agricultural sources. It shows large vulnerability. Specific vulnerable points are karstic springs in its limits and on the lacustrine area.
2. ***GWB-02 Koplik-Skhodër plains***.- The GWB formed by the alluvial fan aquifer of the Koplik-Skhodër plains from the mountain front from Skadar/Shkoder Lake, and its lacustrine sediment strip. Hydrogeological dynamics is comparable to the GWB of the Zeta Plain, and main human pressures are pollution from urban and agricultural sources. It also shows large vulnerability (see Section 3). Similarly, specific vulnerable points are karstic springs in its limits and on the lacustrine area. Porous aquifer of Mbishkodra is used for water supply of Shkodra city with a capacity of 800 – 900 L/s. This pumping station consists of 10 boreholes in Dobraç area.

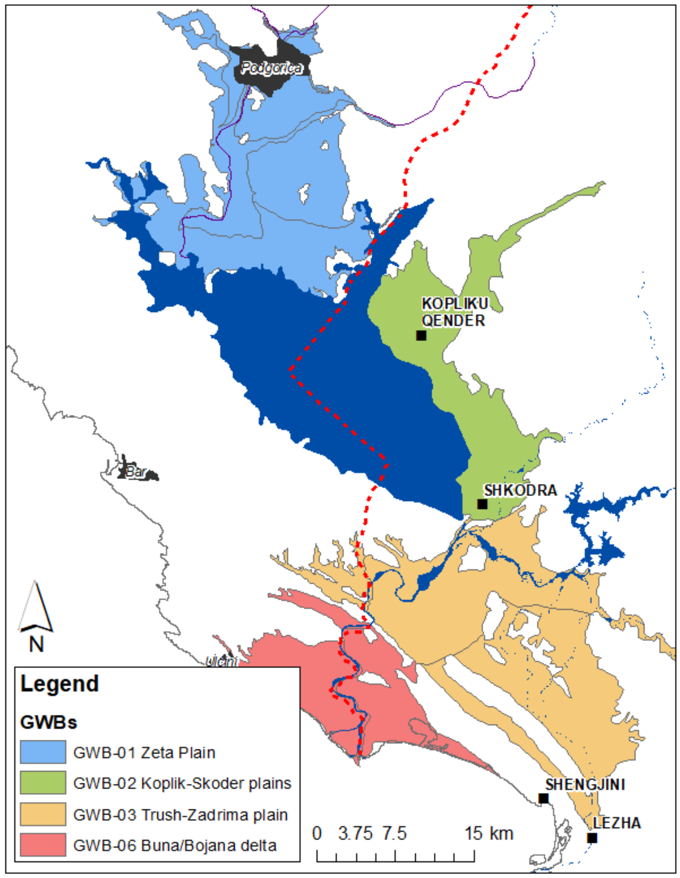

Figure 25 Groundwater bodies that are the object of this study.

Despite their similar hydrogeological features and sharing Skadar/Shkoder Lake as the common discharge unit, both GWBs are considered independent of each other. We also claim that both GWBs cannot be fully understood and managed without considering Skadar/Shkoder Lake as a surface water body by itself. Its categorisation as such is beyond the scope of this study.

- **GWBs in the Buna/Bojana area**

In the Buna/Bojana area, we assume that 1) the Drin and Buna/Bojana rivers, altogether with Skadar/Shkoder Lake, control most of the recharge as contiguous surface water bodies, in addition to local rainfall infiltration, and 2) the wide occurrence of the flysch sediments on the bottom of the Trush plain and between the folded structures, considered of low permeability, behave as aquicludes and, therefore, act as no-flow limits wherever they appear.

According to the hydrogeological information summarized in the previous section, the following GWBs for the Buna/Bojana area are suggested (Figure 25):

1. ***GWB-03 Trush and Zadrima plains.-*** The GWB formed by alluvial aquifer created by the Drin and Buna/Bojana river sediments. It mainly develops in the left-bank of both rivers, but it should also include the right-bank of the Drin River around Vukatanë, and the right-bank of the Buna-Bojana River near along the strip Muriqan-Oblikë still in Albanian territory. As mentioned, this alluvial, productive aquifer gets its recharge from stream and rainfall infiltration. As its bottom is assumed to lay on flysch sediments, the relationship with the underlying karstic aquifer must be limited to fracture zones or local karstic phenomena as buried sinkholes or similar. It also gets lateral recharge from the karstic limestone ranges that lay in its southern boundary. The main pressures are groundwater abstraction for domestic and agricultural use) and pollution of agricultural sources. It shows large vulnerability (see Section 3) and it is subject to periodical floods (Schneider-Jacoby et al., 2006[19]). The aquifer in the Zadrima basin, in the SE part of the Drin and Glader rivers alluvial plain, is not very productive.
2. ***GWB-04 Albanian Karstic coastal ranges.-*** The GWB formed by the Cretaceous limestone ranges: Mali i Kakarriqit and Mali i Rrencit, parallel to the coastline and oriented NW-SE from their north-westernmost outcrops, near the Buna/Bojana River, to the cities of Balldreni and Lezhë. We consider these limestone ranges as a separate GWB, and they control the lateral recharge to GWB-03 and GWB-06. Their structure is given by diverse thrust faults and folds and these ranges can be considered hydrogeologically isolated because of structural limits and the occurrence of flysch deposits as their stratigraphic cover. Recharge is mainly due to local rainfall in its summits, and discharge occurs laterally towards the Quaternary

[19] M. Schneider-Jacoby, U. Schwarz, P. Sackl, D. Dhora, D. Saveljic and B. Stumberger (2006): *Rapid assessment of the Ecological Value of the BojanaBuna Delta (Albania / Montenegro)*. Euronatur, Radolfzell.

sedimentary formations or direct to the Adriatic Sea (e.g., Shëngjin area). They lack intense human land use; therefore, the main (relative) pressure is groundwater abstraction from their karstic springs.

3. ***GWB-05 Montenegrin Karstic coastal ranges.-*** The GWB formed by the Cretaceous limestone ranges of Katërkolle and Gornja Klezna from their west limit in the Adriatic coast to the Buna/Bojana River at the east. It also includes the colluvium formations that develop from both ranges towards the Buna/Bojana River on the foothills near the villages of Vladimir-Sukobin-Sas and Donja Klezna, including Sasko Lake. The GWB excludes the areas where the Eocene flysch outcrops. As their twin limestone ranges in GWB-04, they control the lateral recharge to GWB-06. Their structure is given by diverse thrust faults and folds and they can be considered hydrogeologically separated because of structural limits and the occurrence of flysh deposits. Recharge is mainly due to local rainfall and discharge occurs laterally towards the Quaternary sedimentary formations or direct to the Adriatic Sea. Main human land use happens in the foothill area and the main pressures will be pollution from urban and agricultural sources.
4. ***GWB-06 Buna/Bojana delta area.-*** This GWB integrates the most recent deltaic system of the river, being defined by the triangle between the water gap in Pentar, Port Milena in Montenegro and Velipojë and the Këneta e Vilunit lagoon in Albania. It is a single hydrogeological units constituted by the complex development of the delta and the associated dune and beach ridges, as well as the lagoons of Këneta e Vilunit, and Zoganjs Lake, both related to the delta historical development and human transformation. Some inland wetlands also exist, north of Gomsiqe, yet they are nowadays disconnected from coastal processes (if they have ever been), and related to the draining of the Trush plain southernmost most area and to local springs. In turn, these wetlands artificially drain to the Këneta e Vilunit lagoon and, through a second channel, to the sea. Recharge of the delta aquifer levels are related to stream and rainfall recharge, as well as form lateral contribution from GWBs 05 and 06. Groundwater flow discharge is mainly to the sea. Given a high human activity, mainly touristic, pressures are high, involving groundwater withdrawal and the associated seawater intrusion when high pumping regimes are set in wells close to the coastline. Pollution form urban activity is also expected, and from agriculture

as well. Salt pans, as those in inner bank of the left-bank meander and those of Zoganjs Lake, may also contribute to groundwater salinization.

In order to facilitate assimilation and dissemination of the assessment and characteristics summarized above per groundwater body, a table and map were built.

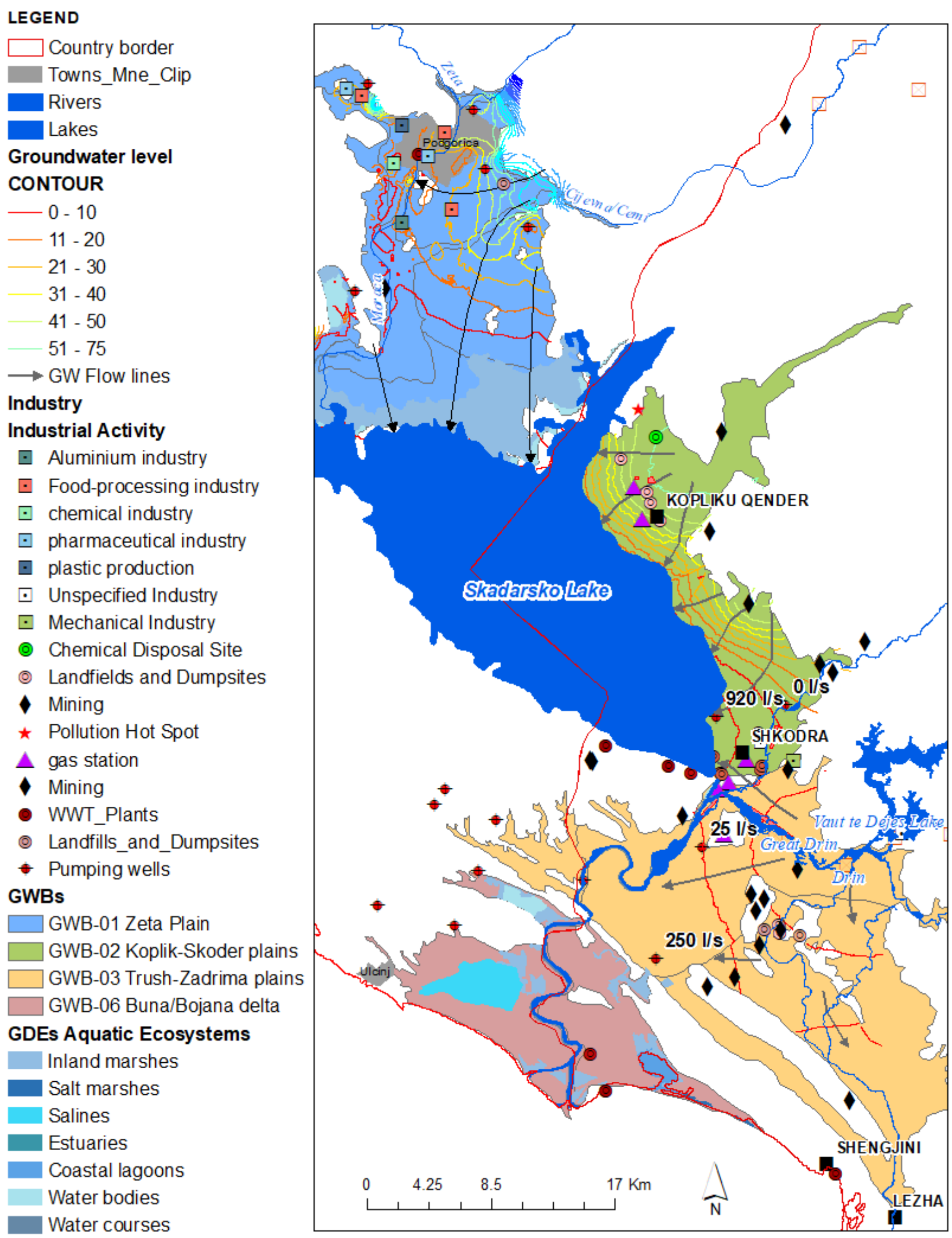

Figure 26 Hydrogeological conceptual model of the Buna/Bojana Shkoder/Skadar transboundary aquifer

Groundwater Bodies	Geomorphology	Average thickness	Recharge / discharge	Potential groundwater quantity risks	Groundwater quality	Potential groundwater quality risks	Groundwater dependent Ecosystems	Environmental protection areas
GWB-01 Zeta Plain	unconsolidated clastic deposits	100 m	Main recharge mechanism: surrounding karst system of the Cijevna River catchment, which upper catchment is located in Albania Main discharge mechanism: discharge to the Skadar Lake though Morača surface discharge and direct groundwater seepage	- Water abstraction in Podgorica urban area (MTN) - Water abstraction due to agricultural activity (MTN).	Dominant facies is calcium bicarbonate In general good quality with EC values below 700 mS/cm	Point sources: -Aluminium production facility (MNT) - Food-processing and plastic industries as potential pollution focuses (MNT) - Gravel mining along Morača River (MNT) Diffuse sources: - Fertilization (MNT) - Stream recharge due to well capture zones (MNT)	Karstic springs Shkoder/Skadar Lake and lake marshes	Lake Shkoder/Skadar and River Buna (RAMSAR)
GWB-02 Koplik-Skoder Plains	unconsolidated clastic deposits	100-150 m	Main recharge mechanism: surrounding karst system Main discharge mechanism: discharge to the Skadar Lake though groundater seepage		Few data available Good quality	- Fertilization (ALB) - Waste Water disposal from Skodra city (ALB)	Karstic springs Shkoder/Skadar Lake and lake marshes	Lake Shkoder/Skadar and River Buna (RAMSAR) Lake Shkoder/Skadar National Park

Groundwater Bodies	Geomorphology	Average thickness	Recharge / discharge	Potential groundwater quantity risks	Groundwater quality	Potential groundwater quality risks	Groundwater dependent Ecosystems	Environmental protection areas
GWB-03 Trush plain	unconsolidated alluvial deposits	50 m	Main recharge mechanism: drainage from Skadar/Skoder lake and surrounding moundatin ranges Main discharge mechanism: seepage towards Buna/Bojana river	- Well field near Fshati i Ri for urban supply (ALB). - Overpumping for agricultural demand (ALB).	Few data available Good quality	Point sources: - Landfill near Shkjezë (ALB). - Saski Lake has been reported to show high heavy metal concentrations. - Gravel mining along the Drin River left-bank, near Ashtë (ALB). - Pollution from septic systems and network (where existing). Diffuse sources: -Fertilization		Managed natural reserve (IUCN)
GWB-06 Buna/Bojana Deltaic Area	deltaic deposits	30 - 50 m	Main recharge mechanism: contribution from Buna/Bojana river and local limestone mountain ranges Main discharge mechanism:groundwater seepage to the sea	- Domestic and agriculture wells near the coastline in Velipojë (ALB) and Doni Štoj (MTN) - Saline water in karstic springs (Gac spring). - River salinization.	Few data available, mainly in shallow wells	Point sources: - Leakage from salt production ponds (ALB, MTN). Diffuse sources: - Fertilization (ALB, MTN). - Stream recharge due to well capture zones affected by wastewater dumping (urban drainage). - Non-farmed stock breading (ALB).	Sasko Lake Viluni Coastal brackish lagoon Ulcinj Saline	Managed natural reserve (IUCN) (ALB) Important Bird Area and EMERALD site (MNT)

Table 9 Main figures characterecing each grundwater body in the Buna/Bojana Shkoder/Skadar transboundary aquifer

4.2 Monitoring zones according to the EU WFD

How the proposed monitoring sites for the DRIN project has been selected?

The proposed groundwater bodies and monitoring networks and plans were selected after the creation of a hydrogeological conceptual model, and a detailed consideration of the WFD and GWD requirements.

The process has been the following:

1) Create a hydrogeological conceptual model of the study area. In this case, the transboundary zone was divided into the area north of the Skadar/Shkoder Lake area that includes the Zeta plain in Montenegro and the Koplik-Shkoder plain in Albania, and the buna/Bojana alluvial plain (Trush and Zadrima plains, Albania) and the delta area involving both Montenegro and Albania[20].

This conceptual model included:

- Describing the main hydrogeological units,
- Considering the water balance and the recharge/discharge pathways,
- Considering the groundwater dependent ecosystems,
- Characterizing the hydrochemistry and the groundwater quality,
- Considering the pressures and impacts upon groundwater resources,
- Finally, delineating and proposing several groundwater bodies, as management-working units where monitoring networks and programs must be developed.

[20] del Val Alonso L (2019). Hydrogeological Conceptual model of the Skadar/Shkoder – Buna/Bojana Transboundary Aquifer System situated between Albania and Montenegro. Project "Design and testing of a multipurpose transboundary groundwater monitoring network in the Extended Drin River Basin" (DRIN). Unpublished, 121 pp.

2. Determine the monitoring network and program for the proposed groundwater bodies[21].

This task involves:

- Reviewing and deeply considering the requirements of the WFD and GWD,
- For each groundwater body, synthesizing its hydrogeological features as well as the actual pressures and impacts,
- Determining the hot-spots that need to be monitored to fulfil the WFD goals given the above synthesized information.
- Defining potential network sites, and according to the type of monitoring (surveillance vs. operational) define a sampling frequency.
- Prioritizing monitoring areas, justify this proposal, and set locations, time frequencies and variables.

At the end, final selected monitoring sites and program must be defined and validated by local technicians and experts, according to the guidance of the nation Water Authorities, and how they want to approach the monitoring tasks: as a knowledge building effort, as a service to the community and to the environment, as a duty to fulfil administrative EU requirements, and so on. Monitoring is a costly task in resources and time that should be planned so all potential objectives are covered in a cost-effective way. Monitoring planning is thus an assignment that it is conducted today, but must have an eye on the future evolution of the whole groundwater system.

Selected monitoring zones

Having in mind the requirements and general objectives of the EU WFD, as well as the conceptual model and vulnerability and risk assessments, it is necessary to prioritize specific monitoring objectives for each groundwater body. First, priority zones are proposed for

[21] Mas-Pla J (2019). Design and development of a groundwater-monitoring network and program for the transboundary aquifer between Albania and Montenegro. Project "Design and testing of a multipurpose transboundary groundwater monitoring network in the Extended Drin River Basin" (DRIN). Unpublish., 37 pp.

groundwater monitoring based on the hydrogeological features of each GWB, as well as the human pressures on its quantity and quality. Secondly, the specific monitoring objectives identified per groundwater body are included in the four types of monitoring networks propose by the Guidance Document No. 15 "Guidance on Groundwater Monitoring" (European Commission, 2007).

Priority groundwater monitoring zones are hereafter proposed for each groundwater body. This zonation aims to translate the results from the conceptual model, risk assessment and vulnerability assessment into concrete actions, by zooming from a larger scale (groundwater body) to a smaller scale (monitoring zones; Figure 27), as a previous step to the selection of specific boreholes or location for new boreholes.

GWB-01 Zeta plain

- **Morača River alluvial plain**.- The Morača river concentrates the drainage of the Zeta plain towards the Skadar/Shkoder /Shkodra lake. Moreover, Podgorica and several heavy industries like the Aluminium plant are located up-flow from the river, which implies that any leakage that might occur will affect the river water quality. In this sense, understanding the relation between the aquifer and the river is essential to determine the impact of these risks along the river alluvial plain and finally to the lake. Therefore, part of the Zeta Plain groundwater monitoring should concentrate in continuous recording of head level evolution along the river to infer surface water - groundwater relationship. Due to the upstream occurrence of heavy industry, additional monitoring combining hydrochemical sampling of surface and groundwater, especially at hot spots as the Aluminium Plant, is advisable.
- **Podgorica urbanized area**.- Podgorica concentrates a large population and several groundwater pumping stations, and probably many more house-hold supply wells. In this case, groundwater continuous monitoring of groundwater level is proposed to set control of depression cones created by domestic supply wells. Wastewater discharges could be also a source of pollution, therefore groundwater quality information is advisable, although these could be provided by the company/institution in charge of operating the supply pumping stations.

- **Cijevna River**.- Groundwater levels in the Zeta plain show most of the groundwater recharge to the Zeta plain occurs laterally through the Easter contact between the granular aquifer and the regional karst formation. The Cijevna River is a good reference to understand the behaviour of the recharge of the Zeta plain, therefore is advisable to monitor head levels and hydrochemistry to infer stream recharge to the aquifer, and the behaviour of the whole aquifer system as well.
- **Groundwater seepage to Skadar/Shkoder Lake**.- Groundwater seepage to the Skadar/Shkoder Lake could be a contributor of diffuse pollution from agriculture activities. Considering that the lake is the most important hydraulic transboundary feature connecting the Zeta plain to the rest of the transboundary groundwater bodies, it is advisable to set at least one monitoring point at the southern part of the aquifer to control groundwater contributions to the lake status.

GWB-02 Koplik-Skhodër plains

- **Groundwater withdrawals**.- It is advisable to monitor head and chemical evolution around areas were groundwater pumping is concentrated. Based on the available information there are two interesting areas. One of the biggest groundwater pumping station is the Dobraç station, able to pump 900 l/s for the Shkodra city supply. Other sites as Hoti Ri near the Kiri River and the area of Shtoji should also be considered.

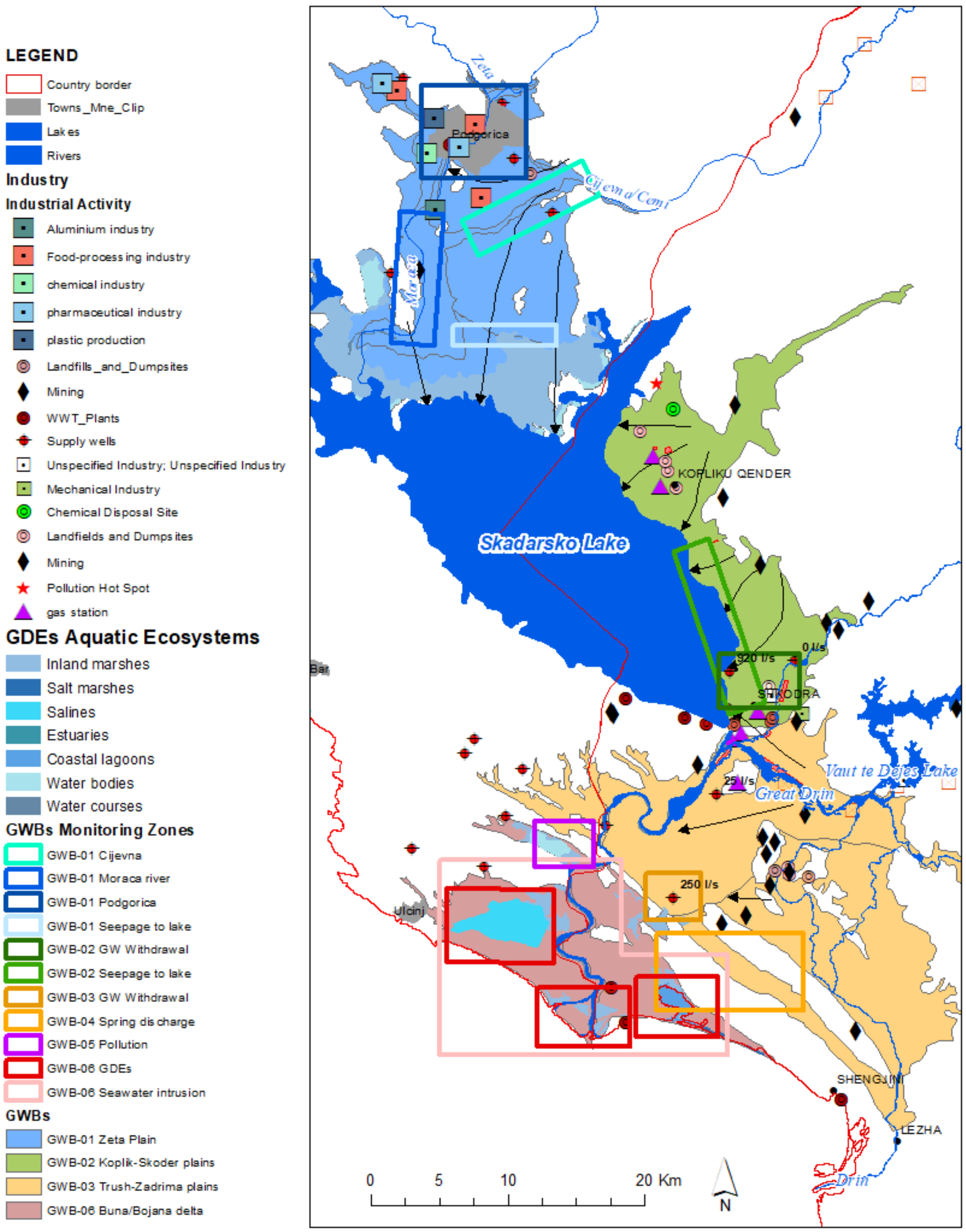

Figure 27 Location of priority groundwater monitoring areas for each groundwater body.

- **Groundwater seepage to Skadar/Shkoder Lake**.- Likewise in the Zeta Plain groundwater seepage to the Skadar/Shkoder /Shkodra lake could be an important source of pollutants. Therefore, it is advisable to monitor groundwater levels and quality. An important are in this regard are the areas down flow Shkodra city. Based on the risk analysis and geochemical data, this area is subjected to high risk of sewage pollution that can contribute negatively to the lake water quality and that of the aquifer.

GWB-03 Trush and Zadrima plains

- **Groundwater withdrawals**.- Main groundwater withdrawal areas in the Trush plain. The Trush Pumping Station for Velipojë, with 5 pumping wells able to pump up to 500 L/s, is a candidate for monitoring site. Wells in the Zadrima plain, near Blinisht have also to be mentioned; however, those are located far away from the transboundary zone.
- **Groundwater/surface water relation.-** It is advisable to monitor the relation to the groundwater body of the Drin and Buna/Bojana rivers. Therefore, it is proposed two monitoring zones at the norther border of the GWB close to the Drin River, near the village of Ashtë, and at the western part of the GWB close to the Buna/Bojana.

GWB-04 Albanian Karstic coastal ranges and GWB-05 Montenegrin Karstic coastal ranges

- **Spring discharge**.- Both groundwater bodies are considered in this analysis as for being one of the recharge are as of the coastal aquifer. Both groundwater bodies lack intense human pressures. Therefore, it is advised to monitor the springs discharge and its water quality.
- **Sasko Lake**.- GWB-05, in Montenegro, includes colluvium formations that link this small lake with the aquifer. Due to occurrence of human pressures WFD goal could be at risk, reason why it is advised to monitor contribution from this area to the aquifer.

GWB-06 Buna/Bojana delta area

- **Seawater intrusion**.- This is one of the most complex groundwater bodies. Its proximity to the sea implies a high vulnerability to seawater intrusion. This fact combined with the touristic increasing activity in the area, could imply an increase in seawater intrusion as already monitored in the Velipojë area. Still, the river acts as a positive boundary. The interaction of fluvial and coastal hydrological processes is a complex puzzle. A dense network of piezometers, and the control of active wells, is needed to depict groundwater flow in this low gradient area and to detect any transboundary effects or seawater intrusion. ACVM analysis suggest that seawater intrusion may also affect limestone/karstic aquifers. Therefore, monitoring this potential impact is also advisable.

- **Groundwater Dependent Ecosystems**.- This groundwater body sustain several groundwater associated aquatic ecosystem, as relevant wetland areas. Therefore, the contribution of fresh groundwater is essential to ensure their sustainability.

4.3 Priority Monitoring zones and pilot test locations

Despite the interest of all listed monitoring zones, specific zones present a higher priority based on the project objectives and limited resources. This selection does not exempt of the overall monitoring required to identify general trends.

Those specific zones with their monitoring requirements are,

GWB-01 Zeta plain

- Groundwater resources along the Morača River, especially those hot-spot sites that represent a high risk of disaster, and
- the intensive groundwater domestic supply well area in Podgorica.

GWB-03 Trush and Zadrima plains

- Trush groundwater withdrawal field as the main pressure to groundwater resources quantity, and

- Nitrate pollution due to agricultural activity and poor sewage systems; however, available data for this area shows that the threshold limit of 50 mg NO_3/L has neither been reached or any upward trends have been detected.

GWB-06 Buna/Bojana delta area

- Monitor seawater intrusion along the coastal area, specifically around main wells for urban or domestic supply, if any. Consider also potential seawater intrusion affection to the limestone aquifers.

Since this project requires **two pilot locations** were to test the monitoring equipment and protocols, the December 2019 reports suggested either one in GWB-01, and that of GWB-06. Both represent the highest risk for human water supply in the transboundary aquifer. That means giving priority to human interest above environmental interests in this selection.

Annex I. Strategy for the generation of a hydrogeological conceptual model[22]

1a. Basic Conceptual model: Qualitative Description		
	Topography	• Morphology • Surface waters • Surface water catchment
	Geology	• Lithology • Tectonics • Stratigraphy
Data	Hydrogeology	• Groundwater catchment area • Aquifer geometry • Hydrogeological units • Aquifer type • Geochemical type • Permeability • Confinement conditions • Consolidation of rocks • Groundwater chemical typology • Single/multi aquifer system • Unsaturated zone • Estimation of flow direction • Local uses of groundwater
Process	• Definition of hydrogeological properties • Derivation of hydrogeological units • Estimation groundwater balance	
Products	• Cross-sections, maps, block diagrams • Spatial distribution of hydrogeological units • Description monitoring network • Groundwater flow directions	
1b. Basic Conceptual model: Quantification of parameters		
Data	Geochemical data	• Clay content • Organic carbon • Mineralogical composition of aquifer matrix

[22] Based on EU-WFD Guidelines Document 26 on "Risk assessment and the use of Conceptual models for Groundwater"

	Hydraulic data	• Hydraulic conductivity • Porosity • Groundwater levels • Hydraulic gradients • Direct recharge (rain) • Indirect recharge (surface water, drainage systems, etc)
	Baic hydrochemical data	• Temperature • pH • Conductivity • Redox potential • Alkalinity • Dissolved oxygen • Dissolved organic carbon • Mineral content (mayor ions)
	Specific hydrochemical dara	• Isotopes for water age determination • Trace compounds
	Soil	• Soil type distribution • Depth of development
Process	Hydraulics	• Groundwater balance • Adjustment of balance area • Is the monitoring network sufficient?
	Hydrochemistry	• Understanding and quantification of natural hydrochemical processes • Natural background levels • Confirmation of hydraulic balance • Confirmation of flow regime
Products	Hydraulics	• Cross section, maps or block diagrams • Quantified water balance • GW flow directions • Depth to water table • Travel times of seepage and groundwater
	Hydrochemistry	• Groundwater chemistry characterization in time and space • Natural groundwater levels
2a. Conceptual model includes risk assessment aspects: Qualitative description of impacts		
Data	Land use and potential stress factors and risks	• Agriculture • Industry • Infrastructure • Abstraction and infiltration points

		• Heat storage
	Receptors	• Protective zones
Process	• Identification of local anthropogenic inputs • Identification of location of receptors • Identification of path-ways between hazard and receptor • Identification of actual risk (magnitude and probability)	
Products	• Maps • Distribution of different types of land use • Distribution of different anthropogenic impacts • Distribution of different receptors	
2b. Conceptual model includes risk assessment aspects: Quantitative description of impacts		
Data	Emission of anthropogenic sources	• Agriculture • Industry • Infrastructure • Mining • Waste management • Diffuse soil contamination
	Inputs from anthropogenic sources	• Case specific pollutants • Degradation products • Potential electron acceptors • Indicators of biodegradation • Metals
	Groundwater use	• Abstraction or infiltration rates • Heat storage
Process	• Spatial delineation of concentrations and fluxes • Variability of concentrations and fluxes • Identification of relevant processes (Check Guidance on Groundwater Status and Trend Assessment)	
Products	• Maps and diagrams • Delineation of areas and receptors affected • Reconstruction of the impact from past events until today • First prediction of the future development of impacts	
3a. Conceptual model includes risk management aspects: effects of existing measures		
Data	Measures for groundwater quality	• Existing concentration data • Temporal and spatial development of anthropogenic input (eg fertilizers) • Results from tracer tests • Degradation rates

<table>
<tr><td></td><td>Measures fro groundwater quantity</td><td>Existing data on groundwater/surface water levels
Existing data on groundwater abstraction
Results from tracer tests</td></tr>
<tr><td rowspan="2">Process</td><td>Groundwater quality</td><td>Time series analysis</td></tr>
<tr><td>Groundwater quantity</td><td>Understanding effect of measures
Evaluate good status</td></tr>
<tr><td>Products</td><td colspan="2">Maps of spatial and time development in impact areas
Diagrams of the development of risk related parameters</td></tr>
<tr><td colspan="3">3b. Conceptual model includes risk management aspects: forecast on effects of measures for groundwater quantity</td></tr>
<tr><td rowspan="2">Data</td><td>Future effects of measures for groundwater quality</td><td>Calculated travel time
Degradation rates
Scenarios of climate development
Scenarios of future development (land use, population and water demand)</td></tr>
<tr><td>Future effets of measures for groundwater quantity</td><td>Effects in groundwater level by changes in abstraction
Scenarios of climate development
Scenarios of future development (land use, population and water demand)</td></tr>
<tr><td>Process</td><td colspan="2">Area measures enough?
Time to reach trend reversal?
Time to reach good status?
Need for prolongation of deadlines?</td></tr>
<tr><td>Products</td><td colspan="2">Diagrams, maps and text description</td></tr>
</table>