European Union Network for the Implementation and Enforcement of Environmental Law

Guidance for Tackling Illegal Groundwater Drilling and Abstraction

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Introduction to IMPEL

The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) is an international non-profit association of the environmental authorities of the EU Member States, acceding and candidate countries of the European Union and EEA countries. The association is registered in Belgium and its legal seat is in Brussels, Belgium.

IMPEL was set up in 1992 as an informal Network of European regulators and authorities concerned with the implementation and enforcement of environmental law. The Network's objective is to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation. The core of the IMPEL activities concerns awareness raising, capacity building and exchange of information and experiences on implementation, enforcement and international enforcement collaboration as well as promoting and supporting the practicability and enforceability of European environmental legislation.

During the previous years IMPEL has developed into a considerable, widely known organisation, being mentioned in a number of EU legislative and policy documents, e.g. the 7th Environment Action Programme and the Recommendation on Minimum Criteria for Environmental Inspections.

The expertise and experience of the participants within IMPEL make the network uniquely qualified to work on both technical and regulatory aspects of EU environmental legislation.

Information on the IMPEL Network is also available through its website at: www.impel.eu

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Executive Summary

Within the IMPEL network (https://www.impel.eu) a project was launched in 2021 titled 'Tackling illegal groundwater drilling and abstractions (TIGDA)'. Background to the project and terms of reference can be found at www.impel.eu/en/projects/tackling-illegal-groundwater-drilling-and-abstractions-tigda

Sharing knowledge and good practices on how to manage groundwater drilling and abstractions are the main goals of the TIGDA-project. This would include specific permitting conditions, accreditations as well as enforcement tools and methods in place in different member states to reduce illegal drilling and groundwater (over)abstraction. Lessons learned in the member states (good ones as well as bad ones) are useful to share and collect.

In order to fine-tune the project objectives to needs of enforcers in each member country, the TIGDA-project group developed a questionnaire within the network to gain valuable input with a topic focus on:

- Illegal drilling activities,
- Illegal groundwater abstractions,
- How permitting is organized for both drilling and abstraction,
- Whether legislation on these topics is sufficiently supporting enforcement,
- How inspections and enforcement can be successfully organized.

We are also encouraged respondents to list any novel techniques, pilot projects, tools or best practices that may be applied in their country or region and may be useful to share with the other network members. The gathered information will inform the direction of the next project phase

Quotation

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1. Objectives

Within the IMPEL network (https://www.impel.eu) a project was launched in 2021 titled 'Tackling illegal groundwater drilling and abstractions (TIGDA)'. Background to the project and terms of reference can be found at www.impel.eu/en/projects/tackling-illegal-groundwater-drilling-and-abstractions-tigda

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The original direction of the project included the objective to understand and quantify the impact of illegal groundwater activities on the Water Framework Directive assessment of both Groundwater Chemicals and Groundwater Quantitative. However, following a questionnaire to Member States it became apparent that the main focus should be on detection techniques for regulation, compliance and enforcement.

The project does consider the following IMPEL projects:

- Water Over-abstraction and Illegal Water Abstraction Detection and Assessment (WODA)
- DIANA – Detection and Integrated Assessment of Non-Authorised Water Abstractions Using EO

There is similarity in the TIGDA project with WODA and DIANA projects. TIGDA has now updated and made advances in understanding the use of earth observation techniques for the detection of illegal groundwater activities. In addition, the TIGDA project proposes a stepped approach from awareness to enforcement which takes account of emerging technologies and the differences in scale and activity type.

2. Questionnaire

The questionnaire was compiled by the project core team and sent around to the project team for comment. It was agreed and finalized during the TIGDA-meeting in October 2021. The questionnaire was sent around to all IMPEL members. In December 2021 nine answers were received. This low outcome was discussed during the TIGDA project meeting, and it was decided to extend the deadline and make another announcement to the TIGDA members. No additional answers were received.

In April 2022, the questionnaire was revised to make it easier to compile for respondents. Several questions within the first questionnaire asking for too information were taken out, and some vague questions or answer options were rephrased. The revised questionnaire was again sent out to the TIGDA members, and another nine answers were received. Two respondents answered both questionnaires, so in total sixteen unique respondents returned an answer (covering ten countries). Given the rather lengthy questionnaire (20 minutes to complete), this can be considered a reasonable response. Still, many member states are not represented in the answers, which may result in blind spots on interesting enforcement or inspection techniques. The full report on the questionnaire was published in December 2022.

Figure 1 shows the ten countries for which a questionnaire response was received: Belgium (Flanders), Croatia, Greece, Italy, Malta, Norway, Portugal, Romania, Slovenia, UK (Wales & England).

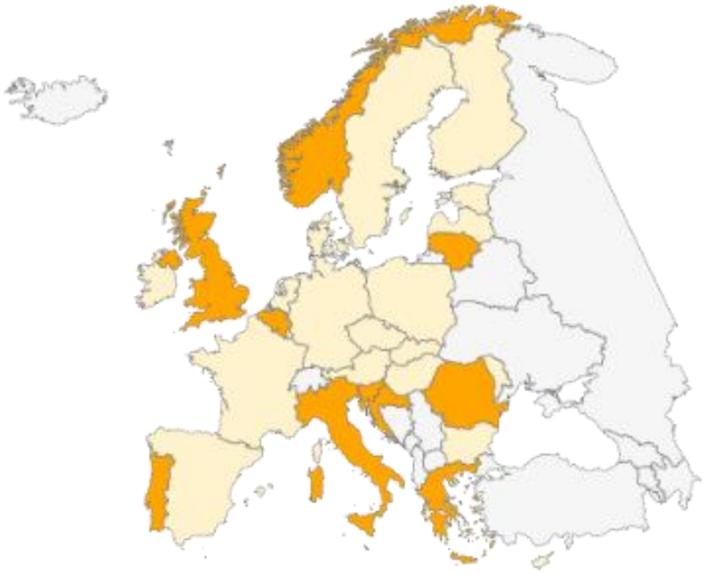

Figure 1: countries for which a questionnaire was returned are indicated in orange.

The completed questionnaires were scanned for any existing methods used for enforcement on detection, monitoring and enforcement of groundwater drilling and extraction. All methods were synthesized in a longlist of TIGDA-methods. This longlist forms the landscape of methods that are used throughout Europe, some may be well-established and generally adopted, others are quite novel and only pioneered in some countries. The longlist was mainly inventoried from responses to the questionnaire and supplemented with answers from a similar questionnaire in 2015 (VMM, BE) and experiences of the project team. The long list is detailed in Table 1

Table 1: Longlist of TIGDA-methods

Building a proper legislative framework • Drilling contractors need a license, • Legal obligation to pre-register drilling activities, • Legal obligation to (post-)register drilling activities, • Legal obligation to register new groundwater abstractions + exemptions, • Legal obligation to register effective parameters of the well, • Efficient penalty principles are foreseen
Legislative instruments • Regulation campaign for existing illegal groundwater abstractions
Compliance Promotion • Raising public awareness, • Information for well operators, • Publication of best-practices for drilling operations, • Publication of best-practices for flow measurement, • Evaluation report for drilling contractor, • Benefits for contractors who perform well

Inspection tools:

- Inspection checklists,
- Detection with helicopters, planes or drones,
- Detection via satellite imagery,
- Risk profiling and validation methods,
- Coupling with groundwater monitoring,
- GPS-tracking of drilling equipment,
- Reporting of illegal drilling or groundwater abstraction,
- Picture database of wells,
- Database of drilling tools

3. Workshops

The project team arrange four workshops and site visits to ensure that the TIGDA project was focused and taking account of variations in approaches across the Member States.

3.1 Portugal

The TIGDA project would like to thank the General Inspectorate for the Agriculture, Sea, Environment and Spatial Planning (IGAMAOT) and the Portuguese National Republican Guard (GNR) for hosting in Lisbon on 13 and 14 October 2022. The field visit on 14 October observed in a drone inspection at Coruche, led by GNR with a live inspection for illegal surface water abstractions.

The TIGDA project appreciated the support from:

- Ana Garcia, Mario Gracio and Claudia Morgardo, IGAMAOT
- Pedro Ribeiro, GNR

The meeting covered the results of the questionnaire from which a decision was made to focus on working on providing guidance on detection and compliance. The initial objective to quantify the level of abstraction and determine the impact on Water Framework Directive quantitative assessment had been covered previously in IMPEL Water Over-abstraction and Illegal Water Abstraction Detection and Assessment (WODA) Project. In addition, the level of data that would need to be processed was considered beyond the scope and capacity of the project.

The presentation by project members also highlighted the range of groundwater activities which needed to be included within the project. This ranged from domestic boreholes, mining, quarrying through to irrigation. The legislative drivers were also different across Member States and groundwater activities. This highlighted that guidance needs to focus on the process of detection and not to cover the unification of legislation.

The demonstration on the use of drones for a wide range of activities highlighted the benefit of unmanned aerial vehicle (UAV) for the detection of groundwater activities. The meeting discovered that drones can be used not only for aerial detection but also has benefits for quantifying land volumes (for example, a raised landfill).

The live compliance inspection was useful to see how drone inspection can be done in the field. The compliance inspection required several operators:

- Base controller – to co-ordinate the compliance inspection and have access to video images and permit data
- Drone operator – to fly the drone following the guidance and direction of the Base controller.
- Inspectors – to move to locations detected by the drone and confirmed by the base controller for a targeted inspection.

In summary, the TIGDA meeting discovered:

- Drone technology is a useful tool for a wide range of compliance and inspection activities, including illegal groundwater activities.
- Requires training and authorisation to fly drones.
- Drone imagery cannot be used for court case files.
- Drones provides “eyes in the sky” to support inspectors undertaking compliance and enforcement.

3.2 Slovenia

The TIGDA Project team held a meeting in Ljubljana, Slovenia on 23 and 25 October 2023. On 24 October a field visit to Murska Sobota to observe a geothermal borehole construction.

The TIGDA project appreciated the support from:

- Martina Gašperlin, Acting Chief Inspector, Inspectorate of Natural Resources and Spatial Planning, Ministry of Natural Resources and Spatial Planning
- Bojan Počkar, Environment and Energy Inspectorate of the Republic of Slovenia , Ministry of the Environment, Climate and Energy. Also IMPEL Vice-Chair Projects.
- Martin Golčer, Environmental and Energy Inspectorate of the Republic of Slovenia , Ministry of the Environment, Climate and Energy
- Nada Kogovsek, Inspectorate of Natural Resources and Spatial Planning, Ministry of Natural Resources and Spatial Planning
- Matej Prkič, Managing Director, GeoGreen

The project covered the complex legislative drivers and compliance requirements for the administration of groundwater activities. In addition, the range of knowledge and skills needed to be a compliance inspector is quite wide ranging.

Case Example: Slovenia

IRSNVP (Inspectorate for the Environment and Spatial Planning) is a body within the Ministry for Natural Resources and Spatial planning. In addition to reporting to the Ministry ISNVP supports on draft regulations. IRSNVP consists of 72 inspectors and 35 public servants across Administration, Public Relations and four key inspection groups, namely Construction and Geodetic Inspection, Natural Resources and Mining Inspection, Division for Systematic Support and Division for General and Legal Affairs. Within Slovenia there are eight regional groups covering: Kranj, Ljubljana, Maribor, Novo Mesto, Celje, Koper, Nova Gorica and Murska Sobota. The IRSNVP covers inspections from building control, mining and the protection of natural resources.

The Inspectorate of the Environment and Energy of the Republic of Slovenia (IRSOE) is a body within the Ministry of the Environment, Climate and Energy. IRSOE also includes the Environment Inspection (EI), which covers the implementation of legislation in a wide range of areas including hydrological services. Overall, the environment is a very broad field and the EI has the power to supervise more than 250 by-laws.

Inspection procedures have become more complex due to the increasing volume of legislation, which makes the involvement or assistance of a lawyer in the inspection process essential. IRSOE have prepared more than 50 acts samples for inspectors in the area of inspection proceedings and more than 50 acts samples in the area of minor offence proceedings.

A system is being put in place to allow inspectors to pass an exam on drone management, which would significantly contribute to easier and more effective control. Drone images can also be used in court as evidence.

Overall Slovenia is experiencing an increasing number of environmental violations which also constitute criminal offences, so better and coordinated cooperation with other law enforcement authorities at international level in the future will be necessary.

The main outcomes of the project meeting were that the detection of illegal groundwater activities can be affected by:

- Resources and capacity within an authority to undertake enforcement on non-permitted activities.
- Inspectors cover a wide range of compliance inspection requiring a detail knowledge of many complex legislative instruments.
- EU Member States can have permitting and compliance procedures over several Ministries or Departments.
- Most EU Member States are aware of the problem of illegal groundwater activities but there can be a low profile, either politically, technically or environmentally.
- Exclusions from permitting of groundwater activities makes it difficult to differentiate between illegal activities and exempted activities.
- The permitting of borehole drilling and construction can be separate from permitting of an abstraction.

Some important learning points for the TIGDA project

- Geo-database systems linked to permitting can be beneficial.
- Detection of illegal drilling and abstraction requires different tools for different types of activity

3.3 Spain

The TIGDA project would like to thank to the Center of Hydrogeology of the University of Malaga (CEHIUMA) for hosting in Málaga our recent project team meeting on the 4 and 5 April 2024. On 5 April a field visit to Fuente de Piedra highlighted the issues of over-exploitation of a groundwater body for high value olive tree cropping.

the In particular the project team would like to acknowledge and thank:

- Bartolomé Andreo Navarro, Juan Antonio Barberá Fornell and Pedro Marín Troya from Center of Hydrogeology of the University of Malaga (CEHIUMA)
- Paloma Ramos from the Spanish Ministry for the Ecological Transition and the Demographic Challenge.
- Antonio Chambel, University of Evora, Portugal

The meeting focused on the impacts of illegal groundwater activities. The presentation on regulating illegal domestic well abstractions in Lithuania highlighted the difficulty in moving from a position of exempt activities to a position where regulation is needed for the improvement of groundwater quality.

The presentation by Rafeal Seiz (Freshwater Policy Co-ordinator – WWF Spain) noted that there are tensions between regional governments and environmental groups on the regulation of over abstraction in areas where there is a high economic value for the irrigated crops, particularly for the main production of berries (including strawberry, blueberry, raspberry and blackberry)

Rafael Seiz highlighted these tensions in the Doñana National Park. This is a nature reserve in Andalucia and is a diverse ecosystem of lagoons, marshes, forests and dunes that stretches across 100,000 hectares. The Doñana is on the annual migratory route of millions of birds and is home to many rare species, such as the Iberian lynx. However, the park has been struggling due to an ongoing drought and is threatened by intensive agriculture in the area.

The berry crops require an intensive use of water, estimated annual water request ranging from 4,500 to 9,000 m^3/ha. Over the past decades the large landuse change from non-agricultural areas transformed into berry cultivation under greenhouses has resulted in agriculture increasingly becoming a major driver of change to the environment within Doñana, by reducing the groundwater resource available to wetlands.

Case Example: Fuente de Piedra lake basin

Spain is the world's biggest exporter of olive oil and the European Union's biggest producer of fruit and vegetables and around 80% of water resources are used in agriculture.

Fuente de Piedra lake basin at the Laguna de Fuente de Piedra is classified as Wetland of International importance (RAMSAR) and part of the European ecological network "NATURA 2000" with many migratory birds, especially with colonies of Greater Flamingo from Europe.

Laguna de Fuente de Piedra (Fuente de Piedra Lake) is a good example of a water-stressed endorheic basin in south of Spain, located in the northern sector of Málaga province. The rains constitute the only source of water to the system, divided between direct precipitation on the lake, surface runoff and underground contribution. The only outlet for water from the lake is by evaporation, which determines its closed or endorheic character. The overexploited aquifers, due to intensive pumping over many decades, has severely limited groundwater discharge to the lake which has impacted the hypersaline wetland sustainability.

Intensive groundwater pumping for urban use and agriculture (predominately olive production) during more than 40 years have resulted groundwater decline of several tens of meters (up to 90 m) and increased salinity in the carbonate Jurassic aquifers.

The carbonate Jurassic aquifers extend into both the hydrographic confederations of Cuencas Mediterraneas de Andalucia and Guadalquivir. Unfortunately, the groundwater balance within Guadalquivir is positive and would allow further abstraction, while in the Andalucia has a strong deficit groundwater balance and is looking to recover to a more sustainable position.

Consequences of overexploitation is the loss of good quality drinking water. Located within the village of Fuente de Piedra is a desalination plant treating water from saline Triassic aquifer.

In summary, the TIGDA meeting discovered:

- Illegal drilling and abstraction is a consequence of poor water governance.
- Socio-economic drivers creates a tension on good groundwater governance between Adminstrations and environment.
- Illegal groundwater activities are more common in areas supporting high economic value crops.
- Simplification of administrative to legalise abstractions is key to avoid long deadlines and the risk of illegal groundwater activities.
- Encouraging participation of abstractors in good governance may tackle illegal drilling and abstractions.
- Compliance and enforcement is needed to avoid the feeling of impunity by abstractors, however, it must be supported by other participatory actions.

3.4 Italy

The TIGDA team held a two day earth observation workshop in Milan on 22 and 23 October 2024. The TIGDA project would like to thank Agenzia regionale per la protezione dell'ambiente della Lombardia (ARPA Lombardia) for hosting the workshop.

The TIGDA project appreciated the support from Dario Bellingeri, Allesandro Loda and Vito Sacchetti (ARPA Lombadia) and Lorenzo Solari, Copernicus Land Monitoring Service

The main focus of the meeting was to understand the use of earth observation (EO) techniques, including satellite imagery, for the detection of groundwater activities. The use of EO is an invaluable tool for compliance, from targeting activities to inspection areas. The benefit to Member States is that there is free software and data available and which is simple to use. The open source software and access to different Copernicus products, including European Ground Motion Service (EGMS), which can assist Member States to initiate a robust compliance campaign

In summary, the TIGDA meeting discovered:

- Earth observation (EO) data and GIS technology can detect and monitor groundwater activities.
- EO is a beneficial technology within a stepped approach to compliance and enforcement
- European Ground Motion Service (EGMS) has processed images to support on monitoring groundwater levels and subsidence
- EU Member States have access to a wide library of processed imagery through Copernicus
- Most software needed for visualisation are free and software is open-source
- A stepped approach is needed to move from awareness to undertaking a compliance visit.

4. Earth Observation Techniques for the Detection of Illegal GW Activities Project

The TIGDA project team delivered a project on Earth Observation Techniques for the Detection of Illegal GW Activities. The project was completed by

- Professor Radu Gogu, Groundwater Engineering Research Centre, Technical University of Civil Engineering, Bucharest, Romania
- Ion Nedelcu, Research Engineer, Agentia Spatiala Romana (Romanian Space Agency)

The overall objective of the project was to review the different types of earth observation (EO) methods and data that can be used for the detection of illegal GW activities. Within the scope of the project the definition of illegal GW activity covers any combination and types of illegal drilling illegal abstraction, including activities that could result in the direct input of pollutants to GW, for example discharges to wells, boreholes or soakaways.

The project reporting contains information on the different ways EO data can be accessed and processed in order to derive information, as needed for the following levels of awareness while tackling the illegal groundwater abstraction cases:

- Awareness Level 1: only suitable for filtering in potential illegal GW activity abstraction. Will help understand if more detailed inspection techniques are required.
- Advanced Level 2: ability to map clearly the location of illegal GW activities.
- Specialist Level 3: ability to clearly indicate the clusters and scale of illegal GW activities for prioritisation by the regulatory authority
- Expert Level 4: ability to provide sufficient evidence to automatically fine without local inspections activities

The project included four reports, in addition to a final report, covering:

- Earth Observation Techniques Accessible within EU for the Detection of Illegal Groundwater Activities;
- Identification of Earth Observation Methods and Data for Detection of Illegal Groundwater Activities;
- Obtaining and Processing Earth Observation Data;
- Recommendations for Earth Observation Methods and Data Against Scale of Illegal Activity.

The final report covers:

- Why detection of illegal groundwater activities is important
- How earth observation can help with detection
- Recommended methods, data and infrastructure

The project concluded that the detection of potential locations or areas of illegal groundwater activity can be done by analysing processed earth observation images from services such as Copernicus. The processed imagery from Copernicus and European Ground Motion Service is free but are not current, however, the use of these images can provide access to awareness level 1 and most probably the advanced level 2. However, to reach the specialist level 3 is likely to require quantification methods (including processing of site specific and recent satellite data) to be designed, developed and made accessible. UAS or drone inspection allows reaching expert level 4 in some cases.

Advances made in relation to quantification methods involving AI or other advanced analytics show promising perspectives and would be an area for future development.

5. Environmental Crime Directive

The EU Environmental Crime Directive includes within Article 2 (3)(m):

> „The abstraction of surface water or groundwater within the meaning of Directive 2000/60/EC of the European Parliament and of the Council (33), **where such conduct *causes or is likely to cause* <u>substantial damage</u> to:**

- the ecological status, or ecological potential of surface water bodies, or
- to the quantitative status of groundwater bodies"

The ecological status of surface water bodies can be dependent on the quality and quantity of groundwater. Therefore, it is important that measures are put in place to ensure that all groundwater activities are permitted, controlled and sustainable. Groundwater can also provide clean and plentiful water for other ecosystems, such as public water supply, irrigation and tourism. Therefore, the detection of illegal groundwater activities can help to mitigate and reduce substantial damage to the environment and human health.

The outcomes of the TIGDA project is a step forward in achieving the aims of the EU Environmental Crime Directive.

6. Guidance for a Stepped Approach from Detection to Compliance

The approach from detection to compliance of illegal groundwater activities must be conducted in a stepped manner to ensure that the correct data is analyzed and that resources are targeted effectively. The stepped approach is presented in Figure 2.

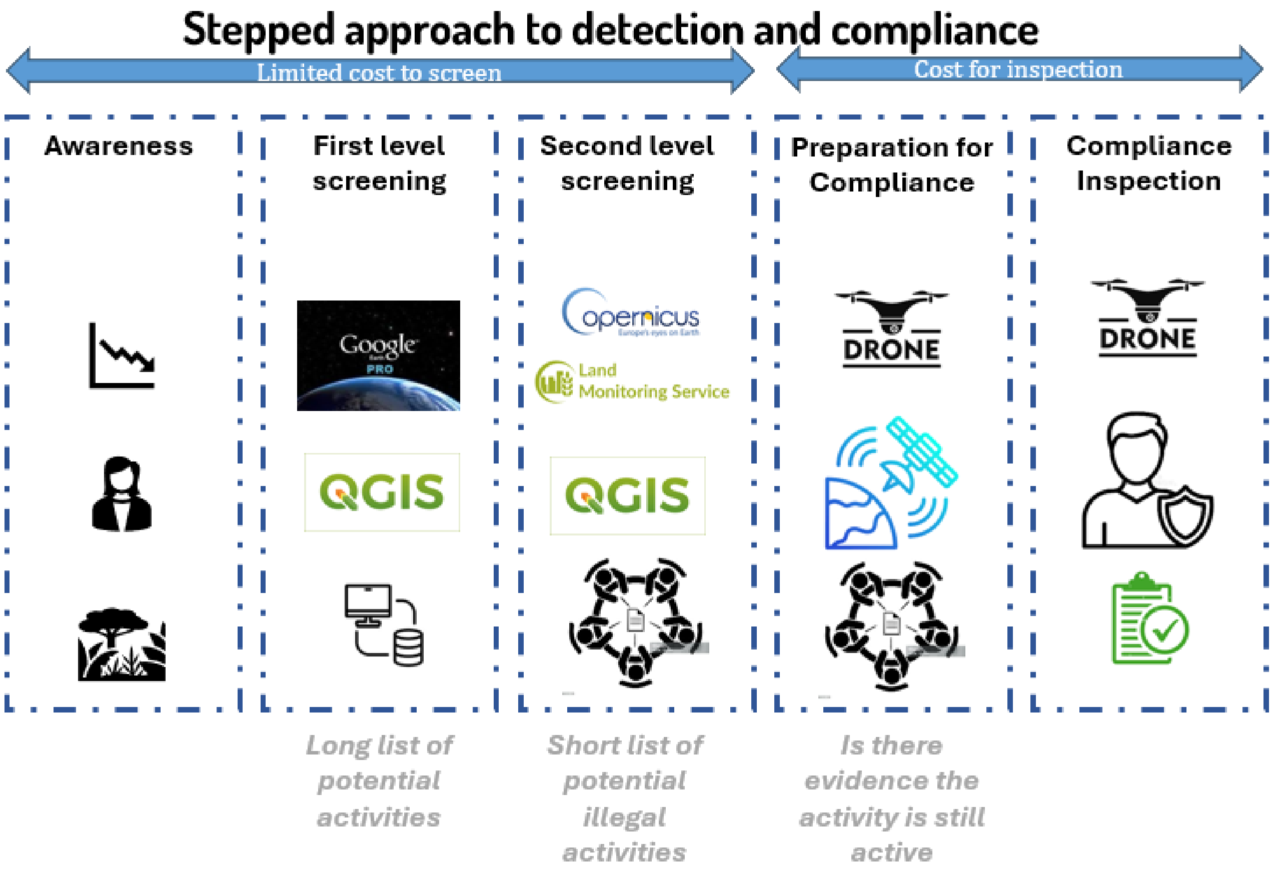

Figure 2 - Stepped Approach

The first three steps are generally low cost and can be considered part of routine business for the authority.I**1.**

I. Awareness and Detection

I.1 Awareness Campaigns

- Implement public outreach programs to educate stakeholders about the importance of compliance with groundwater laws.
- Develop materials emphasizing the environmental, legal, and societal impacts of illegal groundwater activities.
- Promote community participation by providing mechanisms for anonymous reporting of suspicious activities.

I.2 Observations

Awareness is gained from different types of observations. These can include (but are not limited to):

- Unexpected changes in groundwater trends.
- Pollution of groundwater.
- Degradation of ecology and ecosystems.
- Rivers and streams drying up.
- Reporting by the public.

It is important to record these observations, as the impacts of changes can take years to manifest. Keeping records helps link several non-concurrent observations and builds awareness of underlying issues that need investigation.

I.3 Advanced Detection Techniques

- Utilize Earth Observation (EO) technologies like satellite imagery and drones to effectively identify illegal activities. Leverage free resources such as Copernicus data for initial assessments.
- Develop an integrated geo-database consolidating detection data, permitting records, and risk assessments.
- Implement automated cross-referencing systems to identify discrepancies between detected activities and permits.

II. Initial Response and Investigation

II.1 First Level Screening

It is essential that the authority maintains a database of permitted activities and incident reporting. This database should be georeferenced so it can overlay authority shapefiles within a GIS environment (e.g., QGIS, which is open source).

Additional Earth Observation data can be accessed via free EO services such as Google Earth. Combining all georeferenced information provides a long list of potential activities or defines areas of concern, which may link to the observations detected during the awareness phase.

A georeferenced permit database does not need to be sophisticated. It can be as simple as an MS Excel spreadsheet, where compliance data includes grid coordinates for georeferencing.

II.2 Second Level Screening

The long list of activities or areas of concern should be reviewed using professional judgment and supported by advanced Earth Observation processing.

It is recommended that this step involves an expert working group, including:

- **Hydrogeologist**: To conceptualize the interactions between illegal activities, geology, groundwater flow paths, and potential impacts on receptors (e.g., rivers or drinking water).
- **Compliance Officer**: A quasi-legal expert who understands the legislation and whether the activity requires regulation or is exempt. The officer also has access to previous compliance visits and enforcement case history.
- **Data Analyst**: To present georeferenced information, including reported observations, permitted activities, requisite monitoring, and EO data.
- **Case Manager**: To manage the process and provide an audit trail for potential court proceedings.

The working group should be agile and relevant to the inspection area and issues of concern. By reviewing evidence, existing compliance data, and incident reports, the team can create a shortlist of potential illegal activities or locations. Multiple iterations may be required, supported by field monitoring and additional observations, to confirm evidence of illegal activity and likely harm to the environment or human health.

II.3 Evidence Collection and Documentation

- Conduct meticulous records of inspection activities, including geospatial data and photographic evidence.
- Use secure, standardized forms for capturing inspection outcomes to support enforcement actions.

III. Compliance Promotion

III.1 Preparation for Compliance

This step requires additional resources to prepare and undertake targeted compliance inspections:

- Use drones for covert surveillance.
- Deploy enforcement officers for remote surveillance.
- Process recent satellite data using specialized third-party services.
- Involve legal representatives and additional enforcement agencies in the working group.
- Base controller to make the Go/No-Go decision for on-site inspections.

III.2 Operator Engagement

- Facilitate workshops to educate stakeholders on legal requirements, sustainable practices, and compliance benefits.
- Provide actionable improvement plans for minor infractions, supporting operators in achieving full compliance.

III.3 Incentives for Compliance

- Introduce recognition programs for operators demonstrating consistent compliance.
- Offer streamlined permitting processes or reduced fees as incentives for voluntary compliance.

IV. Compliance Inspection

IV.1 Targeted Inspections

- Conduct on-location verification of data collected through Earth Observation.
- Utilize drones and GPS-enabled equipment for efficient data collection and validation.
- Use standardized checklists to ensure thorough and consistent inspection processes. (Annex 1)

IV.2 Administrative Enforcement

- Issue notices detailing non-compliance issues, corrective actions required, and timelines for resolution.
- Apply penalties or suspend operations for persistent non-compliance.

IV.3 Criminal Prosecution

- Escalate severe cases to criminal proceedings, ensuring robust evidence collection to support legal outcomes.
- Strengthen collaboration with judicial authorities to align enforcement actions with legal frameworks.

V. Monitoring and Continuous Improvement

V.1 Post-Compliance Monitoring

- Conduct follow-up inspections to ensure long-term adherence to compliance requirements.
- Use real-time monitoring systems and community reporting tools to identify emerging risks.

V.2 Feedback Mechanisms

- Analyze enforcement outcomes to refine policies and strategies for future detection and compliance efforts.
- Publish compliance performance reports to maintain transparency and accountability.

VI. Capacity Building and Resource Allocation

VI.1 Training for Inspectors

- Provide ongoing training programs covering advanced detection methods, legal frameworks, and communication techniques.
- Certify inspectors in using specialized tools like drones and EO data analysis.

VI.2 Optimizing Resources

- Foster inter-agency collaborations to share resources and knowledge.
- Partner with academic and research institutions to access the latest technologies and expertise.

Conclusion

The stepped approach ensures effective detection and compliance with illegal groundwater activities. It involves systematic steps that increase in resource intensity, beginning with awareness and screening, followed by preparation, inspections, and long-term compliance monitoring. By leveraging modern technologies like drones and EO data, and fostering collaboration across agencies, authorities can enhance their capacity to protect groundwater resources efficiently and sustainably.

7. Next steps

In the next project phases potentially promising methods can be selected for further investigation, during which more data can be gathered from current users, and a proper description can be worked out. The project proposes further development and will take forward the knowledge and learning and move towards implementation and adaptation. In further refining guidance the phased project will work towards embedding and ensure that recommendations can be implemented at a Member State level, keeping in to account the help of new technologies (Drones and Geospatial Intelligence) and innovation.

The desired outcome of the project is to report and demonstrate that all Member States can have the skills, knowledge and capacity to detect illegal groundwater activities and use the information within a compliance and enforcement programme, being also updated with the new technologies and innovation.

Linking in with the Geospatial Intelligence for Environmental Damage Assessment (GIEDA) project will provide additional benefits of integrating the knowledge discovered with TIGDA with the scope of the detection of environmental damage.

The next phase will include:

- Developing synergies between the desired outcomes of the IMPEL projects, especially GIEDA, and will enhance the reputation of IMPEL to have a strong emphasis on compliance of EU legislation
- Working with the 4N group to understand the definition of illegal groundwater activities and the different legislative drivers across the EU
- Use the knowledge gained to help shape an understanding of the EU Environmental Crime Directive to improve guidance on how illegal groundwater abstraction could cause, or is likely to cause, substantial damage to ecology or to the quantitative status of groundwater bodies.

The TIGDA project team will work with IMPAL Knowledge and Information Programme (KIP) team to develop training sessions in across Member States to support the implementation of detection together with compliance protocols and methodology.

Annexes

Annex 1 - Illegal Abstraction Site Inspection Checklist

1. Preliminary Preparation

☐ Confirm inspection schedule with authorities and, if necessary, coordinate with law enforcement.

☐ Review geospatial data to identify suspected illegal abstraction points.

☐ Prepare legal documentation authorizing inspection of unpermitted activities.

☐ Ensure personal protective equipment (PPE) and additional safety measures are ready.

☐ Bring tools for evidence collection, such as flow meters, cameras, and GPS devices.

2. On-Site Entry

☐ Notify site personnel of arrival and provide legal documentation for inspection.

☐ Explain the objectives and scope of the inspection, emphasizing legal authority.

☐ Verify access to all suspected abstraction points, including concealed or unauthorized areas.

☐ Confirm emergency response procedures for potential conflict situations.

3. General Observations

☐ Look for evidence of concealed abstraction points, such as hidden wells or pipelines.

☐ Observe any unauthorized or suspicious activities at the site.

☐ Document unregistered equipment or infrastructure associated with water abstraction.

☐ Evaluate general site conditions for signs of over-abstraction or environmental harm.

4. Permits and Documentation

☐ Check for the absence of legal permits for abstraction activities.

☐ Investigate discrepancies or potential falsification of permits presented by the operator.

☐ Confirm that all required documentation is unavailable or non-compliant.

5. Abstraction Equipment

☐ Inspect pumps, pipes, and related equipment for unauthorized modifications or tampering.

☐ Check for the absence of flow meters or tamper-proof seals on equipment.

☐ Identify newly installed or concealed abstraction infrastructure.\

6. Water Flow and Volume Monitoring

☐ Measure actual abstraction volumes and compare them with known regional or regulatory limits.

☐ Assess flow rates and document excessive or unreported water usage.

☐ Check for discrepancies between recorded and observed water flow data.

7. Environmental Compliance

☐ Inspect nearby ecosystems for signs of over-abstraction, such as dry wells or depleted water bodies.

☐ Evaluate any environmental harm, such as soil erosion, vegetation loss, or water pollution.

☐ Ensure abstraction activities do not violate environmental or legal buffer zones.

8. Compliance with Legal Conditions

☐ Confirm the absence of legal authorization for abstraction activities.

☐ Investigate whether the site violates any environmental or legal buffer zone restrictions.

☐ Ensure compliance with broader water management regulations in the area.

9. Operator Interviews

☐ Ask the operator to explain the basis for the current abstraction activities.

☐ Verify the operator's awareness of compliance obligations and permit requirements.

☐ Investigate any attempts by the operator to hide or justify unauthorized activities.

10. Evidence Collection

☐ Take extensive photographic evidence of unregistered abstraction points and equipment.

☐ Document geospatial coordinates of all suspected illegal activities using GPS.

☐ Record flow rates and abstraction volumes for further analysis.

☐ Collect water samples for quality testing, if required.

☐ Secure tamper-proof seals on collected evidence to maintain chain of custody.

11. Closing Meeting

☐ Summarize initial findings with the operator, focusing on illegal activities.

☐ Provide clear information about potential legal consequences for non-compliance.

☐ Discuss next steps, including deadlines for corrective actions and further investigations.

12. Post-Inspection Actions

- ☐ Compile a detailed inspection report, including all evidence and observations.
- ☐ Submit findings to legal authorities for enforcement actions or prosecution.
- ☐ Coordinate with compliance teams to issue violation notices or escalate the case.
- ☐ Follow up with relevant stakeholders to ensure resolution of illegal activities.

European Union Network for the Implementation and Enforcement of Environmental Law

Tackling illegal GW drilling and abstractions (TIGDA)

"Earth Observation Techniques for the Detection of Illegal GW Activities"

Annex 2 - Literature Review

Date of report: 21.02.2024

Report number: 01

Introduction to IMPEL

The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) is an international non-profit association of the environmental authorities of the European Union (EU) Member States, and of other European authorities, namely from acceding and candidate countries of the EU and European Economic Area (EEA). The association is registered in Belgium and its legal seat is in Brussels, Belgium.

IMPEL was set up in 1992 as an informal Network of European regulators and authorities concerned with the implementation and enforcement of environmental law. The Network's objective is to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation. The core of the IMPEL activities concerns awareness raising, capacity building and exchange of information and experiences on implementation, enforcement and international enforcement collaboration as well as promoting and supporting the practicability and enforceability of European environmental legislation.

During the previous years IMPEL has developed into a considerable, widely known organisation, being mentioned in a number of EU legislative and policy documents, e.g. the 8th Environment Action Programme that guide European environmental policy until 2030, the EU Action Plan: "Towards a Zero Pollution for Air, Water and Soil" on Flagship 5 and the Recommendation on Minimum Criteria for Environmental Inspections.

The expertise and experience of the participants within IMPEL make the network uniquely qualified to work on both technical and regulatory aspects of EU environmental legislation.

Information on the IMPEL Network is also available through its website at: www.impel.eu

Title of the report: Earth Observation Techniques for the Detection of Illegal GW Activities: Literature Review	**Number report:** 2024/01
Project Manager/Authors: Constantin Radu Gogu Ion Nedelcu	**Report adopted at IMPEL General Assembly Meeting**: Date and location **Total number of pages: 33** Report: 33

Executive Summary

With a general objective "to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation", the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) funded the project *Tackling illegal GW drilling and abstractions* (TIGDA) which aims to share knowledge and good practices on how to manage GW drilling and abstractions.

Under the TIGDA project the work package *Earth Observation Techniques for the Detection of Illegal GW Activities* (EOWP) aims to review the different types of earth observation (EO) methods and data that can be used for the detection of illegal GW activities.

As formulated by IMPEL, within the scope of this project the definition of *illegal GW activity* covers any combination and types of illegal drilling illegal abstraction, including activities that could result in the direct input of pollutants to GW, for example discharges to wells, boreholes or soakaways.

This report contains information on literature review performed as a first task supporting the goals of the EOWP under the TIGDA project of IMPEL.

TABLE OF CONTENTS

1. Introduction

This report, a condensed literature review, creates a theoretical preamble needed for the task of "Identification of Earth Observation Methods and Data for Detection of Illegal Groundwater Activities" (Task 3 – second report). Its goal is to introduce several concepts focusing on:

- earth observation methods which can be accessible and useable within the EU;
- earth observation data providers, including free to use or commercial;
- limitations of earth observation methods;
- limitations in the use of different methods and data.

Basic attributes of water rights that circumscribe the extent of the access, use, and control rights granted to the holder of the water right [Fondacion Botin, 2020] can be grouped into:

- those describing the resource - quantity and quality of the water,
- the source and location - surface water or groundwater, desalinated or reused waters,
- the type of use (e.g. irrigation, domestic),
- the duration of the entitlement - temporary vs permanent and
- the management and administration of the right - ownership, security.

According to the same authors, the illegal water use as a term can refer to any taking of water - the entire range from abstraction to consumption - in violation of existing regulations; the same is qualified also as non-authorised, unauthorized, unlawful, theft, stealing, smuggling, misappropriation or even unaccounted water.

Among the illegal use cases, the following categories can be specified:

- Use of water without any water right or use with an on-going but not yet finalized application;
- Use of water beyond the established limits of the water right;
- Non-compliant changes to the characteristics of the water right, e.g. timing, purpose, location, trading.

It was estimated that as many as half of the existing water wells in European Mediterranean countries may be unregistered or illegal and the main drivers of the illegal use are then net benefits, the gaps in governance and institutions and the social norms [Fondacion Botin, 2020].

The many effects of the illegal use include degradation of water ecosystems, depletion of resources for legal use, decrease in water quality. While trying to avoid the numerous effects of the illegal use, it is always necessary first to detect and then to deal with the identified cases. When speaking about detection, a number of actions can be taken, including setting up a water rights system, control of water use, the registration of water uses into databases, monitoring of water abstraction by different means, including remote sensing and integrated management.

According to the same report, using remote sensing and aerial methods for monitoring water abstraction may be done with some strengths and weaknesses:

Strengths	Weaknesses
Effective on large areas with reduced costs and in near real time. Analysis methods based on the detection of changes computed between before and after images Very useful in areas that are not easily accessible by other means Allow production of maps and documents that can be used as evidence in Court Enables water use monitoring without entering the property	Verification on the ground is usually needed Good knowledge of the business practices (agriculture, building, other) is helpful Detection may be affected by a lack of accuracy or details on the definition of the land unit where water rights have been granted It requires specialized technical capacity in terms of tools and human resources Accurate quantitative and qualitative water measurements can be performed only in-situ.

The following sections provide details on different aspects related to the various components - observation systems and data - involved in the detection and quantification of water abstraction and its association with a possible illegal use.

2. Relevant concepts and knowledge

2.1 Groundwater in the water cycle

More than 70% of the earth's surface is covered by water. However, only 3% of this reserve is fresh water that can be used for human consumption. 90% of the earth's fresh water resources is contained in groundwater and ice, and only 10% is contained in surface reservoirs as rivers, lakes, wetlands and streams.

The water cycle (Fig. 1), also known as the hydrologic cycle or the hydrological cycle, is a biogeochemical cycle that describes the continuous movement of water on, above and below the surface of the Earth. The mass of water on Earth remains fairly constant over time but the partitioning of the water into the major reservoirs of ice, fresh water, saline water (salt water) and atmospheric water is variable depending on a wide range of climatic variables.

The water moves from one reservoir to another, such as from river to ocean, or from the ocean to the atmosphere, by the physical processes of evaporation, transpiration, condensation, precipitation, infiltration, surface runoff, and subsurface flow. In doing so, the water goes through different forms:

liquid, solid (ice) and vapor. The ocean plays a key role in the water cycle as it is the source of 86% of global evaporation.

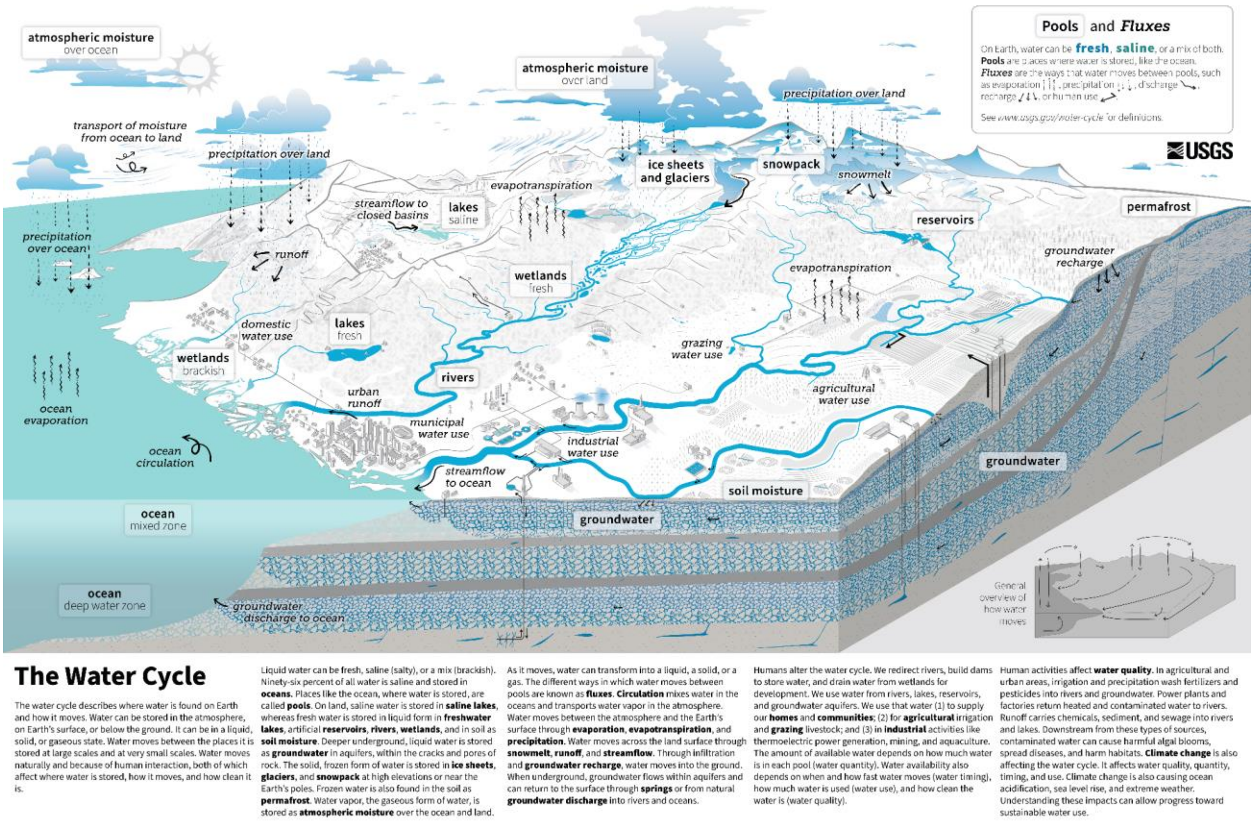

Fig. 1 The water cycle (source: https://www.usgs.gov/media/images/water-cycle-png)

As the main source of freshwater easily available for human activities, groundwater has a significant role in the water cycle. The processes of the water cycle are difficult to monitor, making the groundwater management a complex process. Water cycle (Fig. 1) can be summarized through the water balance equation:

$$P\ (\pm W \pm H_i) = E_t + Q + I + U + \triangle R$$

Where the following terms are expressed

P - precipitation – main water source (rainfall and snow) entering in the hydrological basin;

W - groundwater flow input, another catchment natural water input (in some cases large water volumes are passing from a catchment to another in spite surface water flow established processes);

H_i - human intervention;

Q - direct water flow (in river network);

I - infiltration into soil;

U - human use;

△ R - storage of the water catchment;

E_t - water catchment total evaporation (called evapotranspiration);

$$E_t = E_a + E_s + E_i + E_p + E_z$$

E_a - surface water evaporation (rivers, lakes, sea);
E_s - soil surface water evaporation;
E_i - water evaporation from rainfall intercepted by green cover (plants) and urban fabric;
E_p - plants transpiration (water located in soil);
E_z - water evaporation from surfaces covered by ice/snow;

In order to derive quantitative information on the Storage i.e. quantity of water to be retrieved underground or groundwater, it is necessary to retrieve information on the P, Q and E_t as well as all the others variables of the water cycle equation. The capacity of Earth Observation (EO) systems to help derive this information is presented in the following sections.

The combined effects of industrial development, urbanization and population affect the natural landscape as well as the behavior of groundwater and surface water. The hydrological cycle is greatly modified as a result of continuous urban development and the need to supply water to the population. This not only includes the supply but also the sewerage, collection and waste water management. It has been observed that the hydrological cycle has become much more complex in the urban environment due to anthropic influences on the environment.

Within the urban water circuit, two main sources of water are recognized: water from precipitation and water from the municipal supply. Municipal water is often imported from outside the urban area. This is brought into the urban environment and distributed to various consumers. A fraction is lost in the urban environment groundwater and the rest is used by the population - transformed into municipal wastewater and possibly returned to the surface water or groundwater. Water from precipitation goes through processes of interception, accumulation and evapotranspiration. Some seeps into the soil (contributing to soil moisture and aquifer recharge) and some is partially converted to surface runoff. These in turn are transported to the water collectors by means of natural or constructed transport systems (collector systems). These two sources can be quantified in studies that address problems related to the urban water balance (Marsalek J. et al. 2006).

2.2 Observables and observations

Each element of the water balance equation can be analyzed for identifying the methods and instruments helping to observe or measure it. Earth Observation (EO), either made by direct in-situ or indirect remote sensing observation, performed from aerial or space systems, can help improve water management by providing quantitative estimations for each of these components.
Earth observation by remote sensing offers the possibility to study large areas with reduced time and costs when compared with in-situ measurements that show a greater accuracy. When Earth observation by remote sensing is referred to, EO is defined as the process of acquiring observations on the phenomena on the Earth via remote sensing instruments.

The Earth surface can be observed from different platforms, each presenting its own advantages and limitations. Aerial platforms generally provide the best spatial resolutions and are very adjustable to the users' needs, but the high cost of flying a plane and paying the related manpower restricts its use. Drones or Remotely Piloted Aircraft Systems (RPAS), are a fast-growing technology that tackles this cost problem, but regulations and their low carrying capacity currently limits their range of activity. On the other hand, satellites allow for reliable, true global coverage even above the most remote locations enabling regular repeat observations.

Evidence of Groundwater abstraction

Groundwater flows through pore and interstitial spaces and fractures within sediments and rocks in the deeper subsurface. When this water is removed, for instance through pumping for drinking water or lowering of water levels in mines, the pore pressure or effective stress is reduced and consolidation of the sediments and rocks causes a change in the sediment and rock volume. This can lead to subsidence (Fig. 2).

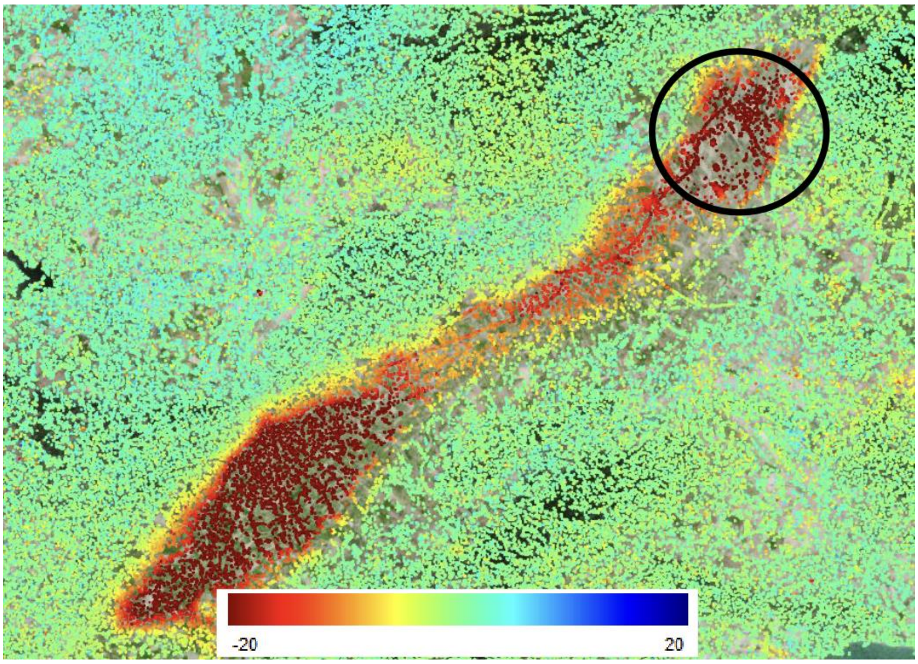

Fig. 2 Subsidence caused by excessive water abstraction in an agriculture area Guadalentín Valley, Murcia [EGMS Product User Manual]

Similarly, when aquifer levels are allowed to recover, uplift may be a result of increasing pore pressure. Deep geothermal energy systems should not lead to ground movement. They involve closed systems where water, which was extracted from a deep aquifer, will be pumped back into that same aquifer. However, geothermal heat pumps are used at shallower depths. Although these are also closed systems, ground movement might occur temporarily (e.g. seasonally) or even permanently [Pangeo Production].

Ground movements due to groundwater fluctuations may occur, among others, as result of excessive water extraction, flooding of inactive mining sites and significant seasonality of rainfalls. Especially in urban and peri-urban areas, groundwater fluctuations may appear due to distinct anthropogenic processes causing land subsidence (e.g. excessive groundwater extraction for agriculture or industry).

Thanks to the satellite's performance to allow systematic observations which, combined with appropriate processing techniques allow detection and measurement of these movements, this type of phenomena can be detected and investigated to identify possible causes.

In addition to the space systems observations, a number of in-situ observation technologies and techniques allow direct measurement or estimation of groundwater resources.

2.3 Sustainability in water management

Sustainability in water management involves matching the natural and the anthropogenic (technical) water use cycles together, with minimum natural damage and maximum human benefit. A correct approach to manage water resources is known as the integrated water cycle management, where surface water, groundwater, water supply, storm water, and wastewater are all considered during the design process.

The diagram in the figure below (Fig. 3) presents the water cycle in terms of stocks and flows. It illustrates the connections between different natural processes and reservoirs and also introduces the anthropogenic water paths into the system.

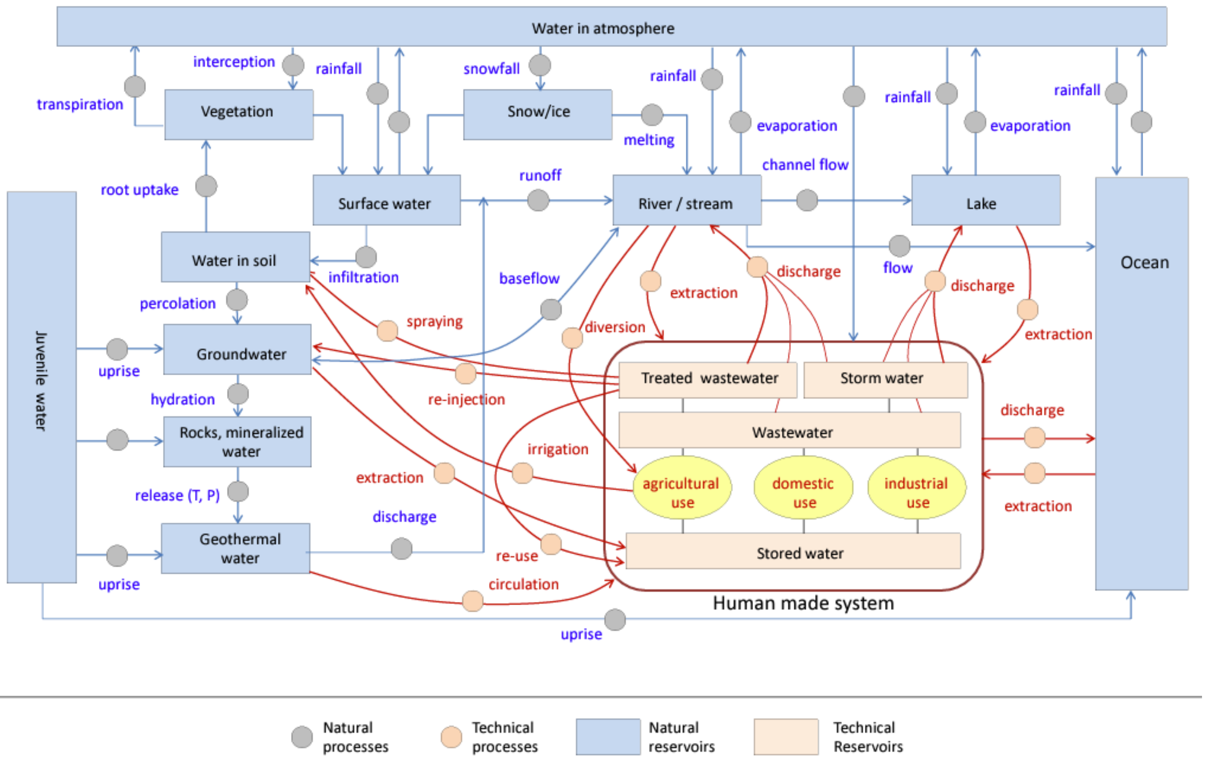

Fig. 3 Natural and human-controlled water cycles (Fedkin, 2023)

The boxes show different water reservoirs - natural (blue) and man-made (peach). The circles denote fluxes between the reservoirs. Blue arrows show the water motion within the natural hydrological cycle; red arrows show the water motion between the natural and man-made reservoirs.

The boundaries between the natural and human-controlled water systems are where the sustainable water treatment technologies should come into action. The bottom line is that the role of sustainable water management technology is to reconcile the natural and anthropogenic cycles and to alleviate mutual harm and system imbalance.

3. Earth Observation for the water cycle

Either passive or active, space systems proved to bring significant contribution to the estimation of the variables in the water cycle equation. Ensuring EO for the water cycle is a priority for the space agencies all over the world and global EO programmes given their relevance for the essential climate variables (https://www.earthdata.nasa.gov/learn/backgrounders/essential-variables) and adaptation to climate change actions. The figure below shows a self-explaining graphic on types of EO systems - space, aerial, in-situ that are considered relevant for the water cycle studies.

Fig. 4 EO Systems for the water cycle

When it comes to local studies related to groundwater, of particular interest are the geodetic techniques. The most relevant geodetic techniques for observations related to groundwater resources are resumed in the figure (Fig.4) below (as published by https://www.unavco.org; a full resolution version of the poster is attached to this report): GPS observations, gravimetry and InSAR.

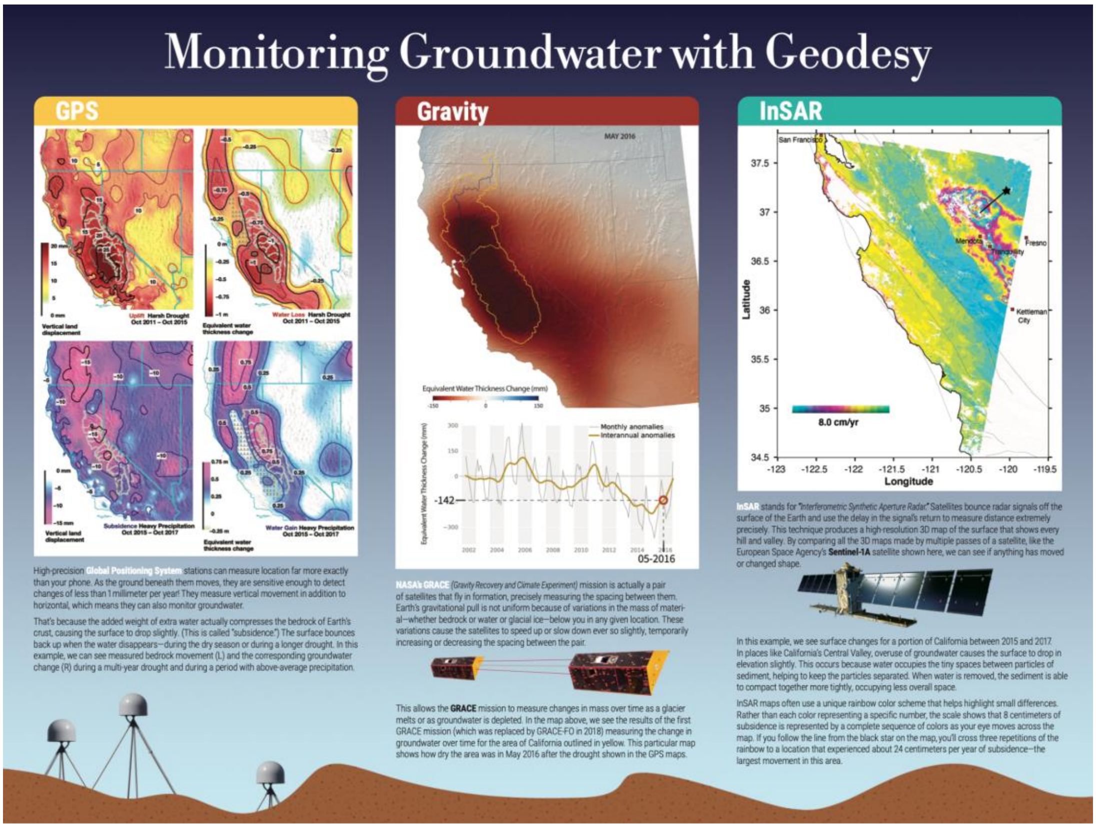

Fig. 5 Geodesy resources for groundwater monitoring

3.1 In-situ observations

Hydraulic head, often simply referred to as "head", is an indicator of the total energy available to move groundwater through an aquifer. Hydraulic head is measured by the height to which a column of water will stand above a reference elevation (or "datum"), such as mean sea level. A water-level measurement made under static (non pumping) conditions is a measurement of the hydraulic head in the aquifer at the depth of the screened or open interval of a well (Fig. 6). As the hydraulic head represents the energy of water, groundwater flows from locations of higher hydraulic head to locations of lower hydraulic head. The change in hydraulic head over a specified distance in a given direction is called the "hydraulic gradient."

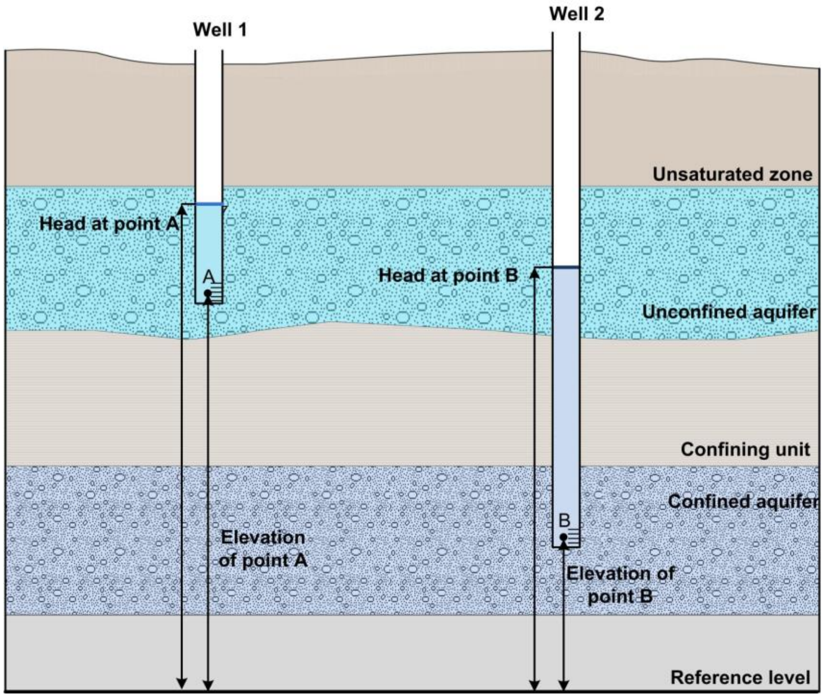

Fig. 6. The relation between hydraulic heads and water levels in two observation wells—Well 1 screened in an unconfined aquifer and Well 2 screened in a confined aquifer. Hydraulic heads in each of these two aquifers are determined by the elevation of the water level in the well relative to a vertical datum—in this case, Reference level (modified after IGRAC,2006)

Two general types of aquifers (unconfined and confined) are recognized (Fig. 6). In unconfined aquifers, hydraulic heads fluctuate freely in response to changes in recharge and discharge. Water levels measured in wells completed in the upper part of an unconfined aquifer help define the elevation of the water table, which is the top of the saturated zone. In confined aquifers, water in the aquifer is “confined” under pressure by a geological body that is much less permeable than the aquifer itself. Water levels in tightly cased wells completed in confined aquifers often rise above the elevation of the top of the aquifer (Figure 6). These water levels define an imaginary surface, referred to as the potentiometric surface, which represents the potential height to which water will rise in wells completed in the confined aquifer. Groundwater levels are controlled by the balance among recharge to, storage in, and discharge from an aquifer. Physical properties such as the porosity, permeability, and thickness of the rocks or sediments that compose the aquifer affect this balance. Climatic and hydrologic factors such as the timing and amount of recharge provided by precipitation, discharge from the subsurface to surface-water bodies, and evapotranspiration, participate in the groundwater balance. When the rate of recharge to an aquifer exceeds the rate of discharge, water levels or hydraulic heads will rise. Conversely, when the rate of ground-water withdrawal or discharge is greater than the rate of ground-water recharge, the water stored in the aquifer becomes depleted and water levels or hydraulic heads will decline.

A monitoring system is a platform where level and quality records that describe groundwater resources are generated, made available, and evaluated. These records are consistent, representative and long lasting.

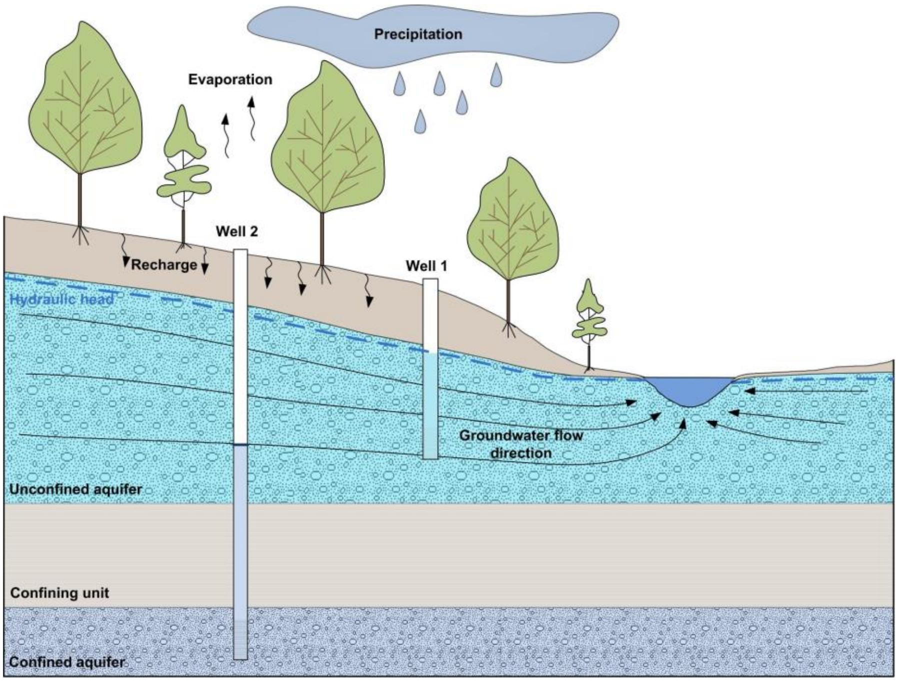

Fig. 7 Hydrogeological cross-section with wells installed in confined and unconfined aquifers

Two main types of wells can be available for groundwater monitoring:

- Monitoring wells (wells with single or multiple piezometers);
- Water supply wells (for domestic, municipal, agricultural or industrial water supply).

In practice, in most situations the hydraulic head is not measured directly.There is only one situation when the hydraulic head is directly measured and this situation is related to the topographical measurement of the springs. In all other situations, when boreholes and wells are used, the measurement provides the depth to groundwater level (DGW). Also, the elevation of the well cap could be obtained by topographical measurement (leveling). There are several types of instruments able to measure the depth to groundwater and the most common is the water-level dipper.

Precise spirit leveling

The most precise method of measuring elevation changes at land surface is the precise leveling. This method consists in determining the elevation in each benchmark belonging to a network at land surface. By repeated surveys of the network of benchmarks at different time intervals, it can be revealed whether vertical movements appeared compared to the control benchmarks. The control benchmarks are placed in a stable area consisting of consolidated rocks, outside the area affected by displacements.

Borehole extensometers

Vertical borehole extensometers are used to measure the movement or change of the vertical distance between the bottom of the borehole and the ground surface, considering the thickness of sediments or rocks.

Ground penetrating radar

Ground penetrating radar (GPR) is an electromagnetic pulse reflection method based on physical principles similar to those of reflection seismics. It is a geophysical technique for shallow investigations with high resolution which has undergone a rapid development during the last two decades. This technique involves transmitting and receiving electromagnetic waves to and from the subsurface. The data collected can be used to create a cross-sectional image of the subsurface as well as to give estimates of the depth to the water table in gravel, sand, limestone, and sandstone. GPR can be also used to determine the location, orientation, size, and shape of underground metal and plastic pipelines, cables, and other buried manmade objects.

Gravimetry

This technique measures the gravitational field of the subsurface using a gravimeter. The data collected can be used to identify changes in the density of subsurface materials, which can indicate the presence of geological structures.

Global Navigation Satellite Systems (GNSS)

Since the 1980s, when the U.S. Global Positioning System (GPS), the first GNSS constellation, a new horizontal and vertical displacement measurement technique has been available. GNSS techniques are based on the use of at least four navigation satellites for giving an estimate of the absolute X, Y, Z coordinates with respect to a global well-defined geocentric reference system. Similar systems have been developed, such as Russia's GLONASS system, or EU's Galileo System, or China's BEIDOU system (GSA, 2018). Considering reference points at ground surface, GNSS networks can be developed in order to survey multiple times various areas of interest. Permanent stations having accurate, known X, Y, Z coordinates can be used for Differential GNSS measurements which allow computing the 3D position of a roving receiver. Currently, GNSS techniques are used not only for revealing land subsidence, but also for validating other subsidence measuring methods, such as those based on Synthetic Aperture Radar (SAR).

3.2 Aerial systems

Aerial survey was and is still being used mainly by Mapping Agencies and local authorities to accurately map the land surface using both passive and active instruments. Historically performed using manned aircraft, a strong trend is visible nowadays on using unmanned aerial systems (UAS) or RPAS (Remotely Piloted Aerial Systems) for performing the task.

Drones offer public and private organizations an opportunity to carry out tasks faster (reduce the time of intervention by approx 80%), safer (improve safety by approx 70%), cheaper (50% in average) and with less impact on the environment than traditional methods. In early 2022, the majority of drone use is for Inspection and Survey (PWC, 2022). To serve these goals, an appropriate framework (technology and legislation) need to be in place: UTM (Unmanned Traffic Management, mainly related to regulations and operational procedures), electronic conspicuity (technology allowing awareness of what is operating in surrounding airspace), capability to detect and avoid obstacles, flight autonomy, Infrastructure (mainly communication, landing and charging). Depending on each use case, each of these components must be ensured at specific rates. For example, allowance of BVLOS (Beyond Visual

Line of Sight) or EVLOS (Extended Visual Line of Sight) flights in addition to VLOS (Visual Line of Sight), inside or outside a segregated airspace, could impact significantly on the number of use cases.

According to [EUSPA Whitepaper, 2022] drones can enable a vast array of different applications that can be categorized along the following classes of applications

- Agriculture & environmental: precision agriculture, crop/field/soil monitoring, variable rate applications, livestock tracking, insurance, forest monitoring & man- agement, etc
- Inspection & maintenance: bridges, gas & oil infrastructure, energy distribution infrastructure, solar panels, windmills, etc.
- Surveying and mapping: environmental monitoring, cadastral surveying, mine surveying, marine surveying, GIS, photogrammetry, etc.
- Government: police applications, crowd observation, border control (including maritime), security, etc.
- Public safety: SAR operations, firefighting, urgent med- icine/medical equipment delivery, other natural disaster monitoring (e.g. floods, earthquakes), etc.
- Scientific: meteorological monitoring, atmospheric measurements, swarm techniques, general R&D, etc.
- Education: teaching tool in schools and faculties (e.g. aeronautics, geomatics, navigation).
- Observation: film, photography, TV/other media-broad- casting (e.g. sport events), etc.
- Communications: local coverage broadcasting using high altitude drones or HAPS (high-altitude platform stations).
- Leisure: toys, models flying, self-tracking/filming drones (first person view), sports (e.g. drone racing), etc.
- Goods delivery: transport of various types of goods or cargo.
- Other applications: calibration of aviation nav-aids, asset management, advertisement, marketing, enter-tainment, etc.
- Military

In the context of this report, aerial platforms, either manned or unmanned, can help to address a number of features:analysis of the land use evolution in time,

- assessment of the geological and environmental situation,
- search for seepage of water at the edges of landfills and mining sites,
- locating water resources and moisture anomalies,
- investigation of natural and artificial drainage systems,
- recognition and analysis of landslides,
- investigation of vegetation health or vitality,
- assessment of surface water conditions,
- inventory of sites suspected to be contaminated,
- search for undeclared well system

Airborne systems provide reliable observations of the Earth surface features from visible - near infrared images but also geo-referenced data records generated by SAR or LIDAR instruments (see section 4.2). These observations can be used for deriving information on the size, shape, and position of objects or phenomena, as well as their color or tone, texture, and spatial patterns and associations.

Photogrammetric techniques are then used to prepare reference and thematic maps and digital elevation models (DEM) from remotely-sensed data produced by the airborne instruments. Usual tasks are the preparation of orthophotography, photomosaics and collection of vector data (infrastructure, land cover etc).

Orthophotographs, photomosaics, thematic maps, elevation models and vector datasets are widely used for site investigations in conjunction with other geological, hydrological, geophysical, and remote-sensing data. Topographic measurements acquired at different times can be used to observe changes as well as for planning and decision-making.

In general, a typical workflow involving Flight Planning - Data Capture - Data Processing - Information Sharing is in place when dealing with aerial (manned or unmanned) systems.

3.3 Space systems

As introduced in this section, the EO systems - space and in-situ - are used in complementarity for deriving the different parameters of the water balance equation (configured for the different use cases) and give, this way, estimations for the water resources in a specific area. Besides qualitative observations (imagery produced by space systems at high and very high spatial resolutions), dedicated missions are developed for specific parameters and they are introduced in the following paragraphs.

Precipitation

The quantity and spatial distribution of rainfall and snowfall can vary greatly over time. Using active microwave instruments, missions for regional and global precipitation observations were launched and operated during the last years to provide the data required for the quantification of the precipitation.

Missions like TRMM (Tropical Rainfall Measuring Mission), GPM- Global Precipitation Measurement or information derived from other satellite observations contributed to a global estimation of the quantity of precipitation. For example, a record of daily global rainfall can be accessed as it has been obtained from ASCAT satellite soil moisture data through the SM2RAIN algorithm. The SM2RAIN-ASCAT rainfall dataset (in mm/day) is provided over a regular grid at 0.1-degree sampling (3600x1801) on a global scale. The product represents the accumulated rainfall between the 00:00 and the 23:59 UTC of the indicated day[1]. Copernicus Land Monitoring Service (CLMS) is also publishing a number of products that are relevant for the estimation of the precipitation. According to the CLMS website[2] “The Snow product group boasts a number of datasets related to snow monitoring across the globe. These data are mostly disseminated in near-real time and derived from high resolution spatial observations from Sentinel-1 and Sentinel-2. Snow datasets can be used for a wide array of applications, including modeling the water supply, risk assessment and hazard management, and energy production.” Other relevant data can be retrieved by means of the same website or by accessing the WEKEO platform[3].

Soil moisture

Soil moisture represents an important variable influencing the water and heat energy transfer between land surface and the atmosphere. The content of soil moisture influences the soil temperature, decreasing the differences between day and night soil temperatures. At the same time, changes of Land-Use / Land-Cover can affect considerably the content of soil moisture. In 2010, soil moisture was recognized as an Essential Climate Variable (ECV). Since the mid-1970's different optical, thermal infrared, passive and active microwave satellite sensors have been used for the estimation of various soil characteristics.

Groundwater depletion

As the main resource of freshwater for many human activities, overexploitation of groundwater can produce serious problems in environmental balance and water management. Satellite gravimetry can be used for reaching the depletion of groundwater at regional or global level, considering the variations of the Earth gravity field.

At continental level, missions like GRACE (Gravity Recovery and Climate Experiment, NASA) and its follow-up and GOCE (Gravity Field and Steady-State Ocean Circulation Explorer, ESA) had and still have significant contributions in tracking the Earth’s water movement to monitor changes in groundwater storage, the amount of water in large lakes and rivers, soils moisture, ice sheet and glaciers, and sea level caused by the addition of water to the ocean.

At local level, if groundwater is intensively exploited, overexploited, or intensively recharged, the effects of these phenomena can arise at land surface, as ground vertical displacements (see also 1.2). Synthetic Aperture Radar (SAR) interferometry (InSAR) offers a suitable way to accurately measure the spatial extent and magnitude of surface deformation associated with aquifer-system compaction or dilation.

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[1] https://zenodo.org/records/7950103

[2] https://land.copernicus.eu/en/products/snow

[3] https://www.wekeo.eu/

InSAR techniques use the phase differences between two radar images acquired over the same area to generate maps of surface displacements or topography (Fig. 8).

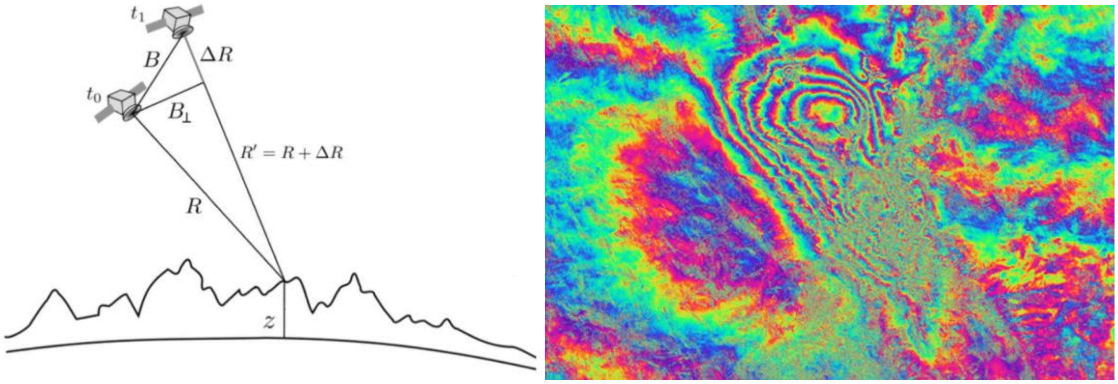


Fig. 8 Principle of Differential InSAR and interferogram generated from SAR observations[4]

The phase difference image is called *interferogram*. Although it contains several terms, the phase difference largely reflects the surface deformation in the radar line of sight during the period between the two acquisition dates. To form the interferograms, the images must be in the same SAR geometry, i.e. cover the same area on the ground and with the same incidence angle. This is achieved by resampling one of the images to the other and calculating the phase difference (European Ground Motion Service: Service Implementation Plan and Product Specification Document[5]).

One important class of algorithms focuses on identification and analysis of pointlike scatterers (PS). A second class of algorithms focus on analysis of distributed scatterers (DS) based on the fact that the coherence of distributed scatterers is higher for small baselines. Depending on the environment being analyzed - urban or natural landscape - a PS, DS or a combination of the two methods can be applied.

4 https://eo-college.org/resource/introduction-to-sar-interferometry/

5 https://land.copernicus.eu/user-corner/technical- library/european-ground-motion-service

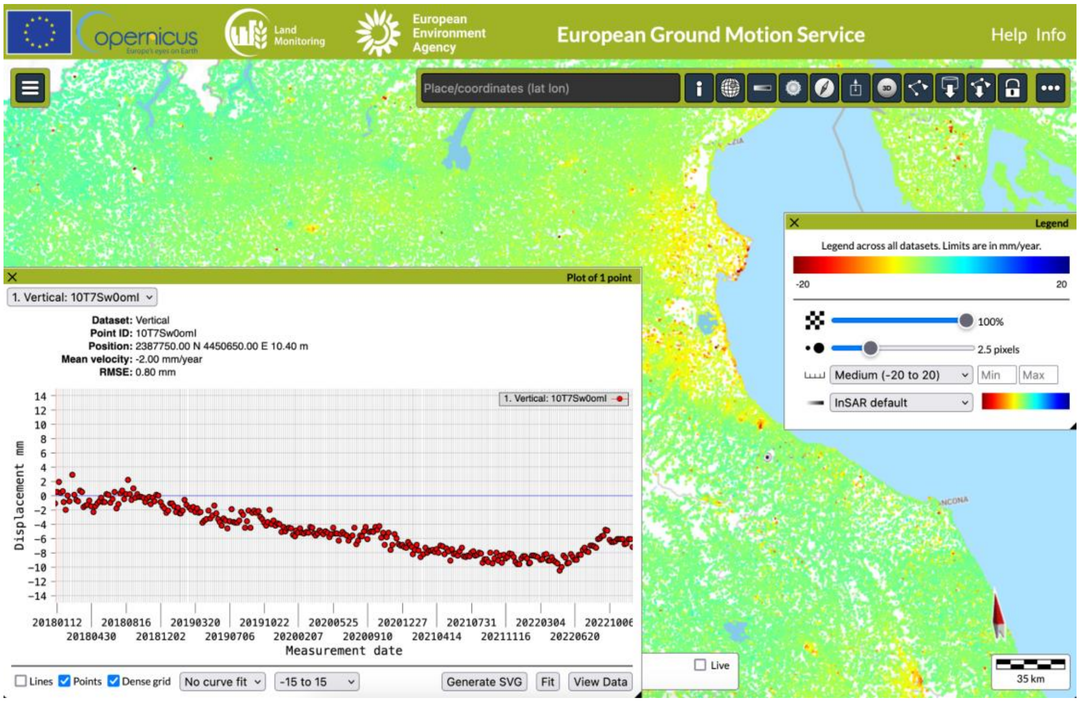


Fig. 9 The EU GMS Explorer

The reliability of this technique and the maturity of its implementation allowed the availability of an operational service developed as part of the EU Earth Observation Copernicus Programme - the EU Ground Motion Service (Fig. 9). According to the official website “The European Ground Motion Service (EGMS) provides consistent and reliable information regarding natural and anthropogenic ground motion over the Copernicus participating states and across national borders, with millimeter accuracy.” The service gives access to ground motion data for a period of time covering the 2018-2022 interval. A data explorer (see figure above) allows direct analysis or download of specific areas of interest[6].

4. Data sources

4.1 In-situ environmental and reference data

National and European Spatial Data Infrastructures

According to the official website of the European Commission, “the INSPIRE Directive aims to create a European Union spatial data infrastructure for the purposes of EU environmental policies and policies or activities which may have an impact on the environment. This European Spatial Data Infrastructure will enable the sharing of environmental spatial information among public sector organizations, facilitate public access to spatial information across Europe and assist in policy-making across boundaries. INSPIRE

[6] https://egms.land.copernicus.eu/

is based on the infrastructures for spatial information established and operated by the Member States of the European Union. The Directive addresses 34 spatial data themes needed for environmental applications."

Based on the current level of implementation, the national spatial data infrastructures established by the EU Member States provide access to environmental data by means of national portals. Details on data availability and access can be found on the INSPIRE website: https://inspire-geoportal.ec.europa.eu/srv/eng/catalog.search#/home

"The European Environment Information and Observation Network (Eionet) is a partnership network of the European Environment Agency (EEA) and its 38 member and cooperating countries. EEA and Eionet gather and develop data, knowledge, and advice to policy makers about Europe's environment. Overall, Eionet consists of the EEA and circa 400 national institutions from 38 countries, with expertise in environmental issues, and 8 centers of thematic expertise contracted by the EEA, called European Topic Centres (ETCs).

The EEA is responsible for developing Eionet and coordinating its activities together with National Focal Points (NFPs) in the countries. The NFPs are the country institutions appointed to serve as the primary link between the EEA and the country. NFPs facilitate and coordinate networks of national experts involved in national activities related to the EEA work programme." EIONET provide access to data by means of its central data repository available at: https://cdr.eionet.europa.eu/.

The same time, EEA is coordinating the land monitoring component of the Copernicus programme in which a large variety of reference and thematic dataset are published (https://land.copernicus.eu/en).

4.2 Airborne system data

As airborne systems can be operated exclusively on-demand, on approved time intervals and meteorological conditions, the access to EO data acquired by means of airborne systems is possible in few different ways:

- Access and use of aerial photography provided by the national mapping agencies running aerial survey programmes;
- Invitations to Tender organized by user organizations, following specific technical requirements, adapted to specific use cases;
- Operation of an owned systems composed of flying equipment, communication and data processing resources.

Depending on the frequency of use and affordability in terms of cost and human resources availability, one of the ways can be followed. In all cases, the licensing conditions and GDPR need to be applied.

4.3 EO Satellite Data

Accessibility

The easiest and most affordable way of accessing and using satellite data is buying archive data i.e data that have been previously acquired, is stored in the database of the owner and can be bought for a specific area of interest. If no data is available for a specific area of interest fulfilling the formulated needs expressed as acquisition date, cloud-cover, resolution etc, orders can be placed at a higher cost.

The satellite data products, especially for high resolution and multi-spectral band images are, in general, data heavy files (e.g. 1 Gb for a 10x10 km, 3 bands, 50 cm resolution). These files can be delivered online (ftp downloading) or via physical media delivery (disk).

To address these Big Data challenges, it was necessary to move away from traditional local processing (desktop computer) and data distribution methods (file download) and lower the barriers caused by data size and related complexities in data preparation, handling, storage and analysis. This paradigm shift is currently represented by EO Data Cubes, an approach that is receiving increasing attention as a new solution to store, organize, manage, and analyze EO data in a way that was not possible before. Data Cubes (DC) are aiming to realize the full potential of EO data repositories by addressing Volume, Velocity, and Variety challenges, providing access to large spatio-temporal data in an analysis ready form (Gregory et al., 2017).

Very high spatial resolution EO data is available through the commercial market and well established EO product providers. Other high-resolution EO data is available free of charge as is the case for example with the European Copernicus programme that offers free and open access to Sentinel satellites data or the USGS Landsat programme. In some cases (military operations, high-security facilities, other) the access to satellite EO data might be subject to restrictions imposed by national governments, especially for very high resolution images and this is why governmental approval before ordering data.

In the case of the Sentinel EO satellites, developed by ESA for the European Commission's Copernicus programme, access to data is provided through multiple channels.

1. The Copernicus Open Access Hub (https://scihub.copernicus.eu/) provides free and open access to a rolling repository of Sentinel user products. A simple and fast registration is required to create an account, before getting free access to the Sentinel data. The data access is configured to avoid saturation resulting from massive downloads by a limited number of users (e.g. maximum number of parallel downloads, maximum volume per retrieval,...).
2. A collaborative ground segment is also in development in several member states. It is intended to allow complimentary access to Sentinel data and/or to specific data products by establishing additional pick-up points (e.g. mirror sites).
3. Copernicus Space Component Data Access (https://spacedata.copernicus.eu/) (CSCDA) is restricted to users eligible to Copernicus Services, as defined by the European Commission (bodies of the EU, point of contacts established by the member states, etc).
4. Copernicus Data Space Ecosystem. According to the website, "The Copernicus Data Space Ecosystem is the next step in the evolution of Earth observation data. The ecosystem offers immediate access to large amounts of open and free Earth observation data from the Copernicus Sentinel satellites, including both new and historical Sentinel images, as well as Copernicus Contributing Missions. The Copernicus Data Space Ecosystem supports users in accessing, viewing,

using, downloading, and analyzing data.The Copernicus Data Space Ecosystem is set up to further improve access and exploitation of the EU's Copernicus satellites data. The service aims to support users in building various applications needed to provide accurate, timely and objective information which are crucial to create a more sustainable future.

Recent progress shows that the EO from space sector is moving from large, complicated and expensive satellites to numerous small and cheaper satellites, with the focus for better coverage and revisit time, near-real time monitoring. With these new directions, data prices are expected to decrease and the business models to evolve from the selling of data to information or even intelligence.

Additional progress is expected with the advent of new technologies related to sensors, including video from space, configurable payload, in-orbit flexibility, etc.

Pricing

Indicating prices for EO data can be difficult, as the acquisition cost depends on a large number of criteria: the image provider, the satellite, the spatial and temporal resolutions, from archive or a new acquisition, the spatial dimension of the dataset, the other users demand for the area of interest, the number of acquisitions required in total. List prices available are most of the time indicative while real prices might be lower and can be negotiated depending on the business case. An application running for years might be able to get lower prices per image or to choose a cost model.

Surcharge may apply for additional processing treatment of images, emergency tasking of a satellite, selection of hard drive as a delivery means, etc. Discounts may apply when tasking over an area of lesser interest (e.g. over the oceans), and when ordering a certain number of images over a long period of time, etc.

Sources

Earth Observation data can be acquired through different channels. Free of cost data is generally provided by public agencies, under potential conditions linked to the application envisaged and the nationality of the entity requiring access. Information on access to Earth Observation data products from ESA can be found at https://earth.esa.int/eogateway, where search can be made by mission, instrument, topic etc.

Data can also be accessed by the means provided by the companies operating the satellite systems, or by their certified resellers. An indicative list of provider websites can be found at: https://business.esa.int/newcomers-earth-observation-guide#ref_2.

Based on the considerations presented, private initiatives were stimulated and this led to development of cloud platforms providing access to data cubes allowing not only access but also processing of the data without the need to download it (see https://up42.com/ for an example).

5. Performance and limitations of EO systems

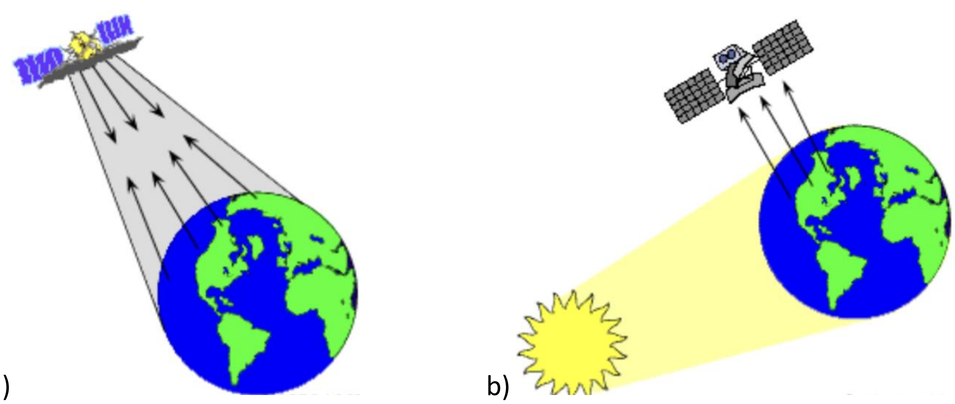
5.1 Active and passive sensors

Based on the principles applied for their design and development, the instruments used for EO from space, aerial or in-situ platforms can be active or passive i.e. using specific emitted energy for the observation process or relying on the energy emitted by the Sun or the reflected and / or emitted by the Earth surface (see figure below).

A. Passive

In the case of passive systems, sensors detect electromagnetic emissions from the Earth's surface and atmosphere. These emissions can be locally produced (such as thermal radiation from vegetation in the infrared spectrum) or be the result of reflected sunlight in the visible spectrum. This is why the passive sensor data is usually dependent on the day-night cycle and can be affected or even blocked by unwanted sources or cloud cover (ESA, 2020). Data collected this way can be displayed as grayscale or color images (see fig. 10).

Panchromatic images are obtained when observations are made over a broad range of the electromagnetic spectrum. Considering emissions in a wide range of wavelengths more energy can be detected and collected for a specific area and higher spatial resolution images can be generated (see also the next section on spatial resolution).



a) b)

Fig. 10 Active (a) vs Passive (b) Remote Sensing[7]

An example of a panchromatic image is the one obtained after measuring the light intensity coming from an observed area in the full visible spectrum. This measurement covers wavelengths between 0.47 and

[7] https://natural-resources.canada.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/resource/tutor/fundam/pdf/fundamentals_e.pdf

0.83 µm (ESA, 2020). The resulting product is generally an image displayed in gray tones, such as presented in the figure below.

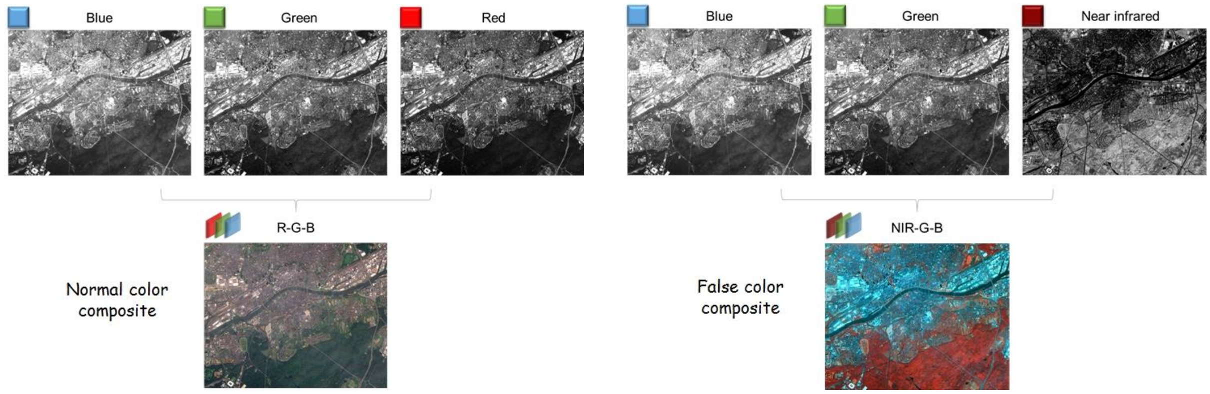


Fig. 11 Formation of true and false color composites (https://learn.opengeoedu.de)

Multi-spectral imagery is a term used to refer to remote sensing data acquired by observing a scene in several narrow bands of the electromagnetic spectrum. Observations in narrow bands produce low energy levels detected, resulting in a lower spatial resolution than for panchromatic images.

A common example of multi-spectral images is the production of natural color images i.e images generated by the combination of data acquired in 3 bands of the visible spectrum (blue, green and red), the same way as is done by common photo cameras. See Figure 11 (left) for an example of a natural or normal color image.

As multi-spectral observations are not limited to the visible spectrum, observations and measurement of emissions are done in the infrared (IR) fields, ultraviolet (UV), etc. The figure 11 (right) presents an example of a false color image, animage combining the blue, green and the near infrared bands to generate a false color composite which, in this case, allows highlighting the presence and health of the vegetation: healthy vegetation creates chlorophyll which reflects near-infrared energy, and therefore appears in darker red on the image (ESA, 2020).

B. Active

In the case of active systems, instruments send out a specific electromagnetic signal and receive the answer of the interaction of the signal with the Earth's surface. Such observations are not dependent on solar illumination and, due to their wavelengths, are not affected by the atmosphere and so by the clouds. The most common active sensor used for Earth Observation is the *Synthetic Aperture Radar (SAR)*. This instrument transmits electromagnetic pulses towards the Earth's surface where they are reflected or scattered by the surface features. The intensity of the return energy and the time it takes to arrive back at the antenna are used to generate SAR imagery (ESA, 2020).

As with most of the active instruments, the main advantage of radar imaging is that it is insensitive to the day / night cycle and most of the time to the meteorological conditions (shorter wavelength signals such as X-band can be degraded by heavy intense rain cells).

LIDAR (Light Detection And Ranging) EO uses the same principle as SAR but works in the IR, visible or UV wavelengths. Lidars are used for precise measurement of topographic features, monitoring evolution of the glaciers, profiling clouds, measuring winds, studying aerosols and quantifying various atmospheric components (ESA, 2020).

Other types of active instruments have been developed and used for specific observation purposes, such as radar altimeters, GNSS receivers or radar scatterometers.

C. Gravity field

Gravity field measurements from space rely on one of three types of techniques relating directly or indirectly gravity to different types of observations (ESA, 2020):

- Use of single or multiple accelerometers on one or more satellites to derive gravity or gravity gradient information.
- Precise satellite orbit determination and separation of satellite motion induced by the Earth's gravitational force from other forces such as solar radiation and aerodynamic drag.
- Satellite-to-satellite tracking to measure the relative speed variations of two satellites induced by gravitational forces.

Gravity field measurements from space provide significant advances for improved measurement of the shape and size of the Earth or the geoid (the mathematical approximation of the Earth) and its variations in time. The geoid (the surface of equal gravitational potential at mean sea level) reflects the irregularities in the Earth's gravity field at the surface due to the inhomogeneous mass and density distribution in the Earth's interior, including groundwater.

5.2 Resolution characteristics and quality parameters

The **spatial resolution** of an image is a key parameter and relates to the level of detail or smallest object that can be observed. This is given by the Ground Sample Distance (GSD) i.e. the distance between adjacent pixel centers measured on the ground.

Based on the spatial resolution, satellite images are classified into low, medium, high and very high resolution. It's considered that low resolution images are those with a GSD larger than 300 m. Medium resolution have a GSD between 300 m and 30 m, high resolution have a GSD from 30 to 5 m and very high resolution (VHR) below 5 m. Considering the performances of the newly launched commercial satellites, a "very very high" resolution class could be introduced for resolutions better than 1 m. The best commercially available data has a GSD of 30 cm (see Figure below for an example).

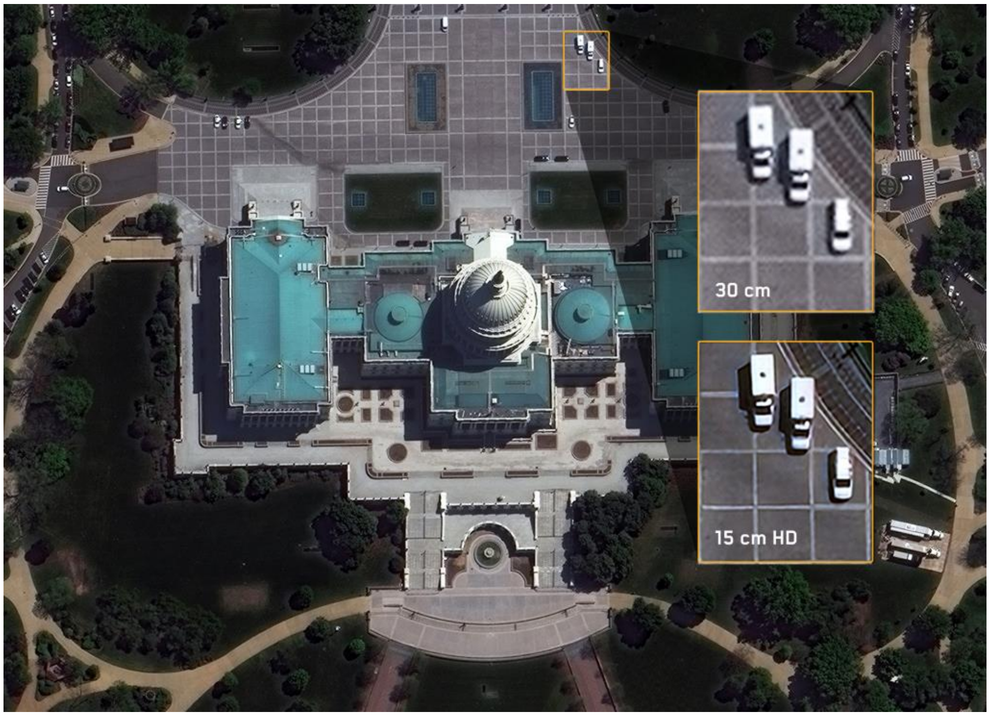


Fig. 12 Very high resolution satellite image (https://explore.maxar.com/30-cm-Leader.html)

The **revisit time** or **temporal resolution** of a satellite EO system is the time between subsequent observations of the same area of interest. This is closely linked to the type of orbit of the satellites composing the system. Most EO satellites are placed in low Earth polar, Sun-Synchronous orbits (SSO), whose altitude and inclination are precisely calculated so that the satellite will observe, over time, the same scene with the same angle of illumination coming from the Sun. Typically an SSO has an altitude of around 700 km and an inclination of 98̊. Due to this inclination angle, the revisit time for a satellite will be longer for equatorial areas and shorter for polar regions.

The **Sun-elevation angle** is the angle of the sun above the horizon. When data is collected with low sun elevation angles it may be too dark to be usable and this will be more obvious in high-relief areas and areas with taller objects, such as trees and buildings. A common acceptable Sun elevation angle is 30 degrees. Due to the fact that most EO satellites are in SSO, there is little control over the time an area of interest is observed and this is usually around 10:30 AM for optical imagery, or 6:00 AM for active sensors imagery (dawn-dusk orbits)

Due to the wavelengths considered, optical imagery will be affected by the presence of **clouds** above the area of interest. For checking data availability, the providers offer the possibility of reduced-resolution preview or quick look to check if no clouds are covering the area of interest before purchasing it. When ordering new data, the maximum percentage of cloud cover can be specified together with the time window indicated or desired for the acquisition (time of interest), maximizing this way the probability of obtaining cloud-free data.

6. Data licensing and liability

6.1 Licensing principles

Authorities, public or private, are applying a data policy based on open or restricted access to geographic information data or geospatial data and services. For example, at a state level (inside EU) a data policy can specify that:

- National Reference Basic Geographic Information and Metadata are Public Sector Information accessible under conditions of: open access, free use, free of charge, with no licensing need;
- Digital Geographic Information is accessible for non-commercial uses under conditions: free access, free of charge, licensing needed with mention of origin and ownership:
- Online services for viewing, analysis and geoprocessing is free of charge.
- Online services for downloading: free of charge with conditions specified in a licensing document.
- Downloading offline: marginal costs.
- Direct internal use at companies, in company management systems, is considered non commercial use. Geographic information national mapping agencies used as internal information can be published on the Internet giving added value to the original GI when the uses are non commercial.
- Digital Geographic Information will be accessible for commercial uses under agreement with national mapping agencies. These uses do not require initial fees, only commercial profits sharing. Fees can be established by agreement taking into account a reference value of the digital geographic data and the total business value.

Despite many regulatory acts, such as the INSPIRE Directive[8] or the Public Sector Information[9], some data is still difficult to access and use and national legislation and rules need to be applied, including those transposing EU legislation, while considering the different types of licenses attached to the data.

[8] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32007L0002

[9] https://digital-strategy.ec.europa.eu/en/policies/psi-open-data

6.2 GDPR

In the EU GDPR was adopted in 2018, the definition of personal data was given as “any information relating to an identified or identifiable natural person (data subject); an identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person”.

Someone’s current location is personal data. Someone’s living place is personal data and so is his / her route to work. In some cases (e.g. better transportation planning) these things can still be published as open data to unlock greater value for companies, public bodies and society in general (Diaz, 2016).

According to the EU GDPR, datasets containing personal data can only be published as open data by authorized controllers or processors with the consent of the data subject. Data can also be published if it is anonymised.

Most spatial information such as maps, road networks, cadastre boundaries and information are not personal data as they do not include information about the ownership of those areas. However, Geospatial can make identification of individuals easier.

Whether a given dataset contains personal data or not depends on how easy it is to link it to a person. Depending on the scale or level of detail contained, geospatial data could allow this or not. Geospatial data will be considered personal data if it is linked to a person, property or has an impact on the person.

Knowing and determining whether geospatial data is personal data can be a difficult task and becomes very important, especially if that geospatial data is open data. Before publishing it is crucial to ascertain whether that geo-information is personal data or not, and if it can be legally published as open data. Initially, geospatial data is not considered personal data, but when this dataset includes other data (attributes) that is personal data, the whole dataset is personal data, GDPR applies and anonymisation mechanisms need to be applied (Diaz, 2016).

While monitoring the use of the groundwater resources is not GDPR relevant, the detection of abusive use and investigations made for setting the legal character of the use can lead to organizations and persons and GDPR should apply.

7. Concluding remarks

This report contains information on literature review performed as a first task supporting the goals of the Earth Observation Techniques for the Detection of Illegal Groundwater Activities work package under the Tackling illegal groundwater drilling and abstractions project of IMPEL. It shows relevant information from the perspectives of using EO spatial systems for deriving information on illegal groundwater activity i.e. any combination and types of illegal drilling or illegal abstraction, including activities that could result in the direct input of pollutants to groundwater, for example discharges to wells, boreholes or soakaways.

Data acquired by Earth observation systems can be used for the deriving information of groundwater resources. These can be grouped into:

- Observations from space using satellites
- Aerial reconnaissance by manned or unmanned aircraft or helicopters
- In-situ observations

These types of observations produce data which, in combination with processing and analysis methods, can be used to identify and assess existing activities of groundwater exploitation. Preliminary information on EO data characteristics and processing and analysis methods is given. However, discriminating between legal and illegal groundwater activities requires information on existing groundwater resources, exploitation activities and the existence of the exploitation permit and the quantitative and qualitative conditions set by the permit.

The EO space systems allow analysis of large areas with reduced time and costs. Thanks to their revisit capabilities, space systems could allow detection of excessive groundwater activity (e.g. based on the identification of a subsidence phenomenon). However, for a specific area of interest, EO systems allow quantitative and qualitative information to be derived and considered as an input for the water balance equation or a more complex model based on consideration included in section 1.3, combining EU data and ancillary data such as characteristics and performance of water management systems, consumption rates etc. In addition, space-based or aerial systems can serve detailed investigation towards identifying installations (e.g. wells or activities such as agriculture or construction). In-situ observations allow quantitative and qualitative assessment of the groundwater resources by direct measurements, and they should be required to validate the EO spatial investigation results.

This is why a complex data acquisition, integration, processing and analysis system needs to be deployed for such a purpose.

At the base of such a system, the surface of the terrain for which the analysis is to be performed is considered as a reference element and needs to be chosen considering appropriate criteria. Considering the perspective of detecting illegal activities, the study area should be spatially limited to streamline the analysis and an Index corresponding to the Risk of Illegal Groundwater Exploitation (RISE) will need to be defined in respect to the analyzed surface (hydrological basin, water catchment, country, county, department, other).

To derive such an index, several questions must be answered and integrated: Is there groundwater? Is it exploitable? Are there already water extraction systems? Where are their declared locations? What are their approved operating rates? How do those rates match the water management / exploitation model in the specified area? Answers to these types of questions could lead and represent the first steps in a process of planning and implementing a system supporting the identification of illegal groundwater activities.

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European Union Network for the Implementation and Enforcement of Environmental Law

Tackling illegal groundwater drilling and abstractions (TIGDA)

"Earth Observation Techniques for the Detection of Illegal Groundwater Activities"

Annex 3 - Identification of Earth Observation Methods and Data for Detection of Illegal Groundwater Activities

Date of report: 11.03.2024

Report number: 02

Introduction to IMPEL

The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) is an international non-profit association of the environmental authorities of the European Union (EU) Member States, and of other European authorities, namely from acceding and candidate countries of the EU and European Economic Area (EEA). The association is registered in Belgium and its legal seat is in Brussels, Belgium.

IMPEL was set up in 1992 as an informal Network of European regulators and authorities concerned with the implementation and enforcement of environmental law. The Network's objective is to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation. The core of the IMPEL activities concerns awareness raising, capacity building and exchange of information and experiences on implementation, enforcement and international enforcement collaboration as well as promoting and supporting the practicability and enforceability of European environmental legislation.

During the previous years IMPEL has developed into a considerable, widely known organisation, being mentioned in a number of EU legislative and policy documents, e.g. the 8th Environment Action Programme that guide European environmental policy until 2030, the EU Action Plan: "Towards a Zero Pollution for Air, Water and Soil" on Flagship 5 and the Recommendation on Minimum Criteria for Environmental Inspections.

The expertise and experience of the participants within IMPEL make the network uniquely qualified to work on both technical and regulatory aspects of EU environmental legislation.

Information on the IMPEL Network is also available through its website at: www.impel.eu

Title of the report: Identification of Earth Observation Methods and Data for Detection of Illegal Groundwater Activities	Number report: 2024/02
Project Manager/Authors: Constantin Radu Gogu Ion Nedelcu	**Report adopted at IMPEL General Assembly Meeting**: Date and location
	Total number of pages: 23 Report: 23

Executive Summary

The IMPEL TIGDA project team are identifying different methods and techniques for the detection of illegal groundwater activities. The IMPEL have raised a project with the aim to review the different types of earth observation methods and data that can be used for the detection of illegal activities.

Groundwater is a globally vital resource that has always contributed to a safe water supply for domestic, industrial, and agricultural activities. As shown in the previous report, It was estimated that approximately half of the current water consumption may be illegal. Among the illegal use cases, the following categories can be specified and are analyzed in the following paragraphs:

- Use of water without any water right or use with an on-going but not yet finalized application;
- Use of water beyond the established limits of the water right;
- Non-compliant changes to the characteristics of the water right (timing, purpose, location, trading).

As the second and the third categories involve detailed in-situ investigations, in this report and the following ones, the illegal use will be treated in the sense of the first point i.e. the use of water without any water rights or with an on-going but not yet finalized application.

From Report 2 , the identification of earth observation methods and data are cross-referenced against the scale of the illegal groundwater activity, including: irrigated crops, industrial use, dewatering in construction, dewatering in mineral extraction, abstraction for domestic use, sewage discharge, soakaways for trade effluent.

The indications of the appropriate observation methods deemed to be relevant for each of these cases are given in relation with the description of in-situ, aerial and space observation methods described in the previous report.
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1. Introduction

Groundwater is a globally vital resource that has always contributed to a safe water supply for domestic, industrial, and agricultural activities. As shown in the previous report, It was estimated that approximately half of the current water consumption may be illegal. Among the illegal use cases, the following categories can be specified and are analysed in the following paragraphs:

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As the second and the third categories involve detailed in-situ investigations, in this report and the following ones, the illegal use will be treated in the sense of the first point i.e. the use of water without any water rights or with an on-going but not yet finalised application.

From Task 2 (Report 1), the identification of earth observation methods and data detailed on Task 2 are cross-referenced against the scale of the illegal groundwater activity, including: irrigated crops, industrial use, dewatering in construction, dewatering in mineral extraction, abstraction for domestic use, sewage discharge, soakaways for trade effluent.

The indications of the appropriate observation methods deemed to be relevant for each of these cases are given in relation with the description of in-situ, aerial and space observation methods described in the previous report.

2. Anthropogenic Activities

2.1. Irrigated crops

Groundwater is a globally vital resource that has always contributed to a safe water supply for domestic, industrial, and agricultural activities.

Globally, irrigated agriculture is the largest abstractor and predominant consumer of groundwater resources, with important groundwater-dependent agro-economics having widely evolved (Foster & Shah, 2012). But in many arid and drought prone areas, unconstrained use is causing serious aquifer depletion and environmental degradation, and cropping practices also exert a major influence on groundwater recharge and quality.

Continuous groundwater depletion resulting from long-term excessive resource exploitation can in some cases result in a number of other serious environmental quantitative and qualitative consequences.

Environmental Quantitative consequences:

- *troublesome* ***land subsidence*** due to the settlement of interbedded aquitards in alluvial and/or lacustrine formations.
- ***depletion*** *of resources available for legal uses*. River Basin Authorities cannot control the characteristics of illegal wells (eg. the location of a particular well in relation to others or in relation to the protection perimeter of rivers and wetlands) or the volume of water that can be extracted without damage to a third party or the environment. This leads to non-sustainable aquifer exploitation, with slumps in groundwater levels leaving the authorized users without water in their wells (eg. in the Upper Guadiana and the Segura river basin), disappearance of springs (eg. in Pegalajar, Granada) and reversal of the river-aquifer dynamics that leaves rivers and streams dry.

Environmental Qualitative consequences:

- ***the salinization of aquifers*** – which is a very insidious and often complex process arising from a variety of physical mechanisms
- ***alteration and degradation*** *of water ecosystems*. Most wetlands are formed when groundwater seeps to the surface. Therefore, the uncontrolled exploitation of an aquifer results in the wetlands' water input diminishing or even disappearing, which in turn results in the deterioration of related ecosystems

Agricultural land-use practices in general also exert a major influence on groundwater recharge quality (Foster et al, 2000; Foster & Candela, 2008) through:

- leaching of soil **nutrients**: this problem has been exceptionally widespread in the industrialised nations with (largely successful) attempts to increase grain, oil-seed, vegetable, fruit and milk production per unit area through the replacement of traditional crop rotations with near monocultures, but as yet has been less severe in the developing world where inorganic fertiliser applications have generally been much lower – in theory at least the problem of soil nutrient leaching should also be more manageable in irrigated than rain-fed agriculture;
- contamination with **pesticides**: a potentially serious problem but one more confined geographically to recharge areas of aquifers exhibiting high vulnerability to pollution from the land-surface, where the more 'mobile' pesticides (mainly certain herbicides and soil insecticides) have been regularly used at high application rates;
- mobilisation of **salinity**: this issue is of very serious concern in arid and hyper-arid areas where the 'irrigation frontier' has (or is) being extended through clearing of native desert scrubland with high

salinity levels retained in the subsoil profile.

According to the Spanish Ministry for the Environment, there are 510,000 illegal wells in Spain. At least 3,600 hm^3 of groundwater is extracted illegally each year, which equals the average water consumption of 58 million people. This probably underestimated volume, is in contrast with the volume that is legally extracted, which is estimated at 4,500 hm3/year2. This means that at least 45% of all water pumped from aquifers each year is extracted without regard to legal constraints. This water is used for the irrigation of about one sixth of the total irrigated land in Spain, plus numerous golf courses, and for the supply of a disproportionate urban development. One of the areas most affected by this problem is the Doñana Natural Park where the number of illegal wells for irrigated crops is affecting the ecosystem of a protected area drying out a large part of the wetlands of the place.

In Brazil, there are about 2.5 million tubular wells in which 88% of them are illegal, extracting more than 17,580 Mm3 /yr. This irregular use may cause sustainability issues that may be economic, social, or environmental (overexploitation, well losses and associated increases of water conflicts; aquifer contamination; and land subsidence). Additionally, the increasing number of illegal wells, that is, those who do not have a license or registration for pumping, may compromise effective groundwater management.

In Iran central desert illegal groundwater pumping mainly for regional agricultural use during recent years has caused groundwater quality degradation due to saline water intrusion from eastern areas (central Kavir desert and salt lake) and connate water coming from deeper aquifers (Baghvand et.al, 2010).

Detection and quantification methods

Typically, two kinds of "non-compliance" can be distinguished, according to [DIANA Report]:

- irrigated areas which do not have the necessary water rights;
- irrigation water consumption which does not remain within the legally allowed or assigned water volume.

In the first case, all irrigated areas need to be identified and cross-checked with all available information on irrigable areas. Depending on applicable legislation, the legal right to irrigate may be linked to the land, an abstraction point or a water source, either permanently or for limited periods of time. In the second case, irrigation water consumption should be monitored and cross-checked with regulated allocation or hydrological planning data.

Earth Observation can supply two key products to tackle both the above-mentioned cases of non-compliance:

- maps of irrigated areas;
- maps of irrigation water consumption and abstracted volumes.

These will allow the authorities to monitor irrigated areas and the abstracted volumes on a systematic basis, to better target field inspections aimed at assessing compliance with legal water allocation and to ensure the legitimacy of self-declared irrigation water abstractions.

2.2. Industrial use

Industrialization has a significant impact on groundwater extraction. In many industrial areas, the quality of groundwater is deteriorating due to the disposal of untreated effluents from industrial units, resulting in high concentrations of heavy metals and rendering the groundwater unsuitable for drinking purposes (Mahfuzur et.al, 2022). The contamination of groundwater in industrial areas is a global concern, with studies showing excessive concentrations of various water quality parameters, making a significant percentage of groundwater non-potable.

Industry and mining cover a vast spectrum of activities and processes, and an equally large range of scales. By no means all of them will generate significant pollutant loads and, just because an industry employs hazardous chemicals in its production processes it does not follow that it will necessarily be a groundwater polluter. Industry-specific, process specific or even site-specific factors such as the method of effluent disposal and storage practices (Tabel 1), the integrated pollution control procedures used and the vulnerability of the underlying groundwater will all influence whether an industry will have a negative impact (Morris et al, 2003). The pollution sources and pathways to groundwater mentioned in Table 1 are largely the same as those identified for general urban impacts, but are probably derived more often from point than diffuse sources.

Tabel 1. Sources of groundwater pollution from industry (modified from Morris et al, 2003)

Source	Mechanism - main contributory factors
Underground and surface storage tanks, processes and effluent pipe work or other transfer system	Undetected leakage or inadequate bunding to retain major failures
Industrial sewers / collectors	Leakage because of poor maintenance
Soakaways, waste injection wells	Pollution because of inappropriate disposal practice
Bulk chemical storage areas	Leaks due to poor handling and storage procedures

Liquid effluent and process lagoons	Leakage because of poor construction / maintenance
Solid process-waste disposal sites	Leakage of leachate through poor construction or failure of design
Accidental / catastrophic discharge	Plant fire, explosion, impact and loss of material to ground

The heavy industrial abstraction in certain areas poses a threat to the **intrusion of seawater** and land **subsidence**. The stress on groundwater resources due to industrial activities has led to environmental problems such as **water table drawdown**, land subsidence, and saltwater intrusion, which hinder the sustainable development of cities. Other effects and ways of observing them are summarised in Section 3, Transversal analysis on data and observation methods for detection of groundwater activities

2.3. Constructions - Dewatering

Most of the times, the interventions on groundwater is justified in the case of construction sites with a high water level and is referred as dewatering. Lowering the groundwater level by pumping wells may reverse the normal flow of groundwater to the stream, causing the intrusion of surface water into groundwater and, eventually, drinking water wells. The Potential Groundwater Impacts of Dewatering are summarised below.

Contamination

Dewatering can cause the development of hydraulic gradients that are also necessary for drawing out water towards wells. Dewatering near a site with a history of pollution in groundwater can result in hydraulic gradients that can carry the **polluted groundwater** towards the dewatering system and cause contamination. In most cases, contaminated water requires filtration. To avoid this problem, the best method is to install screen walls and vertically separate areas using bentonite seals.

Geotechnical Damage

Dewatering can cause the ground to **lose structural integrity**, which causes ground settling. If the extent of ground settling is large, it can damage nearby buildings and structures. When groundwater is extracted from the soil, it causes the soil to compress. It can also be caused by small soil and ground partials being extracted with the groundwater through wells.

Impacts on Water Features

Water-dependent features that include rivers, lakes, and springs have a close relationship with groundwater and are, therefore, affected by dewatering and groundwater control by exclusion. It is vital to keep into consideration that groundwater, and water dependent features have eco-systems and serve as habitats. An adverse effect of these water bodies will have a significant **negative impact on the environment**.

Water Resource Depletion

When groundwater is extracted for lengthy periods and in large quantities for drinking or industrial use, it can potentially lower groundwater levels and decrease yields. This **depletion** results in a reduction of valuable water resources for others. A solution to this problem can be an artificial recharge technique that injects discharge from pump water back into the ground.

Monitoring dewatering during construction activity by using remote sensing

Several study cases demonstrate how the integration of Differential Interferometric Synthetic Aperture Radar (D-InSAR), Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) and Multi-Temporal Interferometric Synthetic Aperture Radar (Mt-InSAR), for surface deformation monitoring and levelling improves the monitoring of ground deformation phenomena in the case of dewatering systems.

The complementarity between D-InSAR and levelling has been demonstrated through a case study (Bassols et al, 2021) of the construction of a road tunnel in Barcelona city where D-InSAR was employed to continuously monitor the dewatering of the site. D-InSAR data obtained from the processing of Sentinel-1A data following a persistent scatterer interferometry procedure allowed the study of the spatial distribution of the deformation and its temporal evolution together with detailed hydrogeological and hydraulic head data. The magnitude of deformation has been analysed using levelling data and an analytical estimation based on the hydromechanical parameters of the ground obtained from a pre-existing hydrogeological numerical model and pumping tests. The D-InSAR results shown to be essential to identify the origin of ground deformation and the constraints on its spread, whereas levelling offered a more accurate quantification of the deformation.

In Korea, tunnelling-related surface deformation (Ramirez et al, 2022) was analysed using the persistent scatterer InSAR (PS-InSAR) technique and Sentinel-1B SAR data; the PS-InSAR results were compared with those from the conventional levelling method. The velocity map of the study site revealed a localised subsidence trough associated with the construction of vertical shafts and shield tunneling. The cumulative time-series displacement map successfully tracked the spatial and temporal progression of ground deformations related to the phases of tunnel construction activities. The maximum subsidence rate in the radar line-of-sight direction was estimated to exceed 40 mm/yr, with maximum cumulative subsidence of ~ 200 mm. The results clearly showed that dewatering during tunneling aggravated the subsidence phenomenon. It has been observed that the subsidence accelerated during the pumping of groundwater inflows, but slowed when the groundwater table was restored. The consequent compaction and consolidation of the compressible soil layers due to the lowered groundwater table were the main causes of subsidence.

2.4. Mineral extraction

Activities associated with mining and mineral processing operations have significant potential to pollute groundwater either directly or indirectly. Mining areas are quite often located in the mountainous upper parts of catchments and, via the surface water system, impacts can be observed downstream, as in the Baia Mare case (UNEP, 2000). The broad term mining includes both open pits and underground workings for minerals and quarrying for building materials. The sources, pollution pathways and potential impacts on receptors are summarized in Table 2. Both open pit and underground mines often require substantial withdrawals of groundwater to create an artificial cone of depression within which the mining operations can take place.

Table 2. Groundwater problems arising from mining activities (modified from Morris et al, 2003)

Mining activity or process	Potential impact on subsurface if inadequate design and implementation	Resulting environmental problem
Mine drainage	Mine water rebound	Groundwater or surface water pollution from acid mine drainage
Mine gas generation	Migration through strata	Mine gas emission at the surface
Shallow mining	Ground instability	Subsidence
Deep mining	Enhanced transmissivity above workings due to collapse fractures	Localized dewatering of overlying aquifer on intrusion of lower quality water on rebound
Extractive operations	Pollutants used for mine operations used and left in situ	Residual, fuels, hydrocarbons, solvents, explosives leached to groundwater
Tailings lagoons	Effluent seepage, tailing dam failure	Pollution of groundwater and surface water

Solid waste dumps / spoil heaps	Acidic and metal-rich leachate	Pollution plumes below tailings

Remote sensing to monitor dewatering during mining activity

Remote can be applied to evaluate the spatio-temporal distribution of ground movements caused by groundwater head changes induced by mining.

Using multi-temporal differential interferometric synthetic aperture radar analysis integrated with pumping and site geologic data is used, in crescent valley – Nevada USA (Woldai at al 2007), to demonstrate hydrologically induced large subsidence in and around an ongoing open-pit mine with intensive dewatering operations. Analysis of numerous differential synthetic aperture radar interferometry (DInSAR) pairs spanning the period 1993 to 2001 reveals the abrupt appearance of these features to intervals of a few to several months. DInSAR has been also used to extract several individual kilometre-length, centimetre amplitude normal fault reactivation events in the alluvial sediments adjacent to the mine dewatering operation. High-resolution remote sensing analyses provide strong evidence that these features align with faults active in the last several thousand years. These reactivations have been interpreted as mechanically involving only the upper few hundred metres of the existing fault plane above the alluvial aquifer affected by the mine dewatering.

Another study (Malinowska et al 2020) carried out in an area of copper ore and anhydrite mines (Konrad mine), near the city of Bolesławiec, Poland. To determine ground movements, classical surveying results and the persistent scatter Satellite Radar Interferometry (PSInSAR) method were applied. The mining operation triggered significant subsidence, reaching 1.4 m in the years 1944–2015. However, subsidence caused by groundwater pumping was about 0.3 m. After mine closure, an ongoing groundwater rebound was observed. Hence, land uplift occurred, reaching no more than 29 mm/y. The investigation focused on developing a novel method for uplift prediction by comparatively analysing the dynamics of ground movements correlated with the mine life and hydrogeological condition. These analyses allowed the time factor for the modelling of land uplift to be determined. The investigation also revealed that in the next few years, the uplift will reach up to 12 mm/y. The developed methodology could be applied in any post-mining area where groundwater-rebound-related uplift is observed.

2.5. Intensive Groundwater Abstraction for Domestic Use

Intensive groundwater abstraction modifies the hydrological regime of an aquifer. Direct hydrological responses include:

– **depletion** of stored volumes of groundwater (accompanied by declining groundwater levels and pressures);

– **intrusion** of seawater or water from other hydraulically connected water bodies (not only surface water but also groundwater from overlying or underlying strata)

– **reduction** of natural groundwater discharge (by springs, baseflows of streams, evapotranspiration and evaporation from shallow water tables, outflow into lakes or the sea); and,

– **increased** recharge from connected components of the hydrological system (streams, lakes, other hydrogeological units).

These hydrological responses, in turn, have their impacts on human society (in particular on groundwater users) and the environment. Figure 1 lists the most common impacts (Van der Gun, 2022). Some brief explanatory comments will follow, with selected references to mega aquifer systems for which the impacts have been reported.

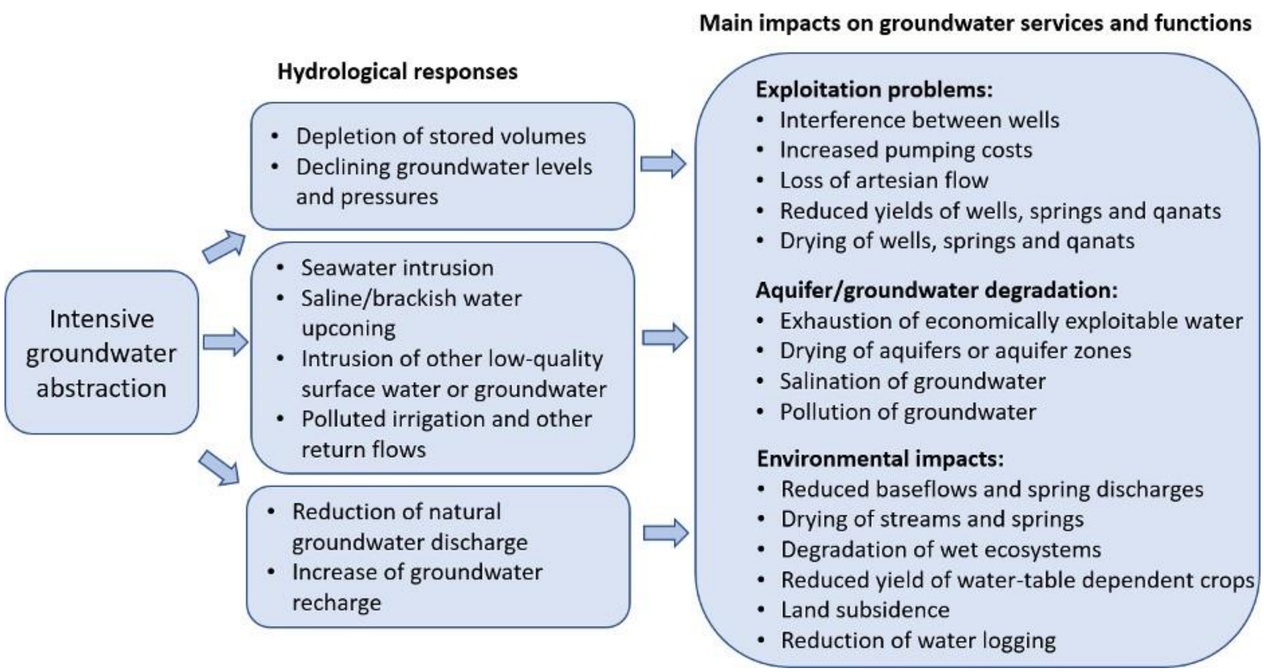

Figure 1. Side-effects of intensive groundwater abstraction including hydrological responses and the main impacts on groundwater services and functions (Van der Gun, 2022)

Detection of drilling rigs and evidence of boreholes by drone

Drones provide a versatile and effective solution to identify and monitor suspected illegal activities of onshore drilling rigs, providing real-time information on operations and environmental impact. By harnessing the monitoring capabilities of drone technology, operational efficiency in identifying illegal drilling installations used to capture groundwater for domestic use, as well as in the scope of other activities, such as identifying dewatering systems in construction or mineral extraction, agriculture or industrial use. Key applications of drones in the identification and monitoring of onshore drilling rigs include:

1. Drones can conduct aerial patrols in distinct areas to identify drilling sites. Real-time video feeds allow monitoring personnel to identify evidence of drilling rigs and surrounding areas.
2. Drones can perform visual inspections to identify drilling equipment such as drill rigs, pipes and machinery. High-resolution cameras and sensors capture detailed images and data.
3. Drones survey the environment for signs of pollution, such as spills or leaks, and monitor air and water quality near the drilling site.
4. Drones capture aerial images of drilling operations, allowing monitoring operators to track the progress of drilling activity. Time-lapse photos and video documentation provide valuable information about the pace of drilling activities over time.

By integrating drone technology into onshore drilling platform monitoring, increased efficiency is achieved while achieving greater transparency and accountability in drilling operations.

2.6. Sewage discharge

In urban areas where sewerage coverage is nearly 100%, the primary route of groundwater contamination by domestic wastewater is **leaking sewers**. Sewage in sewer pipes and groundwater surrounding sewers interact with each other. That is, when the groundwater level is above a sewer pipe, groundwater infiltration into sewers and dilutes sewerage water; on the other hand, when the groundwater level is below a sewer pipe, sewage exfiltrates into groundwater through joint defects and corrosion and contaminates ambient groundwater. Spillages from on-site wastewater treatment facilities, such as septic tanks, also cause groundwater **contamination** by domestic wastewater.

Sewage constitutes a major contaminant of groundwater in rural and many suburban areas. Contamination of groundwater in this area is always increasing due to negligence of the aquifer and improper design of toilet facilities in terms of width, depth and other parameters. Hand dug wells are designed and located without proper site investigation to determine nearness to sources of pollution (pit latrines and soak-away pits). Toilet facilities are also constructed without investigation to ascertain the nature of the soil (topography, porosity and permeability), groundwater flow direction and water table depth.

It is estimated that the country's subsoil receives 4,329 mm^3/yr of sewage, which corresponds to the sum of the sewage from the lack of networks (3,747 mm^3/yr) and that resulting from lack of maintenance (582 mm^3/yr). This volume is equivalent to the launch of 1.8 million Olympic swimming pools per year or almost 5,000 swimming pools/day (Hirata et al. 2019).

Industrial sewage that does not meet the emission standards will **pollute the surface water** and groundwater when it is discharged into water bodies, causing serious adverse impacts on human beings and the environment. In Chennai city, the growing urbanization and rapid industrialization lead to the generation of huge quantities of waste water. The uncontrolled discharge of sewage, garbage, and industrial effluents into the downstream of the Cooum river, **percolates through the soil** and contaminates the Groundwater sources.

3. Transversal analysis on data and observation methods

An analysis on data and observation methods for detection of groundwater activities has been processed for this section. For each activity, associated phenomena together with their main observable process and corresponding observation methods, data types, existing datasets and their availability and source are marked in the following table.

The gathered data is to be used in appropriate models (water balance equations) for quantifying the quantity of water being illegally used and deciding whether actions to be taken are worth the cost when compared to benefits. Considering the water balance equation (Report1-Task 2), several parameters using several aerial or satellite based techniques could be used to quantify distinct parameters evaporation and evapotranspiration, water storage in the water catchment, or water infiltration into soil.

$$P\ (\pm W \pm H_i) = E_t + Q + I + U + \Delta R$$

Where the following terms are expressed:

P - precipitation – main water source (rainfall and snow) entering in the hydrological basin;
W - groundwater flow input, another catchment natural water input (in some cases large water volumes are passing from a catchment to another in spite surface water flow established processes);
H_i - human intervention;
Q - direct water flow (in river network);
I - infiltration into soil;
U - human use;

Δ R - storage of the water catchment;
E_t - water catchment total evaporation (called evapotranspiration);

The human intervention (H_i), that could be a legal activity or not, could be also quantified. In some cases, when accurate data could be produced to reliably quantify the other water balance parameters, water discharges corresponding to water exploitation flow rates could be quantified. (e.g. illegal water quantities extracted in the scope of irrigated crops).

In the case of permanent or temporary illegal dewatering systems implemented in the construction activity, a more precise urban area water balance study should be performed to quantify potentially extracted groundwater volumes. Apart, the natural elements of the analysed area (e.g. rainfall-runoff, infiltration into soil, storage volumes, groundwater exchanges with rivers and lakes), this should englobe the water infrastructure exchanges with the area existing infrastructure elements and networks (e.g. water distribution system losses, sewer network water exchanges with groundwater, seepage into tunnels, and stations).

ACTIVITY / CASE	ASSOCIATED PHENOMENA AND / OR PROCESSES	OBSERVATION METHODS AND OBSERVABLES	EXISTING DATA AND POSSIBLE SOURCES	COMMENTS / DETAILS
IRRIGA T ED CROPS	**Groundwater table depletion** (decrease of the groundwater hydraulic head, decreases of the surface water levels, river, springs flow rates decrease, subsidence)	INSAR can be used to derive ground motion / land subsidence	EEA EUGMS or equivalent services; GWL from NGMN (GVTDATA)	Should be used in combination with water rights maps, actual and historical water consumption, meteo data; COPHRL and LULC data such as CLC or LPIS should be used to focus the analysis
	Grown crops in non-declared agriculture area or no valid water rights	Aerial or space RS can be used to map crops and map irrigated area; NGMN Data and Hydro Monitoring Data to estimate water consumption	ESA or EEA Land Monitoring Copernicus data on phenology; GVTDATA	
	Soil salinization (high salts content in groundwater/ aquifers salinization land degradation processes, groundwater dependent ecosystems de gradation)	RS can be used to detect degradation of wetlands ecosystems that are fed by groundwater; RS can be used to detect desertification; RS can be used to map soil salinity in Combination with in-situ observations	Soil salinity maps from ESA, EEA or projects based local data	

ACTIVITY / CASE	ASSOCIATED PHENOMENA AND / OR PROCESSES	OBSERVATION METHODS AND OBSERVABLES	EXISTING DATA AND POSSIBLE SOURCES	COMMENTS / DETAILS
INDUSTRIAL USE	**Groundwater table drawdown** (decrease of the groundwater hydraulic head, decreases of the surface water levels, river, springs flow rates decrease, subsidence)	INSAR can be used to derive motion / subsidence of land or infrastructure elements and produce ground motion maps	EA EUGMS or equivalent services; GWL from NGMN (GVTDATA)	Existing GVTDATA on industrial facilities e.g. EPRTR EEA data can be used to focus the analysis and reduce time to decision
	Groundwater recharge (flooded infrastructure, changes in groundwater balance, uplift, differentiated settlements)	Groundwater wells quantitative monitoring; Cavities increased seepage (sewers, parking, foundations, cellars); Geophysics (GPR imaging); geology analysis, INSAR in cases of uplift (depending of magnitude of phenomena)	GWL from NGMN (GVTDATA)	
	Groundwater pollution (Higher concentrations of dissolved or suspended elements)	RS of surface water bodies or connected ecosystems focusing on detecting anomalies	GWQMW (GVTDATA) or projects based local data	

ACTIVITY / CASE	ASSOCIATED PHENOMENA AND / OR PROCESSES	OBSERVATION METHODS AND OBSERVABLES	EXISTING DATA AND POSSIBLE SOURCES	COMMENTS / DETAILS
DEWATERING - CONSTRUCTION	**Groundwater table drawdown and / or decrease of water level in surface water bodies** **Ground structural integrity degradation and / or earth fissures and structural damage of buildings**	Groundwater wells quantitative monitoring; hydro network monitoring water level data INSAR can be used to derive motion / subsidence of land or infrastructure elements; optical satellite or aerial imagery can be used for detailed check of building	warning or alert can be generated from NGMN (GVTDATA) or local monitoring data ground motion maps can be produced periodically from EEA EUGMS; projects based local data	Existing GVTDATA on public works / building permits can be used to focus the analysis and reduce time to decision
DEWATE RING - MINERAL EXTRAC TION	**Mine water discharges in surface water bodies** **Groundwater table drawdown** (subsidence due to decrease of groundwater level / surface structures damaged by tilting, lowering of the land surface)	RS of surface water bodies or GWQMW data can be used to detect changes in surface water status INSAR can be used to derive motion / subsidence of infrastructure elements, subsidence of land	Copernicus data on lake water quality ground motion maps can be produced periodically from EEA EUGMS	Existing GVTDATA on active and inactive mining sites can be used to focus the Analysis and reduce time to decision

ACTIVITY / CASE	ASSOCIATED PHENOMENA AND / OR PROCESSES	OBSERVATION METHODS AND OBSERVABLES	EXISTING DATA AND POSSIBLE SOURCES	COMMENTS / DETAILS
SEWA GE DISCH A RGE, REINJE C TION WELLS ,	**Groundwater pollution** (higher concentrations of dissolved or suspended elements in groundwater and surface water bodies) **Changes in ground water balance; flooded infrastructure elements**	RS of surface water bodies; focusing on detecting anomalies related to water quality cavities influx monitoring (e.g. sewers, parking, cellars)	GWQMW Data; Geochemical monitoring data (GVTDATA or Municipality, water operators) GWL from NGMN or project based local data	Quite difficult to apply; crowdsourcing or other planned activities could help focusing the analysis
DOMES T IC USE	**Depletion of stored volumes of groundwater and subsidence** **Soil salinization** due to intrusion of seawater or water from other hydraulically connected water bodies **Increased groundwater recharge from connected streams, lakes**	INSAR can be used to derive ground motion / subsidence; for large areas satellite gravimetry data could give indications over longer periods of time RS of soil status applied in order to derive salinity GWL measurement by means of NGMN	EEA EUGMS or equivalent services; GRACE-FO data can be used for satellite gravimetry based methods Soil salinity maps from ESA, EEA or projects based local data GWL Data (GVTDATA)	Cvasi-permanent monitoring of populated places, especially rural area could be necessary, making use of EUGMS

ACTIVITY / CASE	ASSOCIATED PHENOMENA AND / OR PROCESSES	OBSERVATION METHODS AND OBSERVABLES	EXISTING DATA AND POSSIBLE SOURCES	COMMENTS / DETAILS

GWL Groundwater Level

GVTDATA Data provided by Governmental Organizations

NGMN National Groundwater Monitoring Network

CLC Corine Land Cover Data

GWQMW Groundwater Quality Monitoring Wells

LPIS Land Parcel Identification System

LULC Land Use Land Cover

COPHRL Copernicus High-Resolution Layers

ESA European Space Agency

InSAR Interferometric Synthetic Aperture Radar

EEA European Environment Agency

DInSAR Differential InSAR

ECMWF European Centre for Medium-Range Weather

RS Remote Sensing

Forecasts

4. Conclusions

A number of cases are presented together with considerations related to phenomena observed, observables and candidate observation methods that can be used to detect and measure, with an aim to quantify and plan measures to tackle each case. The output (data gathered) is to be used in appropriate methods aiming to detect non-conformities and models (water balance equations) for quantifying the quantity of water being illegally used and deciding whether actions to be taken are worth the cost when compared to benefits. As shown in the previous paragraphs where indications on the amplitude of each of the cases are given, the agriculture case remain, by far the most significant one and is followed most probably by the domestic use.

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European Union Network for the Implementation and Enforcement of Environmental Law

Tackling illegal groundwater drilling and abstractions (TIGDA)
“Earth Observation Techniques for the Detection of Illegal Groundwater Activities’’

Annex 5 - Obtaining and Processing Earth Observation Data

Date of report: 17.06.2024

Report number: 03

Introduction to IMPEL

The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) is an international non-profit association of the environmental authorities of the European Union (EU) Member States, and of other European authorities, namely from acceding and candidate countries of the EU and European Economic Area (EEA). The association is registered in Belgium and its legal seat is in Brussels, Belgium.

IMPEL was set up in 1992 as an informal Network of European regulators and authorities concerned with the implementation and enforcement of environmental law. The Network's objective is to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation. The core of the IMPEL activities concerns awareness raising, capacity building and exchange of information and experiences on implementation, enforcement and international enforcement collaboration as well as promoting and supporting the practicability and enforceability of European environmental legislation.

During the previous years IMPEL has developed into a considerable, widely known organisation, being mentioned in a number of EU legislative and policy documents, e.g. the 8th Environment Action Programme that guide European environmental policy until 2030, the EU Action Plan: "Towards a Zero Pollution for Air, Water and Soil" on Flagship 5 and the Recommendation on Minimum Criteria for Environmental Inspections.

The expertise and experience of the participants within IMPEL make the network uniquely qualified to work on both technical and regulatory aspects of EU environmental legislation.

Information on the IMPEL Network is also available through its website at: www.impel.eu

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Executive Summary

With a general objective "to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation", the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) funded the project *Tackling illegal groundwater drilling and abstractions* (TIGDA) which aims to share knowledge and good practices on how to manage groundwater drilling and abstractions.

Under the TIGDA project the work package *Earth Observation Techniques for the Detection of Illegal Groundwater Activities* (EOWP) aims to review the different types of earth observation (EO) methods and data that can be used for the detection of illegal groundwater activities.

As formulated by IMPEL, within the scope of this project the definition of *illegal groundwater activity* covers any combination and types of illegal drilling illegal abstraction, including activities that could result in the direct input of pollutants to groundwater, for example discharges to wells, boreholes or soakaways.

In this report, reference is made to EO, either direct in-situ, or indirect remote sensing observations, performed from aerial or space systems; the report contains information on the different ways data can be accessed and processed to derive information, as needed for the following levels:

1. Awareness Level 1: only suitable for filtering in potential illegal groundwater activity abstraction. Will help understand if more detailed inspection techniques are required.
2. Advanced Level 2: ability to map clearly the location of illegal groundwater activities.
3. Specialist Level 3: ability to clearly indicate the clusters and scale of illegal groundwater activities for prioritization by the regulatory authority
4. Expert Level 4: ability to provide sufficient evidence to automatically fine without local inspections activities

The same time, indications are given on access methods and cost for data, needed equipment, its cost and skills required for its operation, infrastructure needed for deriving the actionable information for tackling the nonconformities.
Disclaimer This report is the result of a project within the IMPEL network. The content does not necessarily represent the view of the national administrations or the Commission.
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1.0 Introduction

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Following a logic that can be described as “*access or collect data -> process and derive information -> plan and implement actions*”, indications are given on

- access methods and cost for data,
- needed equipment, its cost and skills required for its operation,
- infrastructure or logistics

needed for deriving the actionable information for tackling the nonconformities.

2.0 Data

2.1 Observables and data

As shown in the previous report based on a number of groundwater abstraction cases where illegal issues may be faced, each of the mentioned methods involves access, processing and integrated analysis of various data summarized in the table 1.

Table 1. Data types and sources

Dataset	Details	Data sources
Groundwater data records	Hydraulic head and quality parameters time-series datasets obtained from national and local databases	National and local monitoring systems and databases

Surface water data records	Water level in rivers and lakes, flowrates in streams gauging stations and quality parameters time-series datasets obtained from national and local databases	National and local monitoring systems and databases

Dataset	Details	Data sources
Satellite data records	Time series of high-resolution data covering the entire crop growing season, used to compute various indices	Landsat satellites multispectral; Copernicus Sentinel satellites, multispectral, global cover; Other EO systems allowing multispectral time series at 10-30 m resolution.
Meteorologial data	Daily meteorological data on precipitations, allowing calculation of crops water consumption. Evapotranspiration	Observation networks available at national level. Alternative options: WMO, ECMWF, other EU agencies.
Soil water retention	Data allowing consideration of the capacity of the soil to retain water, as needed for modeling purposes	National databases. European products, however with limited accuracy, currently available in some MS and some areas. Also produced by UN FAO.
Crops maps and phenology	Per season; Supporting water consumption estimation	FAO database; National databases, currently available in some MS and some areas; Relevant publications
Farm information	To be used for better assessing water consumption	Farm characteristics data collected during field inspections; Information systems created and maintained by the ministries / agencies.
Sewage network	Position of the sewage pipes as needed for the urban cases	Local sewage operators/services providers
Construction site information	To be used for detailed analysis of impact	Usually provided for getting the construction permit; should be available at the authority managing the construction processes
Land use land cover	When updated, can give indications on land use and the way water is possibly consumed	CLC / CLC+ and the 5 new Copernicus High Resolution Layers. LPIS (for parcel delineation). Available in all MS since 2006. Data updated every 6 years for CLC and every 3 years for the 5 HRL.

Dataset	Details	Data sources
Irrigable area boundaries	Vector data containing delineation of irrigable areas boundaries.	Water User Association archives. Available in some MS.
Actual and historical water consumption	For calibration and continuous ground truthing of crop water consumption; Historical data on water consumption, as related to a known activity	Water abstraction as flow meter data in selected locations from monitoring networks for pressurized systems; Not available for gravity irrigation systems. For some cases, billing data from the water companies;
Water rights map	Location of parcels with regular irrigation rights.	Water User Association archives. Available in some MS.
Cadastral maps	To allow identification of owner(s) and relate to any other related legal information	Real estate or real property's metes and bounds of a country as provided by national government entities or agency; usually available in all MS.

2.2 Data access

The current Copernicus Services

The EU Satellite Centre (SatCen) was entrusted by the Commission in 2016 with the implementation of the Copernicus security service in support to EU External Action[10]. The Copernicus security service component on Support to EU External and Security Actions (SESA) is a European geospatial information service that assists the EU and its Member States in the framework of applicable Union policies and legislation along the following main policy groups, associated to key responsibilities across EU Institutions and Member States:

i. Union external action supporting the Union and its Member States
ii. Security challenges facing the Union and its Member States
iii. Monitoring of the implementation of EU Law

The SESA service includes new application areas, notably addressing Security of EU Citizens, Humanitarian Aid, Crisis and Conflict, Rule of Law, Transport Safety and Security, Stability and Resilience for Development, Cultural Heritage, International Trade and Economic Diplomacy as well as cutting-edge challenges such as Environmental Compliance, Climate Security or Health Security. With such mandate, SatCen can provide

[10] https://www.copernicus.eu/en/copernicus-services/security

access to a large portfolio of services supporting environment security and TIGDA type of cases can be used for requesting SatCen services.

Copernicus is a European Union Programme aimed at developing European information services based on satellite Earth Observation and in-situ (non-space) data which operates six thematic services relating to Atmosphere, Marine, Land, Climate Change, Security and Emergency[11]. Copernicus collects a vast amount of data from satellites, ground based, airborne and seaborne measurements systems, processes and then analyses it to make usable in order to provide autonomous and independent access for all. Importantly, the information is free to use by anyone – whether it be used by policymakers, public and private organizations or the general public, it allows the development of new applications, products and services, research to be undertaken, policies evidenced or business planning to be improved.

The future EU EO Governmental Service

Based on recent debates, the European Commission made important steps towards developing a dual-use EU EO service restricted to government-authorized EU and MSs users for sensitive applications in the areas of security and defense. This is justified by the need to have access to reliable, fast, secure and global situational awareness enabled by space-based Earth-Observation systems and by the processing of the associated data, combined where available with other data, to generate added-value services and intelligence insight.

In this context, and as identified in the EU Space Strategy for Security and Defense (RD2), the Commission has the ambition to study the development and implementation of a potential new dual-use EU Earth-Observation service for governmental use in the MFF 2028-2034. Only authorized users within the EU and MSs (and possibly third countries and international organizations, under certain conditions) would have access to this service which aim at increasing our collective and individual resilience, in the areas of security and defense. The Commission has already taken action[12] to implement in the current MFF 2021-2027 a pilot and precursor of such a governmental service, within the existing legal framework.

The Copernicus Sentinel satellites and associated services were designed to meet certain environmental, emergency management and civil security needs. Nevertheless, some Sentinel data and service products are also used by defense users in specific non-critical use cases.

The desired capability is relying on EU MSs sovereign high-end space-based ISR (intelligence Surveillance and Reconnaissance) capabilities, the future capabilities i.e. space-based ISR constellation to complement high-end military capability for near real-time tactical use, as well as on various projects related to space-

[11] https://www.copernicus.eu/en/about-copernicus/copernicus-detail
[12] https://etendering.ted.europa.eu/cft/cft-documents.html?cftId=13224

data processing for ISR applications.

Earth Observation Products, Platforms, and Tools

Numerous web portals and services exist to enable discovery, access, and use of Earth observation data and derived information products. Portals exist to support different users and they can be classified into three broad functions, with some crossover:

1. **Earth observation data portals** – users can identify and download satellite images based on criteria such as acquisition date, sensor, and product. Many portals exist for specific groups of sensors (see Table 2). For Landsat, the most common download location is the USGS EarthExplorer and for the Sentinel missions the Copernicus Open Access Hub. Both Landsat and Sentinel-2 optical data provide access to new data that are calibrated. Landsat and Sentinel optical data are also available from other services as well, such as Google Cloud and AWS, but these are aimed at advanced users, particularly for bulk downloading large collections of imagery. Landsat and Sentinel-2 data is available to view alongside PlanetScope data through Planet Explorer.

2. **Earth observation derived information products and services** – users can directly access derived products, which range from simple re-computed spectral indices such as NDVI to products resulting from advanced and complex algorithms such as global tree cover change or ocean water quality (see Table 3). Several portals and applications compile and curate a range of geospatial datasets (e.g. Spatial Agent, OpenDRI portals, World Environment Situation Room (WESR; Box 19), while others offer integration and analytics functions (e.g. Trends. Earth, Global Forest Watch).

3. **Earth observation processing and visualization platforms** – cloud computing platforms for Earth observation data allow users to access, store, and analyze large volumes of EO data when they have limited Internet bandwidth and local computing infrastructure. Earth observation platforms "bring the user to the data and tools" and users access the data, tools, and resources required, as opposed to downloading, replicating, and exploiting data. A user community may be developed in the platform to enable collaboration. Perhaps the most well-known platform is Google Earth Engine, but several others have developed including those focused on specific themes (see table 5). Many platforms are currently free and tools and processes developed on one platform may be transportable to another platform with reasonable levels of ease, which limits the risk of being 'locked in' to a specific platform (table 4).

Table 2. Earth observation data portals

Portal	Provider	Program	Satellites/ Sensors
Copernicus Open Access Hub	ESA/ European Commission	Copernicus	Sentinel-1, Sentinel-2, Sentinel-3
Earth Explorer	NASA/USGS	EOS	Landsat-8, MODIS, etc.
Earth Data	NASA	EOS	Landsat-8, MODIS, etc.
Worldview	NASA	EOS	Over 900 imagery layers, US sources
National Centres for Environmental Information	NOAA	JPSS, GOES, POES	AVHRR
Data Distribution Service	Japan/JAXA	ALOS	PALSAR-1, PALSAR-2
Earth Observation Data Management System*	Canada	Radarsat	RCM
Bhuvan	India	IRS	CARTOSAT
Catálogo de Imagens	China/Brazil	CBERS	CBERS-4
Discover	Maxar	-	WorldView, GeoEye
GeoStore	Airbus	-	SPOT-6/7, Pleiades, TerraSAR-X
Planet Explorer	Planet	-	PlanetScope, SkySat, RapidEye, Landsat-8, Sentinel-2
GPM Data	NASA/JAXA	-	GPM

Acronyms: Earth Observing System (EOS); Joint Polar Satellite System (JPSS); Geostationary Operational Environmental Satellite Program (GOES); Polar Operational Environmental Satellite Program (POES); Indian Remote Sensing Missions (IRS); RADARSAT Constellation Mission (RCM); China–Brazil Earth Resources Satellite (CBERS); Global Precipitation Mission (GPM). *Registration and access method to be confirmed.

Table 3. Earth observation thematic products and services

Portal/Product Name	Biodiversity	Climate change	Land Degradation	Int. Water	SFM	Description	Spatial scale	Temporal coverage
ESA CCI		■	■		■	Land cover	300 m	1992-2015
ECMWF		■				Gridded Climate Datasets	varied	varied
US NOAA PSD		■				Gridded Climate Datasets	varied	varied
IPCC		■				GCM Climate change Scenarios	varied	1961 to 2099
UMD GFC		■	■		■	Global forest change	30 m	2000-present
NASA			■			GPW - Gridded Population of the World v4	1 km	1995-2015
Trends. Earth			■			Provides access to global data suitable for land degradation	varied	varied

Portal/Product Name	Biodiversity	Climate change	Land Degradation	Int. Water	SFM	Description	Spatial scale	Temporal coverage
						assessment		
Protected Planet	■					Provides access to the World Database on Protected Areas (WDPA)	varied	present
JRC Global Water				■		Spatial and temporal distribution of surface water	30 m	1984-2015
DLR – GUF			■			Mapping of global settlement areas	12 m	present
FAO WaPOR			■	■		African continent above ground biomass, evapotranspiration, etc.	30 - 250 m	2009-present

Portal/Product Name	Biodiversity	Climate change	Land Degradation	Int. Water	SFM	Description	Spatial scale	Temporal coverage
CRW	■			■		SST, SST Anomaly, Coral Bleaching Hotspot, etc.	5 km	2014-present
GMW via UNEP Ocean Data Viewer	■				■	Mangrove extent, gain, and loss	0.8 arcsec	1996 - 2015, and 2016
DOPA	■					JRC database of protected areas	varied	present
GBIF	■					Species occurrences in space and time	varied	Historical - present
UN Biodiversity Lab	■					Information on the Aichi Biodiversity Targets and nature-based SDGs	varied	present
OBIS	■			■		Marine biodiversity	varied	present
Map of Life	■					Biodiversity analysis and	varied	present

Portal/Product Name	Biodiversity	Climate change	Land Degradation	Int. Water	SFM	Description	Spatial scale	Temporal coverage
						indicators		

Acronyms: ESA Climate Change Initiative (ESA CCI), European Centre for Medium-Range Weather Forecast (ECMWF), US National Administration for Oceanic and Atmosphere Administration Physical Sciences Division (NOAA PSD), Intergovernmental Panel on Climate Change (IPCC), National Aeronautics and Space Administration (NASA), University of Maryland Global Forest Change (UMD GFC), Joint Research Centre (JRC), German Aerospace Center - Global Urban Footprint (DLR – GUF), Coral Reef Watch (CRW), Global Mangrove Watch (GMW), Digital Observatory for Protected Areas (DOPA), Global Biodiversity Information Facility (GBIF), Ocean Biogeographic Information System (OBIS)

Table 4. Earth observation data processing platforms

Platform / Owner	Description	Access	Business Model
Google Earth Engine/ Google	Platform hosting archive of Landsat, Copernicus, and other public Earth observation data. Provides APIs and other tools to enable the analysis of large datasets.	Google account registration	Free, commercial licensing expected
SEPAL/ FAO	Platform providing Earth observation data processing tools. Infrastructure leverages Google Earth Engine and AWS for data access and processing.	Restricted	Free
Sentinel Hub/ PlanetLabs	Platform to browse and explore Sentinel-2, Landsat 8, DEM and MODIS imagery. Easy to use web-interface with tools to explore band combinations, spectral indexes, and other image effects.	Registration required	Free and commercial licensing
Thematic Exploitation Platforms/ ESA	Platforms to provide access to Earth observation data and thematic tools required to process data and generate products. Several TEPs are hosted in a DIAS, which provides data access and infrastructure.	Registration required	Free and commercial licensing
Copernicus Data Information Access Services (DIAS)/ European Commission	Multiple DIAS established with different private and public sector partners. Provides access to Copernicus and Landsat data and provides infrastructure to establish processing applications. Each DIAS provides some tools to enable users to process Earth observation data.	Registration required	Limited free Access with commercial licensing
Amazon Web Services/ Amazon	Makes available open Earth observation data and provides infrastructure to establish processing applications. No specific Earth observation tools are provided.	AWS account registration	Free data access, commercial infrastructure
Google Cloud/ Google	Makes available open Earth observation data and provides infrastructure to establish	Google account	Free data access, commercial

Platform / Owner	Description	Access	Business Model
	processing applications. No specific Earth observation tools are provided.	registration	infrastructure
Azure/ Microsoft	Makes available open Earth observation data and provides infrastructure to establish processing applications. No specific Earth observation tools are provided.	Microsoft Azure registration	Free data access, commercial infrastructure

2.3 Cost of satellite data

If none of the solutions presented in the above paragraphs can be used, when it comes to purchasing satellite data, a few important aspects need to be considered when planning the use for either long-term monitoring or ad-hoc site inspection:

- Availability as part of public services
- Size of the area and frequency of acquisitions
- Cost-benefit analysis

When a decision is made on acquiring satellite data for serving operational, specific purposes, the price indications given in the following tables (Table 5, Table 6 and Table 7) should be considered (cost of satellite data[13] as made available for June 2024).

[13] https://www.skyfi.com/pricing

Table 5. Daytime (optical) Images

Image resolution	Size (in cm)	Bands	Existing image		New Image		
			Price*	Min. Scene size	Price*	Min. Scene size	Priority Surcharge*
Ultra high resolution	<=15cm	4	$100	$1km^2$	N/A	N/A	N/A
Super high resolution	30-16cm	4	$22.5	$5km^2$	$30	$25km^2$	$60
Very high resolution	50-31cm	4	$8	$5km^2$	$12	$25km^2$	$24
High resolution	100-51cm	4	$5	$5km^2$	$8	$25km^2$	$16
Medium resolution	>100cm	4 or 8	$2.5	$5km^2$	N/A	N/A	N/A

Table 6. SAR Images

Image resolution	Size (in cm)	Existing image	
		Price/25 sq.km scene	Price/100 sq.km scene
Ultra high resolution	<=30cm	$3,250	N/A
Super high resolution	31-40cm	$1,760	N/A
Very high resolution	41-50cm	$950	$1,900
High resolution	100-51cm	$675	$1,500

Table 7. Stereo-pair Images

Image resolution	Size (in cm)	Existing image		New Image		
		Price*	Min. Scene size	Price*	Min. Scene size	Priority Surcharge*
Super high resolution	30-16cm	$45	5km^2	$60	25km^2	$120
Very high resolution	50-31cm	$14	5km^2	$24	25km^2	$48

3.0 Equipment and software

3.1 Unmanned Aerial Systems

As shown in the first report, aerial platforms, either manned or unmanned, can help to address a number of features: analysis of the land use evolution in time, assessment of the geological and environmental situation, search for seepage of water at the edges of landfills and mining sites, locating water resources and moisture anomalies, investigation of natural and artificial drainage systems, recognition and analysis of landslides, investigation of vegetation health or vitality, assessment of surface water conditions, inventory of sites suspected to be contaminated, search for undeclared well systems.

It was also shown that, in general, a typical workflow involving Flight Planning - Data Capture - Data Processing - Information Sharing is in place when dealing with aerial (manned or unmanned) systems. This workflow can be implemented by the organizations mandated to verify the conformance of groundwater exploitation or a service provider.

The main features when selecting a drone are the flight time and range, camera quality, RTK module availability and software compatibility. It is desired to choose drones that can fly for at least 30 minutes per battery charge. A high-resolution camera with a wide dynamic range and a quality lens is needed to capture clear, accurately-exposed aerial imagery. It is very important for drones to seamlessly integrate with GIS software for effective processing and further analysis of the images. RTK provide centimeter-level GNSS positioning that is essential for precision photography. RTK modules corrects location data of each picture recorded in real-time during flight for accurately positioned images.

When planning to use a drone (UAS) you need to take into account other additional costs, including insurance fees, registration fees, and license fees. For inspection purposes, professional or high-end drones equipped with large camera allowing photography or video recording can be used. Prices can range from

3000 to more than 10000 USD.

If services are preferred i.e. hire a company owning the required equipment and providing observation service, prices can range from 300 to 1000 USD for LIDAR survey and from 150 to 500 USD for photogrammetry.

Besides carefully checking the national laws applicable for an area of interest, piloting drones requires some training and / or qualification. Some organizations offer free of charge training for drone piloting. While training can be free of charge, some fees (e.g. 175 USD in the case of FAA) may apply for the examination.

3.2 Software

The main software needed to support operational activities is the GIS software. A Geographic Information System (GIS) is a computer system used to capture, store, manipulate, analyze, manage and present spatial or geographic data. GIS Software is the main software component needed to integrate (read data from multiple sources), process (perform basic or advanced processing of the data) and analyze (understand data and extract information based on their spatial relationship) EO data. It enables users to create maps and perform spatial analysis of the data. It can be desktop, mobile or cloud-based.

Cloud-based GIS is a software system that provides access to geospatial data and tools over the internet. It helps users to store, analyze, manage and generate maps on various devices such as mobile phones, personal computers, or tablets. Cloud-based systems are integrated with various technologies including GNSS, in-situ observation networks (such as groundwater level observation networks), and remote sensing EO systems allowing complex data analysis processes.

Desktop-installed GIS software is a software application that resides on a desktop computer. It includes features for managing and analyzing data that is stored on a local disk or accessed via web service over the internet, including data gathered by mapping, surveying, land control, business information.

Mobile GIS is a type of GIS software specifically designed for use on mobile devices such as tablets and smartphones. It is often used for mapping, field inspection, urban planning or general land control. Mobile GIS software enables users to access and analyze data from anywhere in the world, as well as to create, view, and share maps and other GIS data, based on a mobile internet connection (either GSM or Wireless Communication).

Hardware requirements and cost estimation

An important aspect when considering the desktop solutions is the hardware requirements to be considered for using the software. For Example, the most known GIS software, ESRI ArcGIS, website specifies the following typical configuration for hardware and basic software (Operating System)

1. Windows 10 or 11 Home, Pro or Enterprise Editions
2. X86 or X64 hardware architectures with min 2.2 GHz CPU, min 8 GB RAM
3. Video / Graphics adapter min 64 MB RAM
4. Display with 24 bit color depth

ESRI ArcGIS can be used in a cloud environment on Amazon WorkSpace Graphic Bundle or Microsoft Azure N-series Virtual Machines. The cost associated with the use of a cloud environment such as Amazon or Azure need to be estimated for each particular case using the tools made available by the cloud provider. Additional examples can be checked e.g. on CREODIAS website or Wekeo website.

Training programs and associated cost

In the case capacity building is preferred instead of service providers, governmental organizations in charge with ECA in general and illegal water abstraction in particular should consider:

1. Creating or extending their organizational structure by including the human resources needed to operate or manage additional computer infrastructure or access to cloud environments;
2. If not established by law, concluding agreements on accessing various governmental and local administration data (see table 1 for references);
3. Purchasing UAS equipment and / or piloting and survey services (indications on training and piloting certification are given in the previous sections);
4. Training the selected personnel for using the software and data needed to implement the designed workflows; an average cost of 200/ USD / day / individual should be considered when planning the training and an average duration of 10 days / individual.

Training curricula

For the cases when the training of the personnel is planned, a curricula containing the elements summarized in Table 8 can be considered:

Table 8. Personal training course

Task	Subtask	Hours
Groundwater	Occurrence and movement of groundwater	2
	Interaction between surface water and groundwater	2
	Field investigative methods	2
	Characterize groundwater systems from aquifer tests	5
	Computer modeling of groundwater flow	5
	Plan and manage groundwater extraction	4
Remote sensing	Types of remote sensing and spectral domains: active /	5
	passive; optical / microwave	
	Characteristics of remote sensing (satellite or aerial) data	5
	Processing levels: raw, calibrated, accurate geocoding, ARD (Analysis-Ready Data)	10
Geospatial data processing	Data storage and access: files, web services, cloud	3
	Reference systems and coordinates; geocoding	2
	Data structure, storage formats and visualization	5
	Spatial analysis and geoprocessing	5
	Satellite data processing and information extraction for	5
	Total allocated hours	**60**

Capacity building strategy

- have general knowledge on groundwater and remote sensing and use external service providers for detection (continuous processes) and quantification; perform inspection activities;
- have deeper knowledge on groundwater and remote sensing, externalize detection processes, keep detailed analysis and inspection;
- ensure full capacity for detecting and inspecting on premises, using own personnel and hardware and software infrastructure;
- have general knowledge on groundwater, externalize services for detection and quantification tools running in a cloud environment, perform inspection.

Cost of software

As shown in the previous paragraph, some of the software packages are distributed under commercial licenses. Their cost may vary depending of the licensing and installation type. This can be a permanent one, updated periodically or a yearly fee providing access to a specific type of software. The installation type may vary from desktop to mobile or cloud-based. A permanent license would go from few hundreds to tens of thousands dollars per user. When yearly based licensing is considered, this this can range from few dollars to few thousands per year per user.

Commercial and open source software tools are available to process, integrate, analyze, and visualize Earth observation data, which can be used locally and in cloud computing environments. Table 9 summarizes commercial and open source software tools. Several open source tools are well developed in terms of their capabilities, documentation, and user communities. Many commercial software tools are available with discounts for non-profits and environmental projects.

Table 9. Selected remote sensing and GIS software

Name	Publisher	Main purpose	License	Cost	Complexity
ArcGIS	Esri	GIS analysis and cartography	C	$$$	■■
ENVI	Harris Geospatial	Image processing for most types of remote sensing data	C	$$$	■■
ERDAS	Hexagon Geospatial	Image processing for most types of remote sensing data	C	$$$	■■
Geomatica	PCI Geomatics	Image processing for most types of remote sensing data	C	$$$	■■

Name	Publisher	Main purpose	License	Cost	Complexity
GRASS	OSGeo	GIS and image analysis and visualization	OS	N	■■
TerrSet	Clark Labs	GIS and image analysis and cartography	C	$$	■
ILWIS	52°North open source software initiative	GIS and remote sensing analysis	OS	N	■■
Manifold	Manifold	GIS analysis and cartography	C	$	■
Open Foris	FAO	Land cover and land user data collection	OS	N	■
Orfeo Toolbox	CNES	Image processing for most types of remote sensing data	OS	N	■■
QGIS	QGIS	GIS analysis and cartography	OS	N	■■
Sentinel Toolboxes	ESA	Toolboxes for the scientific exploitation of Sentinel missions	OS	N	■■■
OS = open source; C = commercial. Cost rating: $$$ > $5 000; $$ ≤ $5 000; N = none/free. Complexity rating: ■ = beginner user, training manuals; ■■ = expert user, good documentation; ■■■ = expert user. List of software is not exhaustive and not an endorsement. Source: adapted from Aguilar-Manjarrez et al. 2018					

4.0 Workflows

In the previous sections and reports, a number of considerations and indications are given in relation with analysis methods (see report 2 on detection methods) and data required to produce information required information for each of the cases considered, in close correlation with the information requirements defined. In this section, indications are given on the different cases and the levels of awareness defined by IMPEL that can be reached i.e.

- Level 1 (awareness): only suitable for filtering in potential illegal groundwater activity abstraction. Will help understand if more detailed inspection techniques are required;
- Level 2 (advanced): ability to map clearly the location of illegal groundwater activities;
- Level 3 (specialist): ability to clearly indicate the clusters and scale of illegal groundwater activities for prioritization by the regulatory authority;
- Level 4 (expert): ability to provide sufficient evidential data to automatically fine without local inspections activities.

4.1 Data, equipment and methods

Simple analysis leading e.g. to specific information on a specific site, emphasizing quantitative or qualitative indicators (such as vegetation phenology) can be performed based on simple computations doubled by CAPI (Computer-Aided Photo Interpretation) on workstations with adapted configurations (storage and computing power).

Tasks involving continuous monitoring of large area and by consequence processing of Image Time Series (ITS) could require access to complex infrastructures such as cloud-based platforms storing both data and processing resources. A short list of such platforms was given in the previous sections of this document. A special attention should be given to the newly developed Copernicus Data Space Ecosystems platform providing access to all Copernicus Space and in-situ data, as well as to a large variety of services allowing access and processing of specific data either by downloading of individual scenes or in-cloud high-performance computing.

4.2 Awareness and operations

The detection and the monitoring of non-authorized uses like irrigation and abstractions are still challenging for water managers and water authority of EU member countries. The qualification of e.g. irrigation as “non-authorized” implies having access to a database of individual users’ water rights and spatial independent information to verify, by cross-checking, their compliance.

For example, the monitoring and identification of irrigated areas involves in-situ inspections and possibly the use of water meter records when available. When water meter is not available, the water consumption is estimated indirectly based on the identified crops and an average crop-specific, known water requirement.

Table 10 summarizes the workflows recommended to reach the specific awareness levels defined by IMPEL, focusing the illegal use cases when the use of water is done without any water right or use with an on-going but not yet finalized application (considering the observables and detection methods presented in the previous report).

Table 10. Workflows and awareness levels

	Level 1 Awareness	Level 2 Advanced	Level 3 Specialist	Level 4 Expert
Agriculture	Detection of activity in area with no water rights based on vegetation phenology analysis	Repeated observations confirm agricultural Activities and information on crops is derived based on RS	Estimation of the volume of ground water abstraction is estimated based on RS, crop information and meteo data	A water rights data base confirm missing permit; Inspection based on UAS confirm presence of water abstraction points
Industrial	Leakage or pollution phenomena detected based on aerial or satellite RS around known installations	Repeated observations confirm leakage on ground or pollution - water and/or soil - around known installations	Sources are identified for each of the impacted soil or water elements based on intelligence derived from RS and in-situ EO data	On-ground inspection still needed for confirming inadequate design or operation. UAS could confirm/facilitate assumptions.
Construction	Affected structural integrity is detected based on InSAR monitoring data	Construction site is identified and repeated observations confirm the trends	Integration of in-situ observations confirm quantitative and qualitative decrease	On-ground inspection still needed for confirming inadequate design or operation. UAS could confirm/facilitate assumptions.
Mining	Emissions, subsidence or surface water pollution effects are detected based on RS or crowdsourcing	Effects are confirmed by repeated observations and the location of the mining site is also detected	All phenomena identified in space and time based on RS and mining site information is correlated	Solid waste dumps and other environmental impact is measured based on UAS observations

	Level 1 Awareness	Level 2 Advanced	Level 3 Specialist	Level 4 Expert
Domestic	Subsidence, dry streams or other effects are detected based on public monitoring data	Environmental imp act is confirmed by repeated analysis of public monitoring data	Identified area is further analyzed based on public data and planned observations and analysis reports	Water abstraction points and lack of installations are confirmed based on UAS inspection
Sewage	Polluted surface water or contaminated soil detected based on RS or crowdsourcing	Pollution of water or soil is confirmed by repeated observations and sewage system is identified	Correlation with industrial facility / source is made and pollution is localized in space and time	Pollution effects and sources are confirmed based on UAS inspection

As shown in table 10, initial awareness is built based on the detection methods associated to each case (awareness level). Repeated observations and association with specific prone area can lead to the advanced level. Quantification based on planned observations and ancillary data is done for reaching the specialist level. An expert level can be reached after confirmation based on in-situ or aerial inspections relying on UAS.

5.0 Concluding remarks

The report contains information on the different ways data can be accessed and processed in order to derive information, as needed for reaching the following levels of awareness defined by IMPEL:

- Awareness Level 1: only suitable for filtering in potential illegal groundwater activity abstraction. Will help understand if more detailed inspection techniques are required.
- Advanced Level 2: ability to map clearly the location of illegal groundwater activities.
- Specialist Level 3: ability to clearly indicate the clusters and scale of illegal groundwater activities for prioritization by the regulatory authority
- Expert Level 4: ability to provide sufficient evidence to automatically fine without local inspections activities

Reference is made to EO data and existing cloud platforms and software allowing the implementation of the recommended workflows associated with each level of awareness. For data and instruments, indications are given on access methods and cost. Also, indications on skills required for the operation and training cost are given as well as on the infrastructure needed for deriving the actionable information for tackling the nonconformities.

However, the first option should be the one relying on or including in the operational workflows the various EU-level developed services, such as the EO Governmental service for the data and the SatCen portfolio of services for detailed analysis.

Even the well-known approach of building capacity inside the organizations mandated with law enforcement can always be a valid one, recent development of data/ thematic platforms storing EO data as well as analysis tools need to be considered with priority as it can ensure more flexibility and reduce implementation cost and duration especially when combined with workload sharing with service providers covering e.g. monitoring activities or advanced analysis of different area of interest that are prone to illegal abstraction.

Annexes

Annex I. EO Data Platforms

Name, URL	Available Data	Functionality	Access	Funding and legal
CREODIAS https://creodi as.eu/	Copernicus Services, Envisat, Jason-3, Jilin-1, KOMPSAT, KazEOSat, Landsat-5, Landsat-7, Landsat-8, SMOS, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, WorldView3	Repository; processing: virtual Machines (VMs), virtual storage volume; platform services	fee-based use; free test version available; the three cloud-based elements are available after single-sign-on	part of the DIAS initiative; on behalf of the EU; EU legal basics full-filled
sobloo https://sobloo .eu/	Copernicus Services, Muscate, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P	Processing on demand: automated data fusion; radio- und geometric processing; computing statistics; image interpretation (object detection) further services, designed and shared by the community	Fee-based: data: Pleiades and FluxVision (Population);infrastructure: managed and cloud services (main services); desktop version; professional services (e.g. statistics)	Part of the DIAS initiative; On behalf of the EU/Copernicus, EU legal basics full-filled

Name, URL	Available Data	Functionality	Access	Funding and legal
Mundi Web Services https://mundi webservices.c om/	Copernicus Services, Landsat-8, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, VHR EUSI	Open Telekom Cloud: versions/ enteties: free: EO data search and download; fee-based include extended: WPS processing, time series, geometric correction, automated processing, ready-to-use workflows and algorithms; open source tools: Orfeo Tool Box, ESA SNAP	registration required; free access to platform is limited: Sentinel and Landsat data and open source tools are available; fee-based: high and very high resolution data, advanced and extensive processing and cloud storage and functions	Part of the DIAS initiative
ONDA DIAS https://www.o nda-dias.eu/c ms/	Copernicus Services, Deimos-2, Envisat, KOMPSAT, Landsat-8, MAXAR Konstellation, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P	virtual server can be individually designed; with consulting; fee-based tools depend on the virtual server /package designed	cloud services only fee-based available; registration required; free and fee-based versions (upon request)	Part of the DIAS initiative

Name, URL	Available Data	Functionality	Access	Funding and legal
WEkEO https://www. wekeo.eu/	Copernicus Services, Einladen anderer/eigener Daten möglich, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P	free: access to Copernicus Data (discover and download), Jupyter Notebooks and user support; fee-based: access to cloud-based services and environment (VMs and processing tools), free networking; Integration and combination of Jupyter Notebooks, VMs, Desktop applications and different data sources (other than Sentinel)	1. registration required 2. free account and fee-based ackages/accounts available (6 “sizes”); many tutorials available, see https://www.youtube.com/c hannel/UCvS3VvKmMKs1M2 ZkmQPyRlw	Part of the DIAS initiative; EU funded

Name, URL	Available Data	Functionality	Access	Funding and legal
Sentinel Hub https://www.sinergise.com/	Copernicus Services, DEM, Envisat, GeoEye, Landsat-5, Landsat-7, Landsat-8, MAXAR Konstellation, MODIS, Pleiades, SPOT, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, WorldView	EO Browser: EO data search & selection, visualisation image download, statistics, 3d display, "highlight" cases in the education mode, licences for commercial EO data; Bring your own Data	DATA / EO Browser: limited use without registration: with registration: timelapse, high resolution image download, pin saving and sharing, story builder and distance measurements; commercial data can be ordered via pre-purchased quotas, pricing per km^2 PROCESSING: fee-based upgrade needed	EU funded
CODE-DE https://code-d e.org/de/	Copernicus Services, Copernicus beitragende Missionen, DEM, Landsat-5, Landsat-7, Landsat-8, MODIS, RapidEye, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P	See https://www.notion.so/b5faaef258dd4aad8a6526157b70abba	registration required, then search, display and download for free; use of pre-installed processors; Jupyter Notebook interface and data cubes requires special account	

Name, URL	Available Data	Functionality	Access	Funding and legal
UP42 https://up42.c om/	Pleiades, SPOT6/7, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, weitere Kollektionen	provides many processing blocks relevant in the environmental context: pre-processing; indices, bandmath, statistics; machine learning; algorithms of the provider and of users	(free) registration required for accessing interface/ platform; free starter version; larger packages payed in a credit system, which is calculated after consumption (you only pay what you use)	Airbus (?)
Panda https://panda. copernicus.eu/ web/cds-catal ogue/panda	Deimos-2, Envisat, KOMPSAT, Landsat-5, Landsat-7, Landsat-8, Pleiades, SPOT, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, WorldView, weitere Copernicus Contributing Missions (s. Zusatz)	no processing functionality available; Main features: Search (including diverse filtering options) and display of EO Data; queries are organised in so-called shopcarts; saving and downloading data (collections); option only for anonymous registered users	registration of authorized users needed for save and download; no commercial option	EU funded

Name, URL	Available Data	Functionality	Access	Funding and legal
Worldview https://worldv iew.earthdata. nasa.gov/	use of numerous datasets (of different levels) of NASA's "Earthdata"; for lists and descriptions see "Add layers" in the Application	no EO data processing without login features/ options: EO data search (with filtering functions (location, time, events, data sets)) and display; compare (sets of) images; create time series (with export option for GIFs); distance measurements (ruler); data download and sharing (also snapshots)		
EOC Geoservice https://geoser vice.dlr.de/we b/	Landsat-5, Landsat-7, Landsat-8, MODIS, MetOpA-C, RapidEye, SRTM, Sentinel-1, Sentinel-2, Sentinel-5P, TanDEM-X, TerraSAR-X	discover, visualize, and direct download for a selection of geospatial data	Free; no registration required	

Name, URL	Available Data	Functionality	Access	Funding and legal
Copernicus Open Access Hub https://scihub. copernicus.eu/	previously: Sentinels Scientific Data Hub; Sentinel-1, Sentinel-2, Sentinel-3,Sentinel-5P	functions of the map interface can be used after registration; synchronous access to the latest products (~3 months); asynchronous access to historical data; Sentinel-product search (with pre-defined filtering options), display, inspection and download (also in batch processes)	Open access after self-registration for anybody; all products are free	funded by the EU, connected to DIAS platforms
EarthExplorer https://earthe xplorer.usgs.g ov/	AVHRR, EO-1, IKONOS-2, Landsat, MODIS, OrbView-3, SPOT, Sentinel-2, VIIRIS, weitere Datensets (keine Satelliten)	no data processing; search of satellite, aircraft, and other remote sensing inventories; interactive and textual-based query capabilities	1. EO data search and display without registration 2. Download and order requires registration 3. registration is free	US
G-Portal https://gportal .jaxa.jp/gpr/	operational Satellites from the Japanese program: ADEOS/ ADEOS-II, ALOS, ALOS2, GCOM-W1, GPM constellation satellites, MODIS, SLATS,	no processing on site; search optional filtered by physical quantities/ spacecraft/ sensor/ saved condition; save and download search results/	service is free of charge search without registration download with registration	

Name, URL	Available Data	Functionality	Access	Funding and legal
	TRMM	products		
openEO Platform https://opene o.cloud/	Landsat 1-8, Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, see https://openeo.cloud/data -collectio ns/ for all data sources	collection of processing tools and EO datasets; unites several platforms/ expertises of partners: Terrascope, SentinelHub, Data Cube Facility Services, EODCs cloud infrastructure and HPC experience for structure see image; can be used with different programming languages and environments: R, JavaScript, Phyton, JupyterLab, openEO Platform Editor	free of charge for 30 days to test the platform; no use case required; free of charge when sponsored by ESA for 90 days; enrollment required for specific use cases, larger processes and regular use	funded by ESA

European Union Network for the Implementation and Enforcement of Environmental Law

Tackling illegal GW drilling and abstractions (TIGDA)
"Earth Observation Techniques for the Detection of Illegal GW Activities"

Annex 5 - Summary of Recommendations on Methods, Data, Infrastructure and Capacity for Tackling Illegal Groundwater Use

Date of report: 05.10.2024

Report number: 05

Introduction to IMPEL

The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) is an international non-profit association of the environmental authorities of the European Union (EU) Member States, and of other European authorities, namely from acceding and candidate countries of the EU and European Economic Area (EEA). The association is registered in Belgium and its legal seat is in Brussels, Belgium.

IMPEL was set up in 1992 as an informal Network of European regulators and authorities concerned with the implementation and enforcement of environmental law. The Network's objective is to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation. The core of the IMPEL activities concerns awareness raising, capacity building and exchange of information and experiences on implementation, enforcement and international enforcement collaboration as well as promoting and supporting the practicability and enforceability of European environmental legislation.

During the previous years IMPEL has developed into a considerable, widely known organisation, being mentioned in a number of EU legislative and policy documents, e.g. the 8th Environment Action Programme that guide European environmental policy until 2030, the EU Action Plan: "Towards a Zero Pollution for Air, Water and Soil" on Flagship 5 and the Recommendation on Minimum Criteria for Environmental Inspections.

The expertise and experience of the participants within IMPEL make the network uniquely qualified to work on both technical and regulatory aspects of EU environmental legislation.

Information on the IMPEL Network is also available through its website at: www.impel.eu

Title of the report: Recommendations for Earth Observation Methods and Data Against Scale of Illegal Activity	Number report: 2024/04
Authors: Constantin Radu Gogu Ion Nedelcu	**Report adopted at IMPEL General Assembly Meeting**: Date and location **Total number of pages: 44** Report: 44

Executive Summary

With a general objective "to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation", the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) funded the project *Tackling illegal GW drilling and abstractions* (TIGDA) which aims to share knowledge and good practices on how to manage GW drilling and abstractions.

Under the TIGDA project the work package *Earth Observation Techniques for the Detection of Illegal GW Activities* (EOWP) aims to review the different types of earth observation (EO) methods and data that can be used for the detection of illegal GW activities.

As formulated by IMPEL, within the scope of this project the definition of *illegal GW activity* covers any combination and types of illegal drilling illegal abstraction, including activities that could result in the direct input of pollutants to GW, for example discharges to wells, boreholes or soakaways.

This report is the final one and contains a summary of recommendations on methods, data, infrastructure and capacity for tackling illegal groundwater use and should be read in connection with the four reports prepared under the TIGDA project for details on each of the topics included and the glossary of terms and acronyms accompanying those reports.

TABLE OF CONTENTS

1. Introduction

The report contains information on the different ways EO data can be accessed and processed in order to derive information, as needed for the following levels of awareness while tackling the illegal groundwater abstraction cases:

- Awareness Level 1: only suitable for filtering in potential illegal GW activity abstraction. Will help understand if more detailed inspection techniques are required.
- Advanced Level 2: ability to map clearly the location of illegal GW activities.
- Specialist Level 3: ability to clearly indicate the clusters and scale of illegal GW activities for prioritisation by the regulatory authority
- Expert Level 4: ability to provide sufficient evidence to automatically fine without local inspections activities

This is the final report summarising the facts and recommendations in the previous four reports prepared under the TIGDA project of IMPEL:

- Earth Observation Techniques Accessible within EU for the Detection of Illegal Groundwater Activities;
- Identification of Earth Observation Methods and Data for Detection of Illegal Groundwater Activities;
- Obtaining and Processing Earth Observation Data;
- Recommendations for Earth Observation Methods and Data Against Scale of Illegal Activity.

A glossary of terms and acronyms accompany those reports and can be used while reading them for a common understanding of the terms used.

The facts and recommendations in this report are grouped into four sections addressing the rationale of the study i.e. what can be illegal when groundwater abstraction is in focus, how EO data and various methods can help detecting and quantifying the non-conformal groundwater use, what are the candidate methods and data needed for reaching the four awareness levels defined by IMPEL (awareness, advanced, specialist and expert). In the final section, a number of concluding remarks as well as indications on possible ways forward are given.

This report should be read in connection with the four reports mentioned for details on each of the topics included.

2. Why is the detection of illegal groundwater activities important

Basic attributes of water rights that circumscribe the extent of the access, use, and control rights granted to the holder of the water right [Fondacion Botin, 2020] can be grouped into:
-those describing the resource - quantity and quality of the water,
-the source and location - surface water or groundwater, desalinated or reused waters,
-the type of use (e.g. irrigation, domestic),

-the duration of the entitlement - temporary vs permanent and
-the management and administration of the right - ownership, security.
According to the same authors, the illegal water use as a term can refer to any taking of water - the entire range from abstraction to consumption - in violation of existing regulations; the same is qualified also as non-authorised, unauthorised, unlawful, theft, stealing, smuggling, misappropriation or even unaccounted water.

Among the illegal use cases, the following categories can be specified:
-Use of water without any water right or use with an on-going but not yet finalised application;
-Use of water beyond the established limits of the water right;
-Non-compliant changes to the characteristics of the water right, e.g. timing, purpose, location, trading.

As the second and the third categories involve detailed in-situ investigations, in this report the illegal use will be treated in the sense of the first point i.e. the use of water without any water rights or with an on-going but not yet finalised application.

It was estimated that as many as half of the existing water wells in European Mediterranean countries may be unregistered or illegal and the main drivers of the illegal use are then net benefits, the gaps in governance and institutions and the social norms [Fondacion Botin, 2020].

The many effects of the illegal use include degradation of water ecosystems, depletion of resources for legal use, decrease in water quality. While trying to avoid the numerous effects of the illegal use, it is always necessary first to detect and then to deal with the identified cases. When speaking about detection, a number of actions can be taken, including setting up a water rights system, control of water use, the registration of water uses into databases, monitoring of water abstraction by different means, including remote sensing and integrated management.

3. How EO can help the detection of illegal groundwater abstractions

3.1 The groundwater in the water cycle

More than 70% of the earth's surface is covered by water. However, only 3% of this reserve is fresh water that can be used for human consumption. 90% of the earth's fresh water resources is contained in groundwater and ice, and only 10% is contained in surface reservoirs as rivers, lakes, wetlands and streams.

The water cycle (Fig. 1), also known as the hydrologic cycle or the hydrological cycle, is a biogeochemical cycle that describes the continuous movement of water on, above and below the surface of the Earth. The mass of water on Earth remains fairly constant over time but the partitioning of the water into the major reservoirs of ice, fresh water, saline water (salt water) and atmospheric water is variable depending on a wide range of climatic variables.

The water moves from one reservoir to another, such as from river to ocean, or from the ocean to the atmosphere, by the physical processes of evaporation, transpiration, condensation, precipitation, infiltration, surface runoff, and subsurface flow. In doing so, the water goes through different forms: liquid, solid (ice) and vapour. The ocean plays a key role in the water cycle as it is the source of 86% of global evaporation.

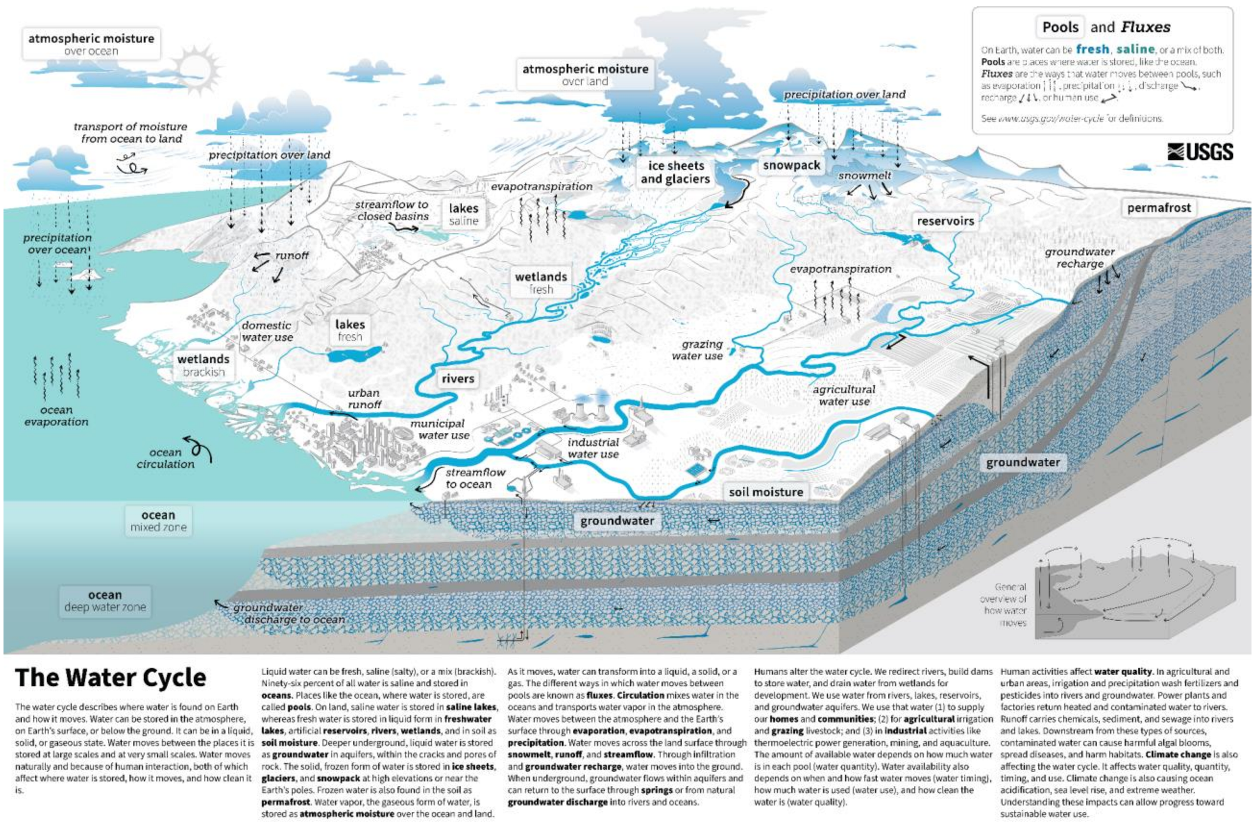

Fig. 1 The water cycle (source:USGS[14])

As the main source of freshwater easily available for human activities, groundwater has a significant role in the water cycle. The processes of the water cycle are difficult to monitor, making the groundwater management a complex process. Water cycle (Fig. 1) can be summarised through the water balance equation:

$$P\ (\pm W + H_i) = E_t + Q + I + U + \triangle R$$

P - precipitation – main water source (rainfall and snow) entering in the hydrological basin;

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[14] https://www.usgs.gov/media/images/water-cycle-png

W - groundwater flow input, another catchment natural water input (in some cases large water volumes are passing from a catchment to another in spite surface water flow established processes);
H_i - human intervention;
Q - direct water flow (in river network);
I - infiltration into soil;
U - human use;
$\triangle$R - storage of the water catchment;
E_t -water catchment total evaporation (called evapotranspiration);

$$E_t = E_a + E_s + E_i + E_p + E_z$$

E_a - surface water evaporation (rivers, lakes, sea);
E_{s-} - soil surface water evaporation;
E_i - water evaporation from rainfall intercepted by green cover (plants) and urban fabric;
E_p - plants transpiration (water located in soil);
E_z - water evaporation from surfaces covered by ice/snow;
In order to derive quantitative information on the Storage i.e. quantity of water to be retrieved underground or groundwater, it is necessary to retrieve information on the P, Q and E_t as well as all the other variables of the water cycle equation. The capacity of Earth Observation (EO) systems to help derive this information is presented in the following sections.

The combined effects of industrial development, urbanisation and population affect the natural landscape as well as the behaviour of groundwater and surface water. The hydrological cycle is greatly modified as a result of continuous urban development and the need to supply water to the population. This not only includes the supply but also the sewerage, collection and waste water management. It has been observed that the hydrological cycle has become much more complex in the urban environment due to anthropic influences on the environment.

Within the urban water circuit, two main sources of water are recognized: water from precipitation and water from the municipal supply. Municipal water is often imported from outside the urban area. This is brought into the urban environment and distributed to various consumers. A fraction is lost in the urban environment groundwater and the rest is used by the population - transformed into municipal wastewater and possibly returned to the surface water or groundwater. Water from precipitation goes through processes of interception, accumulation and evapotranspiration. Some seeps into the soil (contributing to soil moisture and aquifer recharge) and some is partially converted to surface runoff. These in turn are transported to the water collectors by means of natural or constructed transport systems (collector systems). These two sources can be quantified in studies that address problems related to the urban water balance (Marsalek J. et al. 2006).

Either passive or active, space systems proved to bring significant contribution to the estimation of the variables in the water cycle equation. Ensuring EO for the water cycle is a priority for the space agencies all over the world and global EO programmes given their relevance for the essential climate variables[15] and adaptation to climate change actions. The figure below shows a self-explaining graphic on types of EO systems – space (Fig.2), aerial, in-situ that are considered relevant for the water cycle studies.

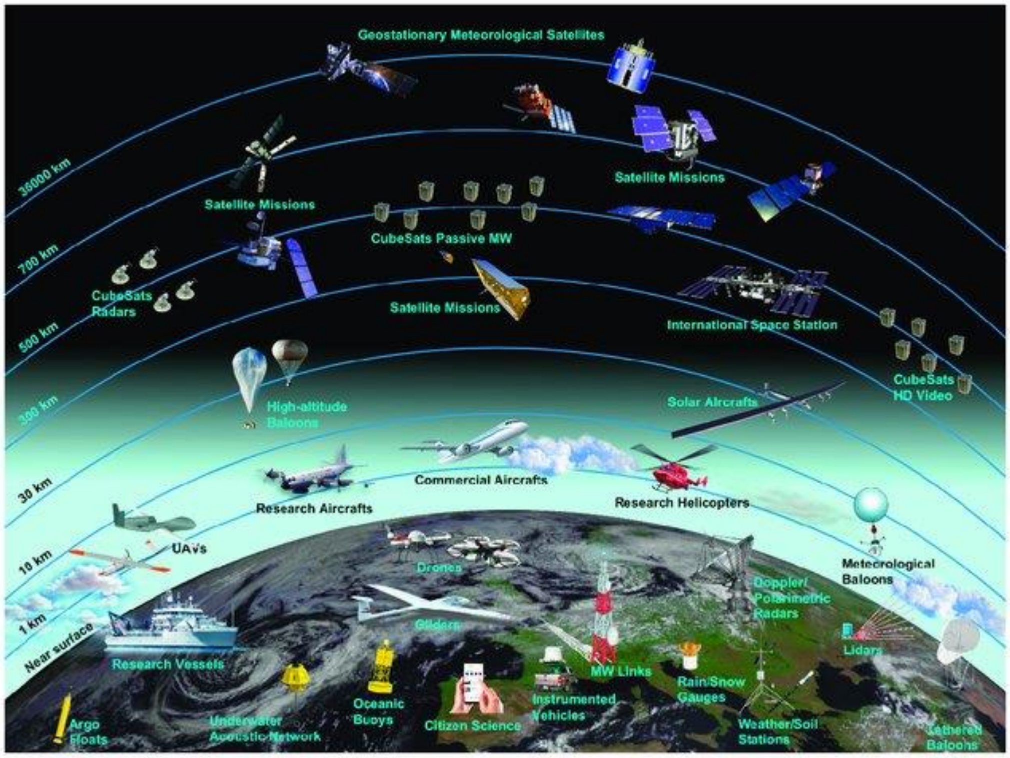

Fig. 2 EO Systems for the water cycle

When it comes to local studies related to groundwater, of particular interest are the geodetic techniques[16]. The most relevant geodetic techniques for observations related to groundwater resources are resumed in the figure (Fig.3) below: GPS observations, gravimetry and InSAR.

3.2 In-situ observations

Hydraulic head, often simply referred to as “head”, is an indicator of the total energy available to move groundwater through an aquifer. Hydraulic head is measured by the height to which a column of water will stand above a reference elevation (or “datum”), such as mean sea level. A water-level measurement made under static (non pumping) conditions is a measurement of the hydraulic head in the aquifer at the depth of the screened or open interval of a well (Fig. 4). As the hydraulic head represents the energy

[15] https://www.earthdata.nasa.gov/learn/backgrounders/essential-variables

[16] https://www.unavco.org

of water, groundwater flows from locations of higher hydraulic heads to locations of lower hydraulic heads. The change in hydraulic head over a specified distance in a given direction is called the "hydraulic gradient."

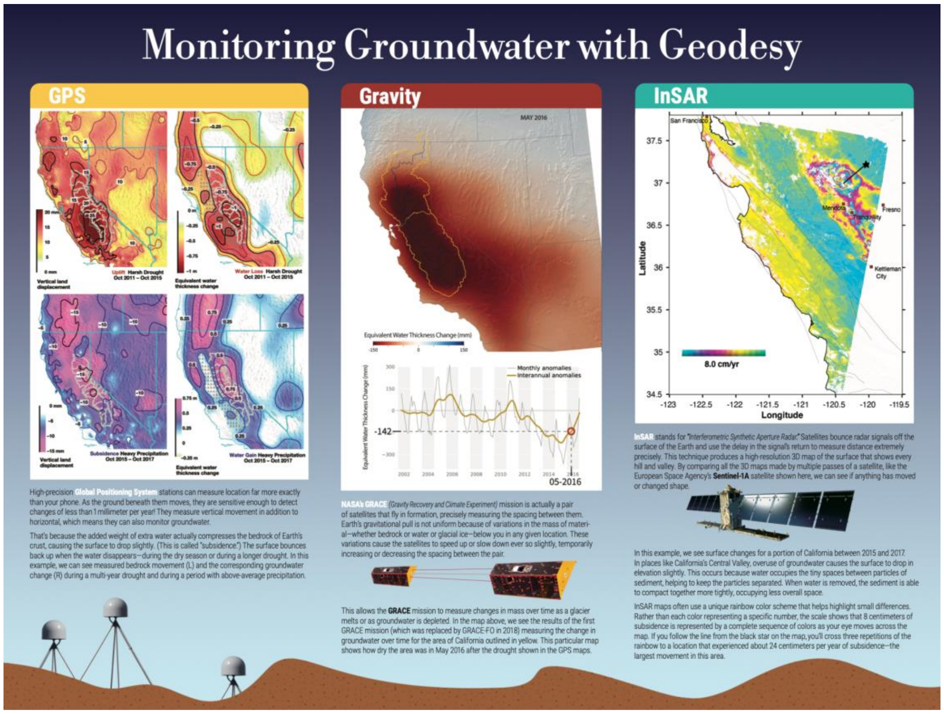

Fig. 3 Geodesy resources for groundwater monitoring

Two general types of aquifers (unconfined and confined) are recognized (Fig. 5). In unconfined aquifers, hydraulic heads fluctuate freely in response to changes in recharge and discharge. Hydraulic heads measured in wells completed in the upper part of an unconfined aquifer help define the elevation of the water table, which is the top of the saturated zone. In confined aquifers, water in the aquifer is "confined" under pressure by a geological body that is much less permeable than the aquifer itself. Hydraulic heads in tightly cased wells completed in confined aquifers often rise above the elevation of the top of the aquifer (Figure 6).

These hydraulic heads define an imaginary surface, referred to as the potentiometric surface, which represents the potential height to which water will rise in wells completed in the confined aquifer. Groundwater levels (hydraulic heads) are controlled by the balance among recharge to, storage in, and discharge from an aquifer. Physical properties such as the porosity, permeability, and thickness of the rocks or sediments that compose the aquifer affect this balance. Climatic and hydrologic factors such as the timing and amount of recharge provided by precipitation, discharge from the subsurface to surface-water bodies, and evapotranspiration, participate in the groundwater balance. When the rate of recharge to an aquifer exceeds the rate of discharge, groundwater levels (hydraulic heads) will rise. Conversely, when the rate of ground-water withdrawal or discharge is greater than the rate of groundwater recharge, the water stored in the aquifer becomes depleted and groundwater levels (hydraulic heads) will decline.

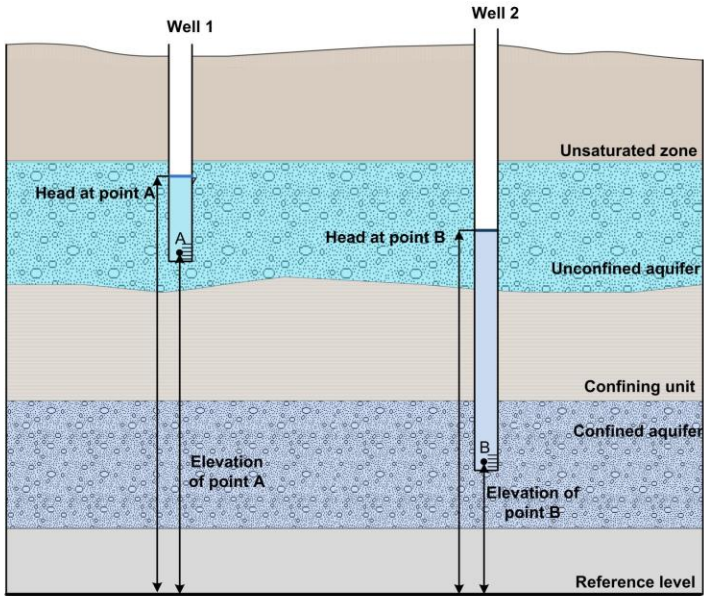

Fig. 4 The relation between hydraulic heads in two observation wells—Well 1 screened in an unconfined aquifer and Well 2 screened in a confined aquifer. Hydraulic heads in each of these two aquifers are determined by the hydraulic head in the well relative to a vertical datum—in this case, Reference level (modified after IGRAC,2006)

A monitoring system is a platform where level and quality records that describe groundwater resources are generated, made available, and evaluated. These records are consistent, representative and long lasting.

Two main types of wells can be available for groundwater monitoring:

- Monitoring wells (wells with single or multiple piezometers);
- Water supply wells (for domestic, municipal, agricultural or industrial water supply).

In practice, in most situations the hydraulic head is not measured directly. There is only one situation when the hydraulic head is directly measured and this situation is related to the topographical measurement of the springs. In all other situations, when boreholes and wells are used, the measurement provides the depth to groundwater level (DGW). Also, the elevation of the well cap could be obtained by topographical measurement (levelling). There are several types of instruments able to measure the depth to groundwater and the most common is the water-level dipper.

Precise spirit levelling

The most precise method of measuring elevation changes at land surface is the precise leveling. This method consists in determining the elevation in each benchmark belonging to a network at land surface. By repeated surveys of the network of benchmarks at different time intervals, it can be revealed whether vertical movements appeared compared to the control benchmarks. The control benchmarks are placed in a stable area consisting of consolidated rocks, outside the area affected by displacements.

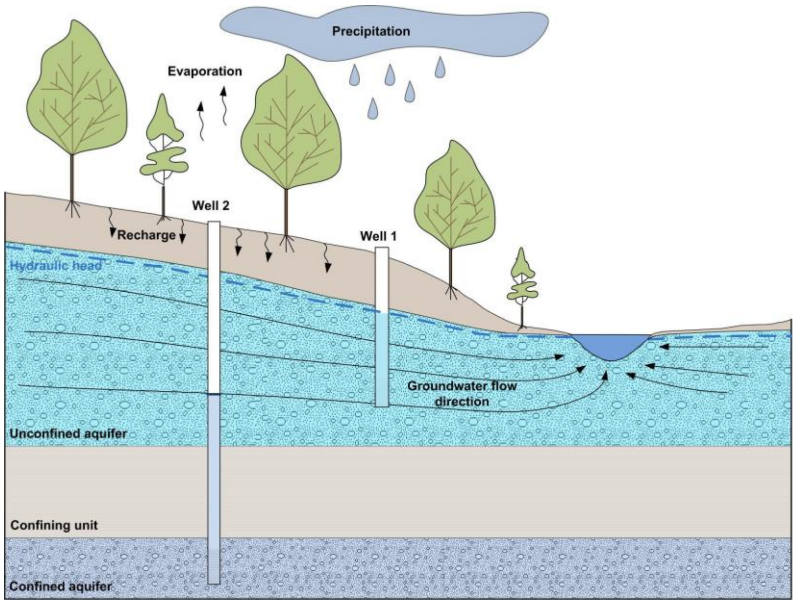

Fig. 5 Hydrogeological cross-section with wells installed in confined and unconfined aquifers

Borehole extensometers

Vertical borehole extensometers are used to measure the movement or change of the vertical distance between the bottom of the borehole and the ground surface, considering the thickness of sediments or rocks.

Ground penetrating radar

Ground penetrating radar (GPR) is an electromagnetic pulse reflection method based on physical principles similar to those of reflection seismics. It is a geophysical technique for shallow investigations with high resolution which has undergone a rapid development during the last two decades. This technique involves transmitting and receiving electromagnetic waves to and from the subsurface. The data collected can be used to create a cross-sectional image of the subsurface as well as to give estimates of the depth to the water table in gravel, sand, limestone, and sandstone. GPR can be also used to determine the location, orientation, size, and shape of underground metal and plastic pipelines, cables, and other buried manmade objects.

Gravimetry

This technique measures the gravitational field of the subsurface using a gravimeter. The data collected can be used to identify changes in the density of subsurface materials. Gravimetry or magnetics are ideal methods to detect faults, if these faults cause sufficient large lateral contrasts in density or magnetization (Tanner and Brandes, 2020). The application of both methods is based on the geological interpretation of anomalies in the Earth's gravity or magnetic field. Gravity and magnetic anomalies are defined as the deviation of the observed quantities, i.e., gravitational acceleration (or simply gravity) and magnetic flux density, respectively, from the expected value of a reference Earth. Although the magnetic flux density is a vector field, magnetic exploration is often based on the interpretation of the anomalies of the Earth's total magnetic field. Change in groundwater storage is often the largest source of uncertainty in catchment-scale hydrological models. On the sub-catchment scale, spatial and temporal variations are difficult to constrain in the absence of direct piezometric measurements. There is significant interest in non-invasive methods for measuring fluctuations in groundwater levels (hydraulic heads). Time-lapse gravimetry is a promising geophysical method that is well-suited to such investigations (Landon and Halloran, 2022).

Global Navigation Satellite Systems (GNSS)

Since the 1980s, when the U.S. Global Positioning System (GPS), the first GNSS constellation, a new horizontal and vertical displacement measurement technique has been available. GNSS techniques are based on the use of at least four navigation satellites for giving an estimate of the absolute X, Y, Z coordinates with respect to a global well-defined geocentric reference system. Similar systems have been developed, such as Russia’s GLONASS system, or EU’s Galileo System, or China’s BEIDOU system (GSA, 2018). Considering reference points at ground surface, GNSS networks can be developed in order to survey multiple times various areas of interest. Permanent stations having accurate, known X, Y, Z coordinates can be used for Differential GNSS measurements which allow computing the 3D position of a roving receiver. Currently, GNSS techniques are used not only for revealing land subsidence, but also for validating other subsidence measuring methods, such as those based on Synthetic Aperture Radar (SAR).

3.3 Aerial systems

Aerial survey was and is still being used mainly by Mapping Agencies and local authorities to accurately map the land surface using both passive and active instruments. Historically performed using manned aircraft, a strong trend is visible nowadays on using unmanned aerial systems (UAS) or RPAS (Remotely Piloted Aerial Systems) for performing the task.

Drones offer public and private organisations an opportunity to carry out tasks faster (reduce the time of intervention by approx 80%), safer (improve safety by approx 70%), cheaper (50% in average) and with less impact on the environment than traditional methods. In early 2022, the majority of drone use is for Inspection and Survey (PWC, 2022). To serve these goals, an appropriate framework (technology and legislation) need to be in place: UTM (Unmanned Traffic Management, mainly related to regulations and operational procedures), electronic conspicuity (technology allowing awareness of what is operating in surrounding airspace), capability to detect and avoid obstacles, flight autonomy, Infrastructure (mainly communication, landing and charging). Depending on each use case, each of these components must be ensured at specific rates. For example, allowance of BVLOS (Beyond Visual Line of Sight) or EVLOS (Extended Visual Line of Sight) flights in addition to VLOS (Visual Line of Sight), inside or outside a segregated airspace, could impact significantly on the number of use cases.

According to [EUSPA Whitepaper, 2022] drones can enable a vast array of different applications that can be categorised along the following classes of applications

- Agriculture & environmental: precision agriculture, crop/field/soil monitoring, variable rate applications, livestock tracking, insurance, forest monitoring & man- ageement, etc
- Inspection & maintenance: bridges, gas & oil infrastructure, energy distribution infrastructure, solar panels, windmills, etc.
- Surveying and mapping: environmental monitoring, cadastral surveying, mine surveying, marine surveying, GIS, photogrammetry, etc.
- Government: police applications, crowd observation, border control (including maritime), security, etc.
- Public safety: SAR operations, firefighting, urgent med- icine/medical equipment delivery, other natural disaster monitoring (e.g. floods, earthquakes), etc.
- Scientific: meteorological monitoring, atmospheric measurements, swarm techniques, general R&D, etc.
- Education: teaching tool in schools and faculties (e.g. aeronautics, geomatics, navigation).
- Observation: film, photography, TV/other media-broad- casting (e.g. sport events), etc.
- Communications: local coverage broadcasting using high altitude drones or HAPS (high-altitude platform stations).
- Leisure: toys, models flying, self-tracking/filming drones (first person view), sports (e.g. drone racing), etc.
- Goods delivery: transport of various types of goods or cargo.
- Other applications: calibration of aviation nav-aids, asset management, advertisement, marketing, entertainment, etc.
- Military

In the context of this report, aerial platforms, either manned or unmanned, can help to address a number of features:

- analysis of the land use evolution in time,
- assessment of the geological and environmental situation,
- search for seepage of water at the edges of landfills and mining sites,
- locating water resources and moisture anomalies,
- investigation of natural and artificial drainage systems,
- recognition and analysis of landslides,
- investigation of vegetation health or vitality,
- assessment of surface water conditions,
- inventory of sites suspected to be contaminated,
- search for undeclared well systems

Airborne systems provide reliable observations of the Earth surface features from visible - near infrared images but also geo-referenced data records generated by SAR or LIDAR instruments (see section 4.2). These observations can be used for deriving information on the size, shape, and position of objects or phenomena, as well as their colour or tone, texture, and spatial patterns and associations.

Photogrammetric techniques are then used to prepare reference and thematic maps and digital elevation models (DEM) from remotely-sensed data produced by the airborne instruments. Usual tasks are the preparation of orthophotography, photomosaics and collection of vector data (infrastructure, land cover etc).

Orthophotographs, photomosaics, thematic maps, elevation models and vector datasets are widely used for site investigations in conjunction with other geological, hydrological, geophysical, and remote-sensing data. Topographic measurements acquired at different times can be used to observe changes as well as for planning and decision-making.

In general, a typical workflow involving Flight Planning - Data Capture - Data Processing - Information Sharing is in place when dealing with aerial (manned or unmanned) systems.

3.4 Space systems

As introduced in this section, the EO systems - space and in-situ - are used in complementarity for deriving the different parameters of the water balance equation (configured for the different use cases) and give, this way, estimations for the water resources in a specific area. Besides qualitative observations (imagery produced by space systems at high and very high spatial resolutions), dedicated missions are developed for specific parameters and they are introduced in the following paragraphs.

Precipitation

The quantity and spatial distribution of rainfall and snowfall can vary greatly over time. Using active microwave instruments, missions for regional and global precipitation observations were launched and operated during the last years to provide the data required for the quantification of the precipitation.

Missions like TRMM (Tropical Rainfall Measuring Mission), GPM- Global Precipitation Measurement or information derived from other satellite observations contributed to a global estimation of the quantity of precipitation. For example, a record of daily global rainfall can be accessed as it has been obtained from ASCAT satellite soil moisture data through the SM2RAIN algorithm. The SM2RAIN-ASCAT rainfall dataset (in mm/day) is provided over a regular grid at 0.1-degree sampling (3600x1801) on a global scale. The product represents the accumulated rainfall between the 00:00 and the 23:59 UTC of the indicated day[17].

[17] https://zenodo.org/records/7950103

Copernicus Land Monitoring Service (CLMS) is also publishing a number of products that are relevant for the estimation of the precipitation. According to the CLMS website[18] "The Snow product group boasts a number of datasets related to snow monitoring across the globe. These data are mostly disseminated in near-real time and derived from high resolution spatial observations from Sentinel-1 and Sentinel-2. Snow datasets can be used for a wide array of applications, including modeling the water supply, risk assessment and hazard management, and energy production." Other relevant data can be retrieved by means of the same website or by accessing the WEKEO platform[19].

Soil moisture

Soil moisture represents an important variable influencing the water and heat energy transfer between land surface and the atmosphere. The content of soil moisture influences the soil temperature, decreasing the differences between day and night soil temperatures. At the same time, changes of Land-Use / Land-Cover can affect considerably the content of soil moisture. In 2010, soil moisture was recognized as an Essential Climate Variable (ECV). Since the mid-1970's different optical, thermal infrared, passive and active microwave satellite sensors have been used for the estimation of various soil characteristics.

Groundwater table depletion

As the main resource of freshwater for many human activities, overexploitation of groundwater can produce serious problems in environmental balance and water management. Satellite gravimetry can be used for reaching the depletion of groundwater at regional or global level, considering the variations of the Earth gravity field.

At continental level, missions like GRACE (Gravity Recovery and Climate Experiment, NASA) and its follow-up and GOCE (Gravity Field and Steady-State Ocean Circulation Explorer, ESA) had and still have significant contributions in tracking the Earth's water movement to monitor changes in groundwater storage, the amount of water in large lakes and rivers, soils moisture, ice sheet and glaciers, and sea level caused by the addition of water to the ocean.

At local level, if groundwater is intensively exploited, overexploited, or intensively recharged, the effects of these phenomena can arise at land surface, as ground vertical displacements (see also 1.2). Synthetic Aperture Radar (SAR) interferometry (InSAR) offers a suitable way to accurately measure the spatial extent and magnitude of surface deformation associated with aquifer-system compaction or dilation.

InSAR techniques use the phase differences between two radar images acquired over the same area to generate maps of surface displacements or topography (Fig. 6).

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[18] https://land.copernicus.eu/en/products/snow
[19] https://www.wekeo.eu/

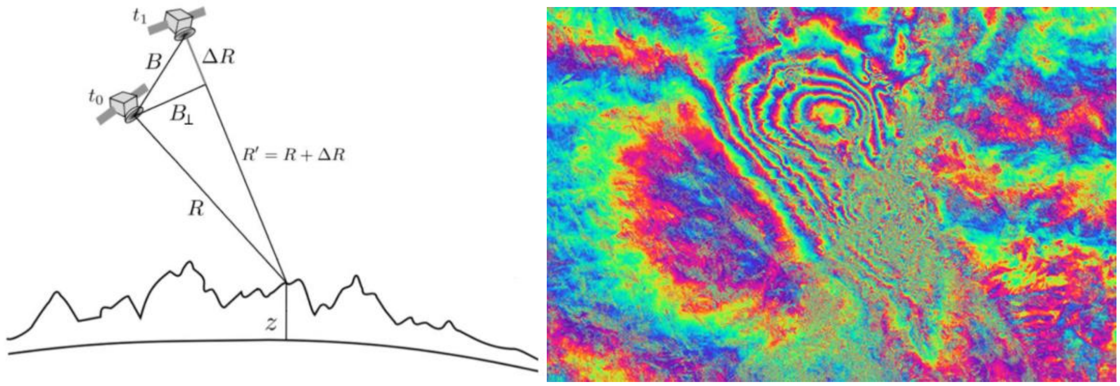

Fig. 6 Principle of Differential InSAR and interferogram generated from SAR observations[20]

The phase difference image is called *interferogram*. Although it contains several terms, the phase difference largely reflects the surface deformation in the radar line of sight during the period between the two acquisition dates. To form the interferograms, the images must be in the same SAR geometry, i.e. cover the same area on the ground and with the same incidence angle. This is achieved by resampling one of the images to the other and calculating the phase difference (European Ground Motion Service: Service Implementation Plan and Product Specification Document[21]).

One important class of algorithms focuses on identification and analysis of pointlike scatterers (PS). A second class of algorithms focus on analysis of distributed scatterers (DS) based on the fact that the coherence of distributed scatterers is higher for small baselines. Depending on the environment being analysed - urban or natural landscape - a PS, DS or a combination of the two methods can be applied.

The reliability of this technique and the maturity of its implementation allowed the availability of an operational service developed as part of the EU Earth Observation Copernicus Programme - the EU Ground Motion Service (Fig. 7). According to the official website "The European Ground Motion Service (EGMS) provides consistent and reliable information regarding natural and anthropogenic ground motion over the Copernicus participating states and across national borders, with millimetre accuracy." The service gives access to ground motion data for a period of time covering the 2018-2022 interval. A data explorer (see figure above) allows direct analysis or download of specific areas of interest[22].

[20] https://eo-college.org/resource/introduction-to-sar-interferometry/

[21] https://land.copernicus.eu/user-corner/technical- library/european-ground-motion-service

[22] https://egms.land.copernicus.eu/

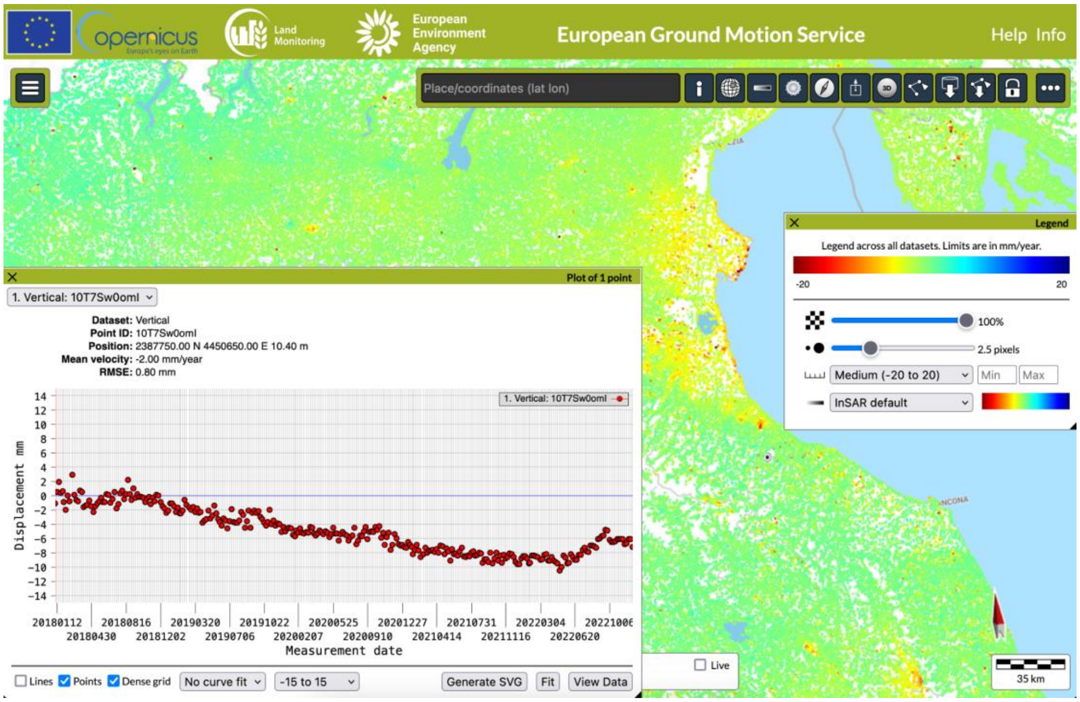

Fig. 7 The EU GMS Explorer

According to [Fondacion Botin, 2020], using remote sensing and aerial methods for monitoring water abstraction may be done with some strengths and weaknesses:

Strengths	Weaknesses
Effective on large areas with reduced costs and in near real time. Analysis methods based on the detection of changes computed between before and after images Very useful in areas that are not easily accessible by other means Allow production of maps and documents that can be used as evidence in Court Enables water use monitoring without entering the property	Verification on the ground is usually needed Good knowledge of the business practices (agriculture, building, other) is helpful Detection may be affected by a lack of accuracy or details on the definition of the land unit where water rights have been granted It requires specialised technical capacity in terms of tools and human resources Accurate quantitative and qualitative water measurements can be performed only in-situ.

The following sections provide details on different aspects related to the various components - observation systems and data - involved in the detection and quantification of water abstraction and its association with a possible illegal use.

4. Recommended methods, data and infrastructure

4.1 Methods

As shown in table 1, initial awareness is built based on the detection methods associated to each case (awareness level). Repeated observations and association with specific prone areas can lead to the advanced level. Quantification based on planned observations and ancillary data is done to reach the specialist level. An expert level can be reached after confirmation based on in-situ or drone inspections relying on UAS. As a special note for level 3, when measuring quantitative or qualitative deviations from the water rights is in focus, the quantification methods to be used need to reach an appropriate accuracy level and recommendations are given in the following sections.

Table 1. Cases and awareness levels

	Level 1 Awareness	**Level 2 Advanced**	**Level 3 Specialist**	**Level 4 Expert**
Agriculture	Detection of activity in area with no water rights based on vegetation phenology analysis	Repeated observations confirm agricultural activities and information on crops is derived based on RS	Estimation of the volume of ground water abstraction is estimated based on RS, crop information and meteo data	A water rights data base confirm missing permit; Inspection based on UAS confirm presence of water abstraction points
Industrial	Leakage or pollution phenomena detected based on aerial or satellite RS around known installations	Repeated observations confirm leakage on ground or pollution - water and/or soil - around known installations	Sources are identified for each of the impacted soil or water elements based on intelligence derived from RS and in-situ EO data	On-ground inspection still needed for confirming inadequate design or operation. UAS could confirm/facilitate assumptions.
Construction	Affected structural integrity is detected based on InSAR monitoring data	Construction site is identified and repeated observations confirm the trends	Integration of in-situ observations confirm quantitative and qualitative decrease	On-ground inspection still needed for confirming inadequate design or operation. UAS could confirm/facilitate assumptions.

	Level 1 Awareness	Level 2 Advanced	Level 3 Specialist	Level 4 Expert
Mining	Emissions, subsidence or surface water pollution effects are detected based on RS or crowdsourcing	Effects are confirmed by repeated observations and the location of the mining site is also detected	All phenomena identified in space and time based on RS and mining site information is correlated	Solid waste dumps and other environmental impact is measured based on UAS observations
Domestic	Subsidence, dry streams or other effects are detected based on public monitoring data	Environmental impact is confirmed by repeated analysis of public monitoring data	Identified area is further analyzed based on public data and planned observations and analysis reports	Water abstraction points and lack of installations are confirmed based on UAS inspection
Sewage	Polluted surface water or contaminated soil detected based on RS or crowdsourcing	Pollution of water or soil is confirmed by repeated observations and sewage system is identified	Correlation with industrial facility / source is made and pollution is localised in space and time	Pollution effects and sources are confirmed based on UAS inspection

Methods and input data for each of the use cases considered were summarised in the second report and are associated with the phenomena tied to each use case - see table 3. Summarising table 3, the following main phenomena included in table 2 can be considered together with the observation processes and related data sources.

Table 2 Summary of detection methods

Phenomena	Observation methods
GW table depletion / drawdown / recharge	The GW table depletion or recharge is associated with changes in piezometric level; combined with other data such as soil maps, meteo data or historical water consumption, InSAR can help to detect subsidence or vertical land motion. Water rights or land cover data can help focus the analysis. In the case of urban activities effects can be observed on buildings; known wells data is checked; new wells can be detected; based on satellite, optical RS;
Land cover change / Greening crops	Land cover change detection can help in detecting dry land being turned into irrigated land or monitoring of crops; satellite RS is used to produce

Phenomena	Observation methods
	vegetation indexes for enabling change detection; crop maps, wells running (new, unauthorised) can help quantifying the water consumption. Water rights maps or land cover data can help focusing the analysis.
Soil salinization	High salts content in GW / aquifers salinization trigger land degradation processes. GW dependent ecosystems degradation can be observed with RS; in-situ observations on soil salinity complemented by chemical analysis, and soil samples can help confirm the effects. Soil salinity can be further quantified using RS methods.
GW and surface water contamination	The landscape is affected by higher concentrations of dissolved or suspended elements; GWQMW can be used in combination with remote sensing methods for collecting information on the degradation of wetlands (ecosystems) that are fed by GW and desertification. Change detection methods can be used to detect affected vegetation and trigger the focused analysis.

4.1.1 Detection methods

Water table depletion

Water table depletion is created when water extraction is higher compared to the water renewal rate (Figure 8). The main causes of the depletion of the water table are deforestation and over-pumping of groundwater. Deforestation is the cutting of trees in the forest land and this affects the rain pattern in that area. It causes the groundwater to run away and results in permanent drying. Excessive pumping of groundwater reduces the levels of groundwater.

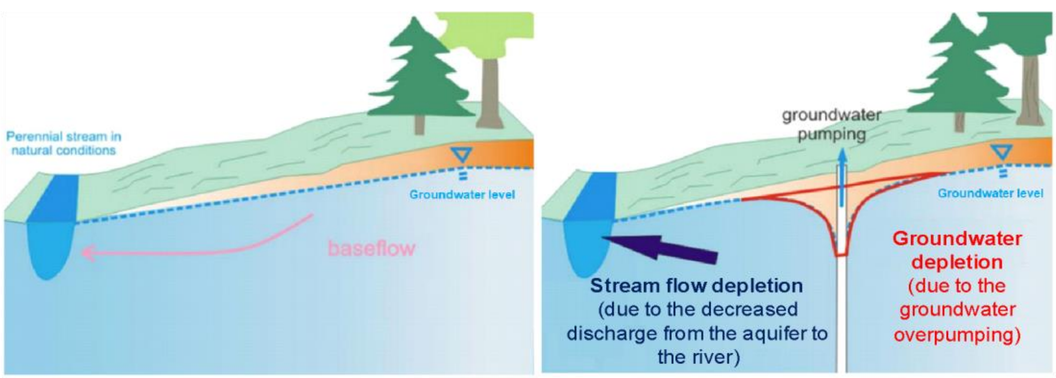

Fig. 8 Streamflow and groundwater depletion[23]

[23] https://onlinelibrary.wiley.com/doi/10.1002/rra.3185

Excessive pumping in coastal areas causes saltwater to move inland and results in saltwater contamination. Increasing industries increase the water requirement on a daily basis and increasing population also leads to a decrease in groundwater. Increasing population leads to increased consumption of water for their activities and leads to increased consumption of groundwater and it also allows only less water to seep into the ground. Agricultural activities increase the use of groundwater day by day and thus result in the depletion of the water table.

The detection of water table depletion is currently done by periodical checks of the groundwater level (hydraulic heads) in monitoring wells (GWLMW), as shown in Fig. 9 Most of the EU countries installed and make use of monitoring networks including GWLMW.

Ground subsidence or uplift detection from Earth observation satellite data has to be applied after field observations. As shown in a previous report[24] Synthetic Aperture Radar (SAR) interferometry (InSAR) offers a suitable way to accurately measure the spatial extent and magnitude of surface deformation associated with aquifer-system compaction or dilation. The same report also specifies that the reliability of this technique and the maturity of its implementation allowed the availability of an operational service developed as part of the EU Earth Observation Copernicus Programme - the EU Ground Motion Service[25] (EGMS).

Due to its complexity, the InSAR methods will not be described here. In the case EGMS will not be considered appropriate for the job, hiring external service providers could be an appropriate way to proceed, with three-month reports delivered.

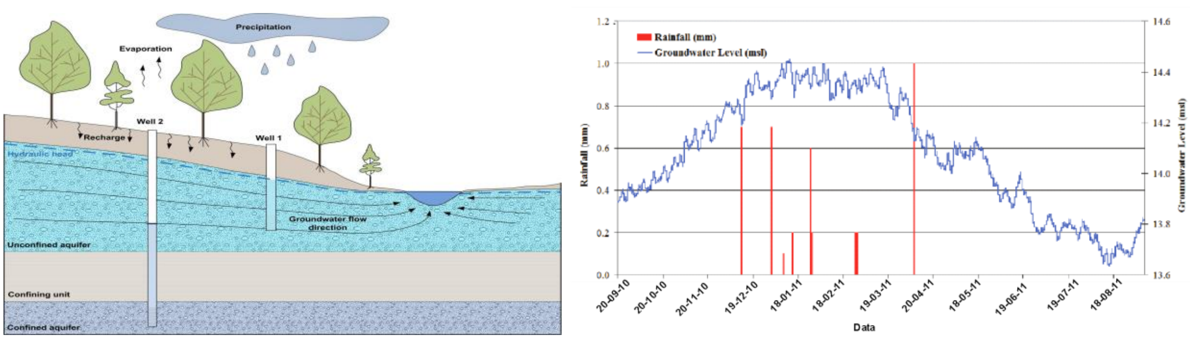

Fig. 9 Groundwater level (hydraulic head) monitoring wells and example of data record

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[24] Earth Observation Techniques Accessible within EU for the Detection of Illegal Groundwater Activities - Literature Review

[25] https://egms.land.copernicus.eu/

Table 3 Cases and recommended methods

ACTIVITY / CASE	ASSOCIATED PHENOMENA AND / OR PROCESSES	OBSERVATION METHODS AND OBSERVABLES	EXISTING DATA AND POSSIBLE SOURCES	COMMENTS / DETAILS
IRRIGATED CROPS	**Groundwater table depletion** (decrease of the groundwater hydraulic head, decreases of the surface water levels, river, springs flow rates decrease, subsidence) **Grown crops** in non-declared agriculture area or no valid water rights **Soil salinization** (high salts content in groundwater/ aquifers salinization land degradation processes, groundwater dependent ecosystems de gradation)	INSAR can be used to derive ground motion / land subsidence Aerial or space RS can be used to map crops and map irrigated area; NGMN Data and Hydro Monitoring Data to estimate water consumption RS can be used to detect degradation of wetlands ecosystems that are fed by groundwater; RS can be used to detect desertification; RS can be used to map soil salinity in combination with in-situ observations	EEA EGMS or equivalent services; GWL from NGMN (GVTDATA) ESA or EEA Land Monitoring Copernicus data on phenology; GVTDATA Soil salinity maps from ESA, EEA or projects based local data	Should be used in combination with water rights maps, actual and historical water consumption, meteo data; COPHRL and LULC data such as CLC or LPIS should be used to focus the analysis
INDUSTRIAL USE	**Groundwater table drawdown** (decrease of the groundwater hydraulic head, decreases of the surface water levels, river, springs flow rates decrease, subsidence)	INSAR can be used to derive motion / subsidence of land or infrastructure elements and produce ground motion maps	EA EGMS or equivalent services; GWL from NGMN (GVTDATA)	Existing GVTDATA on industrial facilities e.g. EPRTR EEA data can be used to focus the analysis and

	Groundwater recharge (flooded infrastructure, changes in groundwater balance, uplift, differentiated settlements)	Groundwater wells quantitative monitoring; Cavities increased seepage (sewers, parking, foundations, cellars); Geophysics (GPR imaging); geology analysis, INSAR in cases of uplift (depending of magnitude of phenomena)	GWL from NGMN (GVTDATA)	reduce time to decision
	Groundwater pollution (Higher concentrations of dissolved or suspended elements)	RS of surface water bodies or connected ecosystems focusing on detecting anomalies	GWQMW (GVTDATA) or projects based local data	
DEWATERING - CONSTRUCTION	**Groundwater table drawdown and / or decrease of water level in surface water bodies**	Groundwater wells quantitative monitoring; hydro network monitoring water level data	warning or alert can be generated from NGMN (GVTDATA) or local monitoring data	Existing GVTDATA on public works / building permits can be used to focus the analysis and reduce time to decision
	Ground structural integrity degradation and / or earth fissures and structural damage of buildings	INSAR can be used to derive motion / subsidence of land or infrastructure elements; optical satellite or aerial imagery can be used for detailed check of building	ground motion maps can be produced periodically from EEA EGMS; projects based local data	
DEWATERING - MINERAL	**Mine water discharges in surface water bodies**	RS of surface water bodies or GWQMW data can be used to detect changes in surface water status	Copernicus data on lake water quality	Existing GVTDATA on active and inactive mining sites can be used

EXTRACTION	**Groundwater table drawdown** (subsidence due to decrease of groundwater level (hydraulic heads) / surface structures damaged by tilting, lowering of the land surface)	INSAR can be used to derive motion / subsidence of infrastructure elements, subsidence of land	ground motion maps can be produced periodically from EEA EGMS	to focus the analysis and reduce time to decision
SEWAGE DISCHARGE, REINJECTION WELLS,	**Groundwater pollution** (higher concentrations of dissolved or suspended elements in groundwater and surface water bodies) **Changes in ground water balance; flooded infrastructure elements**	RS of surface water bodies; focusing on detecting anomalies related to water quality cavities influx monitoring (e.g. sewers, parking, cellars)	GWQMW Data; Geochemical monitoring data (GVTDATA or Municipality, water operators) GWL from NGMN or project based local data	Quite difficult to apply; crowdsourcing or other planned activities could help focusing the analysis
DOMESTIC USE	**Depletion of stored volumes of groundwater and subsidence** **Soil salinization** due to intrusion of seawater or water from other hydraulically connected water bodies **Increased groundwater recharge from connected streams, lakes**	INSAR can be used to derive ground motion / subsidence; for large areas satellite gravimetry data could give indications over longer periods of time RS of soil status applied in order to derive salinity GWL measurement by means of NGMN	EEA EGMS or equivalent services; GRACE-FO data can be used for satellite gravimetry based methods Soil salinity maps from ESA, EEA or projects based local data GWL Data (GVTDATA)	Cvasi-permanent monitoring of populated places, especially rural area could be necessary, making use of EGMS

GWL	Groundwater Level (hydraulic head)	GVTDATA	Data provided by Governmental Organizations
NGMN	National Groundwater Monitoring Network	CLC	Corine Land Cover Data
GWQMW	Groundwater Quality Monitoring Wells	LPIS	Land Parcel Identification System
LULC	Land Use Land Cover	COPHRL	Copernicus High-Resolution Layers
ESA	European Space Agency	InSAR	Interferometric Synthetic Aperture Radar
EEA	European Environment Agency	DInSAR	Differential InSAR
ECMWF	European Centre for Medium-Range Weather Forecasts	RS	Remote Sensing

Land cover change detection

Land cover maps are produced periodically by national[26], European[27], and international[28] organisations, after adopting general-purpose nomenclatures and minimum mapping units. As this data can be produced considering a one-year or even larger time interval, they cannot be used for the detection of illegal groundwater abstraction activities. However, this data can be used as initial input for the configuration of automatic tools aiming to detect illegal abstractions by selecting specific land cover types e.g. agriculture exploitations, urban areas, and others.

When groundwater abstraction is related to illegal use for agriculture, focusing on or monitoring land cover change aims at mapping crop phenology for detecting agriculture activities in areas where no water rights exist. This can be based for example on the computation of high spatio-temporal resolution vegetation index time-series.[29]

As shown in Fig. 10 the computation of vegetation-index time-series allows the extraction of graphs showing the evolution in time of land units (e.g. 10x10m) and detection of moments when changes occurred in terms of land cover. When combined with water rights maps, high values of NDVI can easily give information on crop phenology and further confirm whether the identified crops are part of continuous activities and the dimensions/size of the crop.

Land Use and Land Cover Change (LULCC) is an important aspect of monitoring environmental problems, as for example in the neighbourhood of mining areas. When resources get exploited the correspondent surface disturbances could change the natural landscape pattern around the mines within a short period of time. These can be associated with groundwater illegal abstraction activities. Consequently, monitoring changes or environmental impacts in mining areas has to be performed.

Land cover change detection can be also used to address the problems brought on by increasing urbanisation in the field of urban planning where planners can make well-informed judgments about infrastructure development, zoning rules, and resource allocation by recognizing shifts in land use patterns and urban expansion. The negative environmental impact, many times associated with illegal groundwater abstraction, can be reduced by taking proactive action, by promoting sustainable urban expansion.

Pre-computed vegetation-index images can be accessed and freely used by accessing the Wekeo platform[30] where various types of index images are published as part of the High-Resolution Vegetation Phenology and Productivity (HR-VPP) service.

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[26] https://www.mundialis.de/en/germany-2020-land-cover-based-on-sentinel-2-data/
[27] https://land.copernicus.eu/en/products/corine-land-cover
[28] https://resourcewatch.org
[29] https://www.sciencedirect.com/science/article/abs/pii/S0303243414001755
[30] https://www.wekeo.eu/use-cases/hr-vegetation-phenology-and-productivity-service

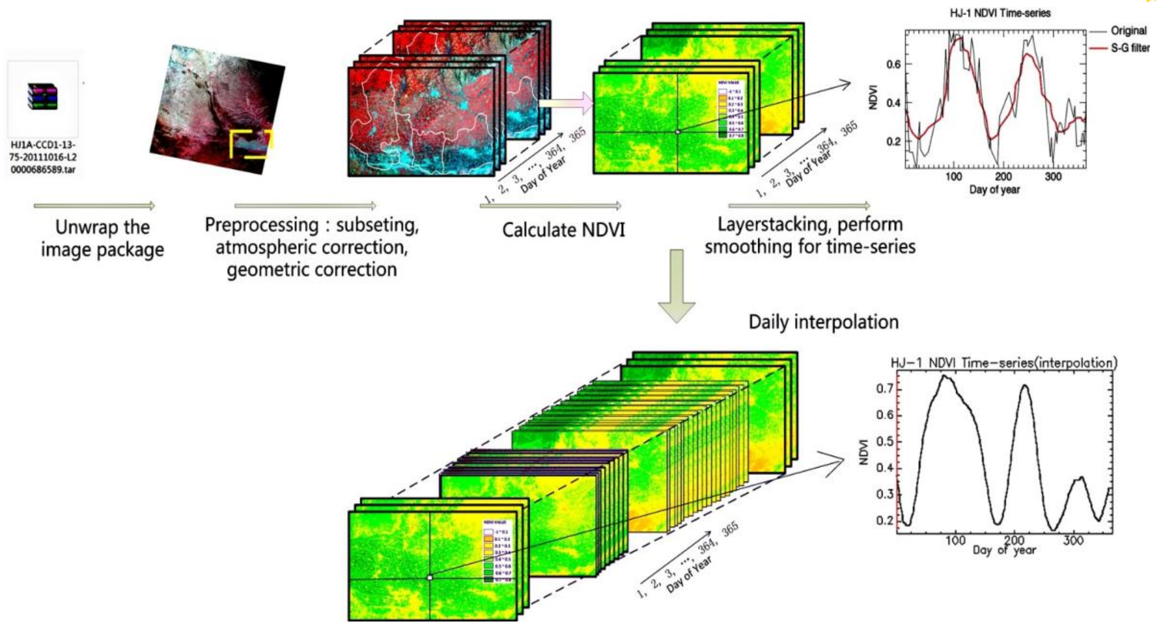

Fig. 10 Computation of NDVI time series for change detection

Detection of non-authorized abstractions for agriculture

The DIANA project[31] proposed a simple method for detecting the non-authorized abstractions in the case of agriculture activities i.e. water used for irrigation where no water rights have been issued (Fig.11).

Surface water bodies quality monitoring

Surface water bodies can be affected by pollutants from stormwater, excess nutrients running off from agricultural areas or wastewater discharges, water temperature changes associated with land cover changes around water bodies, and changes in water flow.

In-situ water quality monitoring data should be available in EU member states as a result of national and pan-European programs. This data is usually collected by sampling and does not cover the entire surface of the water bodies.

Satellite EO data can provide consistent and regular observations over large areas at high revisit rates (weeks) allowing times series analysis. This can complement in-situ observations or can be used to detect areas under risk and plan further investigations.

[31] http://diana-h2020.eu/en/index.html

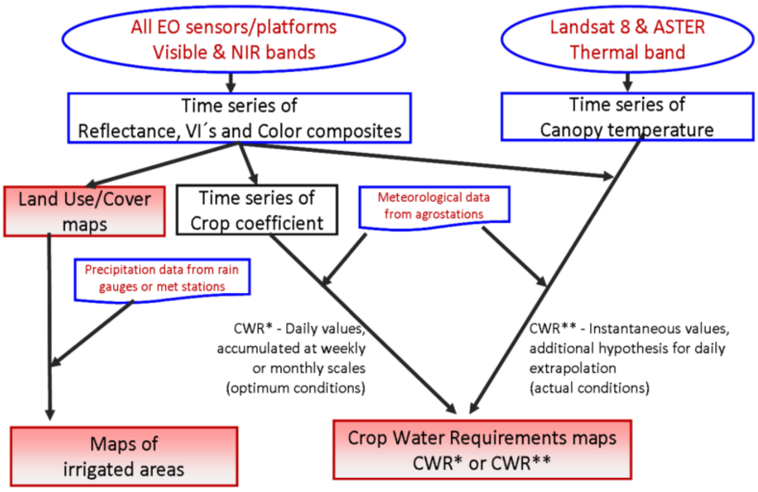

Fig. 11 Detecting the non-authorized abstractions method in the case of agriculture activities (DIANA project)

As water quality affects water's optical properties, the monitoring of the light reflectance on the water surface based on remote sensing made with satellites can be used to assess the water quality. Data records from MODIS, Landsat or Sentinel-2 and Sentinel-3 satellites can be used to derive Colored Dissolved Organic Matter (CDOM), Chlorophyll or Phytoplankton, Total Suspended Solids (TSS), Fluorescence Line Height, Euphotic Depth, Diffuse Attenuation of Light, Surface Temperature, Salinity using various, sensor-specific algorithms monthly or even daily for large water bodies. To derive the water quality indicators algorithms make use of data acquired in many spectral bands ranging from the visible part of the spectrum to near-infrared and thermal infrared.

Copernicus Land Monitoring Service (CLMS)[32] provides access to the Water Bodies product group delivering data on Lake Surface Water Temperature, Lake Water Quality, Water Bodies extent; Lake and River Water Level at 100 m spatial resolution, every 10 days.

Soil salinization

Salinization is a major soil degradation threat in irrigated lands worldwide. Soil salinity is considered one of the major factors affecting the interaction between plants and soil, due to its significant negative impact on the availability of soil nutrients and crop yields. The increasing salinity levels are caused by diverse natural and anthropogenic factors, such as inadequate irrigation practices, fertilizer overuse, and land use changes[33]. These practices, sometimes based on illegal groundwater abstractions, are particularly noticeable in areas with shallow water tables and degraded groundwater quality. Therefore, real-time monitoring of soil salinity levels is essential for effective soil management and sustainable agriculture.

Unlike conventional approaches based on in-situ observations to appraise soil salinity such as electromagnetic induction methods, remote sensing multispectral data have great potential for detecting, monitoring, and investigating soil salinity problems, especially in agricultural areas. Remote sensing data from satellite imagery and aerial photography offer valuable information on various environmental parameters, including vegetation cover, soil composition, and moisture content, which are interconnected to salt content. By analysing and

[32] https://land.copernicus.eu/en/products/water-bodies
[33] https://www.mdpi.com/2073-445X/11/12/2148

interpreting such data, detailed maps and spatial models of salinity distribution can be generated, which inform land management decisions and support the development of effective strategies for risk mitigation[34.]

In recent years, several salinity indicators have been developed to detect soil salt-affected areas from satellite imagery. Vegetation indices can be used to indirectly assess saline soils via the adverse effects of soil salinity on crop growth and plant stress. Two types of multispectral-based indices were calculated from Sentinel-2 satellite imagery: (i) vegetation indices and (ii) salinity indices, namely those based on V and NIR bands and on SWIR bands.

GW properties change and ecosystem degradation

The change of groundwater in terms of chemical properties is usually monitored by means of in-situ networks of groundwater monitoring wells equipped with adequate sensors and producing monthly data records; these data records are usually made available by the governmental organisations in charge of water resources management.

Ecosystems that rely on groundwater on a temporary or permanent basis to sustain their growth and productivity are considered groundwater-dependent ecosystems (GDEs). GDEs provide several ecological services such as habitat for wildlife fauna, carbon sequestration, and water purification. Excessive abstraction has a negative effect on groundwater levels (hydraulic heads), potentially impacting water security, ecosystem services, structure, and functioning. Reduced groundwater levels have resulted in changes in river flow affecting riverine ecology. Reduced river flows have also altered levels in lakes and wetlands. Perturbations in groundwater quantity and quality regimes due to climate change and other anthropogenic stressors such as excessive pumping, sometimes illegal, are placing these GDE biodiversity under threat, which can result in a cascading series of negative effects on GDEs ranging from short-term water stress to the permanent loss of species and habitats.

Remote sensing of groundwater-dependent ecosystems has increased substantially in recent years. Of significant prominence, is the delineation and mapping of groundwater-dependent vegetation (GDV), species diversity, and water quality in these ecosystems.

The delineation and mapping of the spatial distribution of GDEs have been investigated through passive, optical sensors including multispectral and hyperspectral remote sensing satellite images, as well as active sensors such as Light Detection and Ranging (LiDAR) and Radio Detection and Ranging (RADAR) imagery.

The aerial or space EO systems are considered effective and no reliable systems are known for measuring the groundwater quality. However, the aerial and space EO systems can be effective for monitoring the ecosystem's condition on the Earth's surface. By means of large, pan-European programmes such as MAES (Mapping and Assessment of Ecosystems and their Services)[35], the changes related to ecosystem conditions can be detected and measures can be taken to identify the causes.

4.1.2 Quantification methods

Depending on the magnitude of the observed phenomena implying groundwater illegal activities like GW table depletion/drawdown/recharge, Land cover change / Greening crops, or Soil salinization, a higher accuracy estimation could be achieved by solving the water balance equation for a specific area to find the U

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[34] https://bsssjournals.onlinelibrary.wiley.com/doi/epdf/10.1111/sum.12772

[35] https://biodiversity.europa.eu/europes-biodiversity/ecosystems/maes

term. Also in many illegal cases of GW and surface water contamination, the same equation could provide a better and clearer image of the phenomenon.

As a reminder, the water cycle was summarised through the water balance equation:

$$P\ (\pm W + H_i) = E_t + Q + I + U + \Delta R$$

P - precipitation – main water source (rainfall and snow) entering the hydrological basin;
W - groundwater flow input, another catchment natural water input (in some cases large water volumes are passing from one catchment to another despite surface water flow established processes);
H_i - human intervention;
Q - direct water flow (in river network);
I - infiltration into the soil;
U - human use;
ΔR - storage of the water catchment;
E_t -water catchment total evaporation/evapotranspiration.

The water balance equation will need to be adapted to local conditions and climate and ancillary data needed to solve the equation for finding the U term, such as the precipitation or groundwater level, will need to be found/estimated.

At this stage, the desired estimation accuracy must be established, choosing a rigorous approach or an expeditious one. When choosing the rigorous approach, an accurate water balance study could be obtained by quantifying the water balance equation terms, using reliable data.

Irrigation water requirements

In the case of irrigation, the specialist level can be reached once the exploitation sites are confirmed and quantities of water can be estimated. To this goal, the EU project DIANA recommended a procedure based on a time series of reflectance and vegetation indexes (VI), evapotranspiration (ET), precipitation, and soil hydraulic properties (Fig. 12). A crop coefficient indicating the needed volume of water is derived based on VI and used in a soil-water balance, together with ET to derive irrigation needs.

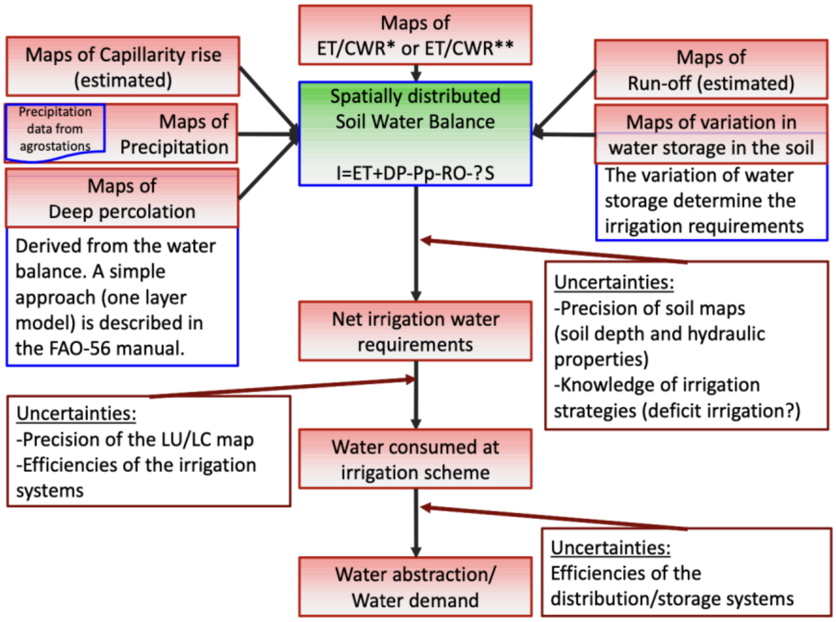

Fig.12 Estimation of irrigation water requirements workflow proposed by DIANA project[36]

4.2 Data

4.2.1 Observables and data

As shown in the previous report based on a number of groundwater abstraction cases where illegal issues may be faced, each of the mentioned methods involves access, processing and integrated analysis of various data summarised in the table below.

4.2.2 Data access

The current Copernicus Services

The EU Satellite Centre (SatCen) was entrusted by the Commission in 2016 with the implementation of the Copernicus security service in support to EU External Action[37]. The Copernicus security service component on Support to EU External and Security Actions (SESA) is a European geospatial information service that assists the EU and its Member States in the framework of applicable Union policies and legislation along the following main policy groups, associated to key responsibilities across EU Institutions and Member States:

1. Union external action supporting the Union and its Member States
2. Security challenges facing the Union and its Member States
3. Monitoring of the implementation of EU Law

Table 4. Data types and sources

[36] http://diana-h2020.eu/en/index.html

[37] https://www.copernicus.eu/en/copernicus-services/security

Dataset	Details	Data sources
Groundwater level (hydraulic heads) data records	Hydraulic head and quality parameters time-series datasets obtained from national and local databases	National and local monitoring systems and databases
Surface water level data records	Water level in rivers and lakes, flowrates in streams gauging stations and quality parameters time-series datasets obtained from national and local databases	National and local monitoring systems and databases
Satellite data records	Time series of high-resolution data covering the entire crop growing season, used to compute various indices	Landsat satellites multispectral; Copernicus Sentinel satellites, multispectral, global cover; Other EO systems allowing multispectral time series at 10-30 m resolution.
Meteorological data	Daily meteorological data on precipitations, allowing calculation of crops water consumption. Evapotranspiration	Observation networks available at national level. Alternative options: WMO, ECMWF, other EU agencies.
Soil water retention	Data allowing consideration of the capacity of the soil to retain water, as needed for modelling purposes	National databases. European products, however with limited accuracy, currently available in some MS and some areas. Also produced by UN FAO.
Crops maps and phenology	Per season; Supporting water consumption estimation	FAO database; National databases, currently available in some MS and some areas; Relevant publications
Farm information	To be used for better assessing water consumption	Farm characteristics data collected during field inspections; Information systems created and maintained by the ministries / agencies.
Sewage network	Position of the sewage pipes as needed for the urban cases	Local sewage operators/services providers
Construction site information	To be used for detailed analysis of impact	Usually provided for getting the construction permit; should be available at the authority managing the construction processes
Land use land cover	When updated, can give indications on land use and the way water is possibly consumed	CLC / CLC+ and the 5 new Copernicus High Resolution Layers. LPIS (for parcel delineation). Available in all MS since 2006. Data updated every 6 years for CLC and every 3 years for the 5 HRL.
Irrigable area boundaries	Vector data containing delineation of irrigable areas boundaries.	Water User Association archives. Available in some MS.

Dataset	Details	Data sources
Actual and historical water consumption	For calibration and continuous ground truthing of crop water consumption; Historical data on water consumption, as related to a known activity	Water abstraction as flow meter data in selected locations from monitoring networks for pressurized systems; Not available for gravity irrigation systems. For some cases, billing data from the water companies;
Water rights map	Location of parcels with regular irrigation rights.	Water User Association archives. Available in some MS.
Cadastral maps	To allow identification of owner(s) and relate to any other related legal information	Real estate or real property's metes and bounds of a country as provided by national government entities or agency; usually available in all MS.

The SESA service includes new application areas, notably addressing Security of EU Citizens, Humanitarian Aid, Crisis and Conflict, Rule of Law, Transport Safety and Security, Stability and Resilience for Development, Cultural Heritage, International Trade and Economic Diplomacy as well as cutting-edge challenges such as Environmental Compliance, Climate Security or Health Security. With such a mandate, SatCen can provide access to a large portfolio of services supporting environment security and TIGDA type of cases can be used for requesting SatCen services.

Copernicus is a European Union Programme aimed at developing European information services based on satellite Earth Observation and in-situ (non-space) data which operates six thematic services relating to Atmosphere, Marine, Land, Climate Change, Security and Emergency[38]. Copernicus collects a vast amount of data from satellites, ground based, airborne and seaborne measurements systems, processes and then analyses it to make it usable in order to provide autonomous and independent access for all. Importantly, the information is free to use by anyone – whether it be used by policymakers, public and private organisations or the general public, it allows the development of new applications, products and services, research to be undertaken, policies evidenced or business planning to be improved.

The future EU EO Governmental Service

Based on recent debates, the European Commission made important steps towards developing a dual-use EU EO service restricted to government-authorised EU and MSs users for sensitive applications in the areas of security and defence. This is justified by the need to have access to reliable, fast, secure and global situational awareness enabled by space-based Earth-Observation systems and by the processing of the associated data, combined where available with other data, to generate added-value services and intelligence insight.

In this context, and as identified in the EU Space Strategy for Security and Defense (RD2), the Commission has the ambition to study the development and implementation of a potential new dual-use EU Earth-Observation service for governmental use in the MFF 2028-2034. Only authorised users within the EU and MSs (and possibly third countries and international organisations, under certain conditions) would have access to this service which aims at increasing our collective and individual resilience, in the areas of security and defence.

[38] https://www.copernicus.eu/en/about-copernicus/copernicus-detail

The Commission has already taken action[39] to implement in the current MFF 2021-2027 a pilot and precursor of such a governmental service, within the existing legal framework.

The Copernicus Sentinel satellites and associated services were designed to meet certain environmental, emergency management and civil security needs. Nevertheless, some Sentinel data and service products are also used by defence users in specific non-critical use cases.

The desired capability is relying on EU MSs sovereign high-end space-based ISR (intelligence Surveillance and Reconnaissance) capabilities, the future capabilities i.e. space-based ISR constellation to complement high-end military capability for near real-time tactical use, as well as on various projects related to space-data processing for ISR applications.

Commercial data

If none of the solutions presented in the above paragraphs can be used, when it comes to purchasing satellite data, a few important aspects need to be considered when planning the use for either long-term monitoring or ad-hoc site inspection

- Availability as part of public services
- Size of the area and frequency of acquisitions
- Cost-benefit analysis

When decision is made on acquiring satellite data for serving operational, specific purposes, the price indications given in the following tables should be considered (cost of satellite data[40] as made available for June 2024).

4.3 Equipment and software

4.3.1 Unmanned Aerial Systems

As shown in the first report, aerial platforms, either manned or unmanned, can help to address a number of features: analysis of the land use evolution in time, assessment of the geological and environmental situation, search for seepage of water at the edges of landfills and mining sites, locating water resources and moisture anomalies, investigation of natural and artificial drainage systems, recognition and analysis of landslides, investigation of vegetation health or vitality, assessment of surface water conditions, inventory of sites suspected to be contaminated, search for undeclared well systems.

It was also shown that, in general, a typical workflow involving Flight Planning - Data Capture - Data Processing - Information Sharing is in place when dealing with aerial (manned or unmanned) systems. This workflow can be implemented by the organisations mandated to verify the conformance of groundwater exploitation or a service provider.

The main features when selecting a drone are the flight time and range, camera quality, RTK module availability and software compatibility. It is desired to choose drones that can fly for at least 30 minutes per battery charge. A high-resolution camera with a wide dynamic range and a quality lens is needed to capture clear, accurately-exposed aerial imagery. It is very important for drones to seamlessly integrate with GIS software for effective processing and further analysis of the images. RTK provides centimetre-level GNSS

[39] https://etendering.ted.europa.eu/cft/cft-documents.html?cftId=13224
[40] https://www.skyfi.com/pricing [accessed 02/07/2024]

positioning that is essential for precision photography. RTK modules correct location data of each picture recorded in real-time during flight for accurately positioned images.

When planning to use a drone (UAS) you need to take into account other additional costs, including insurance fees, registration fees, and licence fees. For inspection purposes, professional or high-end drones equipped with large cameras allowing photography or video recording can be used. Prices can range from 3000 to more than 10000 USD.

If services are preferred i.e. hire a company owning the required equipment and providing observation service, prices can range from 300 to 1000 USD for LIDAR survey and from 150 to 500 USD for photogrammetry.

Besides carefully checking the national laws applicable for an area of interest, piloting drones requires some training and / or qualification. Some organisations offer free of charge training for drone piloting. While training can be free of charge, some fees (e.g. 175 USD in the case of FAA) may apply for the examination.

3.3.2 Software

The main software needed to support operational activities is the GIS software. A Geographic Information System (GIS) is a computer system used to capture, store, manipulate, analyse, manage and present spatial or geographic data. GIS Software is the main software component needed to integrate (read data from multiple sources), process (perform basic or advanced processing of the data) and analyse (understand data and extract information based on their spatial relationship) EO data. It enables users to create maps and perform spatial analysis of the data. It can be desktop, mobile or cloud-based.

Cloud-based GIS is a software system that provides access to geospatial data and tools over the internet. It helps users to store, analyse, manage and generate maps on various devices such as mobile phones, personal computers, or tablets. Cloud-based systems are integrated with various technologies including GNSS, in-situ observation networks (such as groundwater level observation networks), and remote sensing EO systems allowing complex data analysis processes.

Desktop-installed GIS software is a software application that resides on a desktop computer. It includes features for managing and analysing data that is stored on a local disk or accessed via web service over the internet, including data gathered by mapping, surveying, land control, business information.

Mobile GIS is a type of GIS software specifically designed for use on mobile devices such as tablets and smartphones. It is often used for mapping, field inspection, urban planning or general land control. Mobile GIS software enables users to access and analyze data from anywhere in the world, as well as to create, view, and share maps and other GIS data, based on a mobile internet connection (either GSM or Wireless Communication).

4.3.3 Hardware requirements and cost estimation

An important aspect when considering the desktop solutions is the hardware requirements to be considered for using the software. For Example, the most known GIS software, ESRI ArcGIS, website specifies the following typical configuration for hardware and basic software (Operating System)

- Windows 10 or 11 Home, Pro or Enterprise Editions
- X86 or X64 hardware architectures with min 2.2 GHz CPU, min 8 GB RAM
- Video / Graphics adapter min 64 MB RAM
- Display with 24 bit colour depth

ESRI ArcGIS can be used in a cloud environment on Amazon WorkSpace Graphic Bundle or Microsoft Azure N-series Virtual Machines. The cost associated with the use of a cloud environment such as Amazon or Azure need to be estimated for each particular case using the tools made available by the cloud provider. Additional examples can be checked e.g. on CREODIAS website or Wekeo website.

4.4 Capacity building

Training

In the case capacity building is preferred instead of service providers, governmental organisations in charge with ECA in general and illegal water abstraction in particular should consider:

-Creating or extending their organisational structure by including the human resources needed to operate or manage additional computer infrastructure or access to cloud environments;

-If not established by law, concluding agreements on accessing various governmental and local administration data (see table 1 for references);

-Purchasing UAS equipment and / or piloting and survey services (indications on training and piloting certification are given in the previous sections);

-Training the selected personnel for using the software and data needed to implement the designed workflows; an average cost of 200/ USD / day / individual should be considered when planning the training and an average duration of 10 days / individual.

Training

For the cases when the training of the personnel is planned, a curriculum containing the elements summarised in Table 5 can be considered.

Strategy

When planning to build capacity at the level of an organisation mandated with tackling illegal water abstractions, the following can be considered:

-have general knowledge on groundwater and remote sensing and use external service providers for detection (continuous processes) and quantification; perform inspection activities;

-have deeper knowledge on groundwater and remote sensing, externalise detection processes, keep detailed analysis and inspection;

-ensure full capacity for detecting and inspecting on premises, using own personnel and hardware and software infrastructure;

-have general knowledge on groundwater, externalise services for detection and quantification tools running in a cloud environment and perform inspection.

Table 5. Personal training

Task	Subtask	Hours
Ground water	Occurrence and movement of groundwater	2
	Interaction between surface water and groundwater	2

	Field investigative methods	2
	Characterise groundwater systems from aquifer tests	5
	Computer modelling of groundwater flow	5
	Plan and manage groundwater extraction	4
Remote sensing	Types of remote sensing, spectral domains: active, passive, optical, microwave	5
	Characteristics of remote sensing (satellite or aerial) data	5
	Processing levels: raw, calibrated, accurate geocoding, Analysis-Ready Data	10
Geospatial data processing	Data storage and access: files, web services, cloud	3
	Reference systems and coordinates; geocoding	2
	Data structure, storage formats and visualization	5
	Spatial analysis and geoprocessing	5
	Satellite data processing and information extraction for	5
	Total hours	**60**

4.5 Operational aspects

In an operational context, ensuring the awareness level implies a careful planning of the workflows ensuring a smooth use of the detection methods presented in the previous section. Applying the detection methods involves access and use of an advanced data processing infrastructure, as described in report 4[41]. The table in Report 3[42] can be used as a guide on the steps to be achieved according to the 5 main detected phenomena, data needs, and corresponding observation/ measurement frequency.

Spatial resolution

Research has shown that the finer the spatial resolution, the greater the accuracy of e.g. irrigated area class designations. In general, to map accurately irrigated areas, the spatial resolution of the sensor must be equal to or less than the size of the fields of interest. Currently, the Sentinel-2 satellites (10m spatial resolution) can provide useful input for this kind of analysis when performed for detecting illegal water abstractions for agriculture or estimation of irrigation needs for areas bigger than 0.5Ha. Mine monitoring can be done at a variety of spatial resolutions from 0.3 m up to 3 m per pixel, depending upon the detail needed.

Spectral resolution

As shown in the previous paragraphs, a number of vegetation index images need to be derived from satellite data. Consequently, the satellite data records should contain visible, near-infrared, and sometimes short-wave infrared bands.

Temporal resolution

In the case of agriculture, the optimal period of image acquisitions and the minimum temporal resolution can be based on knowledge about the main cultivated crop and its crop calendar (seeding, harvesting, and development). When this information is not available, monitoring procedures can be designed and planned

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[41] TIGDA Report on Obtaining and Processing Earth Observation Data

[42] TIGDA Report on Identification of Earth Observation Methods and Data for Detection of Illegal Groundwater Activities

considering the weekly availability of satellite data (e.g. Sentinel-2 or Landsat). Practice showed that by-weekly or monthly checks could provide adequate information in the agriculture case.

In the case of urban phenomena e.g. related to sewage discharge, when pollution of surface water can be an indication of groundwater misuse, as shown in the previous reports, remote sensing of water bodies can be a solution for detecting it and planning further inspection.

Due to the velocity of the phenomena, subsidence due to intensive abstraction for domestic use can be observed in relatively long time intervals. This is why 6 monthly checks of ground motion maps as is the EGMS one could allow initial detection and confirmation of susceptible areas.

Applying repeatedly the detection methods described in the previous section involves access and use of an advanced data processing infrastructure, as described in Report 4.

Application of quantitative models

As reaching the specialist level involves clustering and quantification, the methods to be used need to be applied by experts. As the investigation of possibly illegal activities is in focus, groundworks and inspections need to be minimised.

In addition, it is recommended to identify specific wells that have to be used as a part of a specific hydro-geological monitoring system. This should focus specifically on the observable phenomenon in relationship to the monitoring objective (e.g. irrigation, urban dewatering system) stage. Consequently, the existing wells should be considered (and checked) to be part of a wells monitoring network allowing both hydraulic head and qualitative measurements.

A good understanding of the local and regional hydrogeological system should be fulfilled in this stage. This starts with an accurate delineation of the geology based on the existing geological and geomorphological maps, borehole logs, and existing geophysical studies. Data delineating the existing aquifers (top, bottom, extension) and their flow regime should be acquired and possible monitoring points should be identified. Understanding the spatial characteristics and relationships of aquifers and aquitards, including their geometry, flow regime (confined/unconfined), and hydraulic properties, is key to any groundwater resource assessment.

Further, the groundwater dynamics should be analysed in order to establish pertinent mechanisms of quantitative or qualitative degradation. Hydraulic head measurements should be performed in the identified monitoring points and compared to hydraulic head time-series datasets obtained from national or local databases. It is also recommended to acquire hydrogeological data respectively hydraulic conductivities (interpret the already existing pumping tests), rock porosity values, interpret existing tracer tests.

If choosing the rigorous approach, when qualitative or quantitative deviations from the water rights are in focus, a detailed analysis process needs to be implemented. In some cases, a hydraulic head and/or groundwater quality monitoring program should be set up. Consequently, an extended network of monitoring wells has to be designed and implemented allowing both hydraulic head and qualitative measurements. The hydrogeological system of the targeted area has to be deeply understood and the groundwater monitoring system could be improved by new observation wells. If necessary, geophysical studies should be performed in order to obtain a better delineation of the local geology.

In some cases, a numerical hydrogeological model of the area should be developed by integrating accurate data. To do this, the existing national/local groundwater monitoring network should be extended by drilling new monitoring wells. These will be used to monitor the groundwater dynamics of the aquifer system as well as to obtain truthful values of hydraulic conductivity in several key locations.

With the entire data sets a groundwater flow model, giving an accurate image of the aquifer dynamics, should be developed. In the case of groundwater pollution, the groundwater flow model will be used in developing a groundwater contaminant transport model. This last represents a solid basis for highlighting groundwater contamination mechanisms. In this last case, tracer tests could be used to derive distinct groundwater contaminant transport parameters (e.g. transfer time, porosity) as well as, in some cases, to prove direct contamination mechanisms.

The goals to be established for drone inspection are different for each of the use cases considered. The following can be considered as initial goals:
-crop irrigation: images showing the wells and pipes; crops images at maturity;
-industrial use: ecosystem degradation, decrease of surface water level;
-mineral extraction: surface structures damaged by tilting, mine water discharges;
-sewage discharge: flooded infrastructure, pollution of surface water bodies;
-domestic use: images showing the wells.

No matter the case, the recommended workflows need to be applied for getting flight clearance, having an authorised pilot and a flight plan and others, depending on local conditions and applicable legislation.

5. Concluding remarks and possible ways forward

This report summarises the findings of the reports produced under the TIGDA (*Tackling illegal GW drilling and abstractions)* project of IMPEL which aims to share knowledge and good practices on how to manage GW drilling and abstractions. Under work package named *Earth Observation Techniques for the Detection of Illegal GW Activities* which aims to review the different types of EO methods and data that can be used for the detection of illegal GW activities, reference is made to EO data and existing cloud platforms and software allowing the implementation of the recommended workflows associated with each level of awareness defined by IMPEL:

- Awareness Level 1: only suitable for filtering in potential illegal GW activity abstraction. Will help understand if more detailed inspection techniques are required.
- Advanced Level 2: ability to map clearly the location of illegal GW activities.
- Specialist Level 3: ability to clearly indicate the clusters and scale of illegal GW activities for prioritisation by the regulatory authority
- Expert Level 4: ability to provide sufficient evidence to automatically fine without local inspections activities

For data and instruments, indications are given on access methods and cost. Also, indications on skills required for the operation and training cost are given as well as on the infrastructure needed for deriving the actionable information for tackling the nonconformities.

When public services are available, the detection of suspicious areas can be done by analysing the data made available by those services to reach the awareness level 1 and most probably the advanced level 2. To reach the specialist level 3, quantification methods need to be designed, developed and made ready to use. UAS or drone inspection allows reaching expert level 4 in some cases.

When possible, the use of satellite EO data should be maximised, especially when weather conditions make it difficult or the area of interest is too large to be covered by drones.

However, the first option should be the one relying on or including in the operational workflows the various EU-level developed services, such as the EO Governmental service for the data and the SatCen portfolio of services for detailed analysis.

Even the well-known approach of building capacity inside the organisations mandated with law enforcement can always be a valid one, recent development of data/ thematic platforms storing EO data as well as analysis tools need to be considered with priority as it can ensure more flexibility and reduce implementation cost and duration especially when combined with workload sharing with service providers covering e.g. monitoring activities or advanced analysis of different area of interest that are prone to illegal abstraction.

Advances made in relation to quantification methods involving AI or other advanced analytics show promising perspectives. In a recent paper[43] groundwater pumping is estimated starting from ET data derived from remote sensing and climate data. It is thus recommended to plan and perform a continuous check of the scientific results and integrate them in operational workflows when appropriate.

[43] Thomas, J Ott. 2024. Toward field-scale groundwater pumping and improved groundwater management using remote sensing and climate data. Agricultural Water Management. https://www.sciencedirect.com/journal/agricultural-water-management

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