European Association of Remote Sensing Companies

Sentinels Benefits Study (SeBS)

A Case Study

Aquifer Management in Spain

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Setting the Scene

Alfredo has just removed the cooking pot from the fire. Today he is preparing his – and one of the whole Murcia region – finest recipe: "*Alcachofas de la abuela*", or grandmothers's artichokes. The simplicity of this dish may be deceiving – it only contains artichokes and a few pine nuts! But to bring out all the richness of this dish, Alfredo had to carefully peel, clean, fry and then cook in special broth the artichoke hearts. Now he is waiting for the mix to "rest". 10 minutes is enough time to browse the latest news on Murciatoday.

As Alfredo browses the headlines, he sighs with exasperation. The current drought – persisting for more than two years now, is putting significant strain on water resources and threatening agricultural production. With Murcia being Spain's largest artichoke producer, and Spain being the EU's second largest producer, Alfredo realises that if the drought persists, the very dish he is now eagerly waiting to taste might be unattainable in a year's time. This will definitely make him savour lunch today. But as he turns his gaze on the wall, he quickly recalls that droughts can have other tangible impacts too.

Back in the period 1992-1995, the previous intense drought period, the side wall of his house cracked. He soon learned that extraction wells located nearby were working "day and night" to address the water deficit. But, as Alfredo and many others also bitterly experienced, this overexploitation of the aquifer resulted in ground subsidence that caused damages in buildings.

The thought that this might happen again brought a shiver up his spine. Almost forgetting about lunch, he dove back into the online newspaper hoping to find some glimpse of positive news. And he did!

A whole "related" article was dedicated to the efforts of the Confederación Hidrográfica del Segura (CHS), the authority responsible for water management in the region to tackle the new drought. In it, a picture of a Copernicus Sentinel Satellite was just under the introductory paragraph. Apparently, CHS had contracted the Geological and Mining Institute of Spain (IGME) and DARES a small company from Barcelona, to monitor ground deformation during the aquifer water extraction operations. The article was reassuring that this cutting-edge technology would aid CHS in ensuring sustainable aquifer management and protecting the properties of citizens from damage.

Finishing the article, Alfredo's mood had instantly changed! With renewed enthusiasm he went back to the cooking board, added a pinch of salt and some olive oil and plunged into a culinary experience that you can only find in Murcia!

This story is entirely imaginary, although realistic based on our knowledge gained through the case interviews. The places are real, as are the characters, although the conversation and the situation are entirely fictional.

Executive Summary

This case deals with aquifer management, a topic little known to the general public yet extremely important. This importance is even greater in semi-arid areas such as Murcia; a region which heavily relies on agricultural productivity yet is often hit by severe droughts. This combination results in extreme strain on the management of water resources, which, in the absence of other alternatives, often results in overexploitation of the aquifer. The impact of overexploitation can be devastating: it leads to ground deformation that can cause building damages (of the order of 50 million euro in the previous drought period, 1992-1995); it results in aquifer depletion, endangering water quality, reducing the productivity of agricultural soils and threatening protected natural areas.

In view of all this and faced with a new extended drought period (2014-2020), the Confederación Hidrográfica del Segura, the authority responsible for managing water resources in the region, sought the help of IGME and DARES to monitor ground deformation. Using Sentinel-1 and advanced algorithms, DARES generated InSAR measurements over an area of 1200km^2. These measurements were used by IGME in conjunction with piezometric data around the wells extracting water from the aquifer, to produce regular ground deformation for CHS.

By using this solution, CHS has been in a much better position than before to make informed decisions on the sustainable management of the aquifer. As a result, the property of citizens and businesses is protected, costly alternative solutions – which anyway do not produce equal results – are avoided, and long-term strategies can be drafted.

The benefits associated with the use of Sentinel-enabled InSAR monitoring of ground subsidence are significant. Economic benefits amount to 31.7-71.8 Million Euros annually; these are related to avoided costs from investment in GNSS total stations, and, very importantly, to avoided costs from damages to buildings. Moreover, the provision of the service by DARES and IGME generates revenues between 0.9-1.8 Million Euros annually. Being linked to sustainable access to water resources, one of the most important challenges faced by societies around the world, this case also presents substantial benefits along the other dimensions studied. It has significant environmental perspectives linked to aquifer depletion – a subject becoming all the more prominent in view of climate change effects; it touches upon sensitive societal dynamics involving the use of water for agriculture vs the use for households; it underpins the important of regulation in this context; and, finally, it highlights how Sentinel-enabled services drive progress in terms of science and technology, but also in terms of entrepreneurship.

The extrapolation potential of the case is also significant. Many other regions both in Spain and beyond (e.g. Italy, Greece, Turkey, Israel, Jordan, Egypt, Morocco, etc.) present similar conditions: semi-arid climate, frequent droughts, strong agricultural productivity. This means that the Sentinel-based InSAR solution discussed here could effectively be applied in many other contexts.

In summary, the findings presented in this case underpin the important role that Sentinels can play in addressing significant societal and environmental challenges (i.e. aquifer management vs aquifer overexploitation) and in bridging the work of innovative companies (DARES) and prestigious research organisations (IGME) to that of forward-looking public authorities (CHS) who need to take informed decisions in the face of critical challenges (i.e. sustainable water management under pressure of climate change).

1 Introduction & Scope

1.1 The Context of this study

The analysis of the case study *'Aquifer Management in Spain"* is carried out in the context of the 'The Sentinel Economic Benefits Study' (SeBS). This 4-year study is looking to develop cases showing how EO-derived products based on data generated by one or more Sentinel satellites deliver value to society and citizens. The Sentinel satellites form a crucial part of EU's Copernicus Programme, providing space-based observations on a full, free and open basis. Data coming from the Sentinels – together with other data collected by contributing missions and ground, sea or airborne instruments – is used to support key economic or societal areas such as agriculture, insurance, disaster management, climate change monitoring, etc. Sentinel data are thus a key component of the Copernicus Services, and a crucial source used by companies to deliver products and services helping different users across the Globe.

1.2 What is the case all about?

The subject of "aquifer management" is, to a large extent, relatively unknown to the average person. Yet, it is truly a critical subject, if one considers that **nearly half of all drinking water in the world and over 40% of the water used for irrigation is sourced from groundwater**[1]. Moreover, with many areas in the world experiencing more frequent and more severe droughts – a direct result of climate change – the sustainable management of groundwater resources becomes essential for the well-being of communities depending on them. Yet, the interests of these communities are often in conflict, with **farmers competing with residents – especially in large urban areas – over the increasingly scarce water resources**[2]. As a result, and due to the lack of appropriate water management policies, for many years now, the typical response to extended drought periods – most prominently in semi-arid and arid regions around the world – has been the over-exploitation of aquifer groundwater. This, together with the extended pressure from climate change, has led to a **global groundwater crisis**[3], whereby groundwater resources in many areas around the world are being depleted. The over-pumping of aquifer groundwater has further adverse effects, both direct and indirect, on the environment (for instance streamflow for native fish populations[4]), on land management (in particular in connection to land subsidence[5]) and on local economies[6].

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[1] See "Groundwater and Climate Change" - http://www.idaea.csic.es/sites/default/files/Groundwater_and_Climate_Change.pdf

[2] See https://www.nytimes.com/interactive/2019/08/06/climate/world-water-stress.html

[3] https://www.ecowatch.com/groundwater-being-rapidly-depleted-2642909578.html?rebelltitem=1#rebelltitem1

[4] https://wildlifemanagement.institute/outdoor-news-bulletin/february-2016/research-identifies-impact-groundwater-pumping-great-plains

[5] https://geochange.er.usgs.gov/sw/changes/anthropogenic/subside/

[6] https://truthout.org/articles/global-groundwater-is-threatened-by-unsustainable-practices-amid-climate-crisis/

In light of all this, **the importance of sustainable aquifer management becomes apparent**. In their efforts to achieve this, **the authorities responsible for groundwater management can use the help of Earth Observation services**. Thus, thanks to the free, full and open access to Copernicus Sentinel data (in particular to the Sentinel-1 SAR), innovative companies can offer reliable services that allow the authorities responsible for groundwater management to monitor ground subsidence and take informed decisions on the operation of groundwater wells. We came across a prime example of such a service in Murcia, Spain. DARES, a leading company in the delivery of ground deformation maps, has teamed up with the Geological and Mining Institute of Spain (IGME), to support aquifer management efforts undertaken by the Confederación Hidrográfica del Segura (CHS) in the very important Segura River Basin.

In this report, you will discover both the story and the rigorous analysis around the benefits experienced by different value chain actors in this case. The analysis relies on clear and openly presented assumptions which have been shaped with the help of the stakeholders we interviewed (see 1.5 below). However, we encourage any reader to contact us if they think the assumptions are unreasonable for any reason through emails to Lefteris Mamais (lef@earsc.org).

1.3 How does this case relate to others?

This case is part of the family of InSAR cases being developed and analysed within the frame of the SeBS project. A previous study analysed the benefits derived from the use of InSAR to monitor ground deformation in relation to Infrastructure Monitoring in the Netherlands[7] and another one regarding road management in Italy. Given the almost exponential growth of InSAR cases all over Europe, it will certainly feature in future cases as well. In the Netherlands case, the use case was focussed on the monitoring of ground deformation linked to the management of gas pipelines. There, the InSAR approach allowed the operator of the pipelines to be much more precise in the maintenance and replacement of dangerous gas pipelines at risk of breaking. Instead of replacing pipelines of whole neighbourhoods to be on the safe side, the application of InSAR has allowed the operators to detect dangerous ground-movement "by the house number" and thus only replace those pipelines that really are at the risk of breaking due to ground movement.

In this use case, InSAR is an invaluable tool to coordinate and determine in drought periods where and which drought wells can be sourced to provide a stable water supply in this agriculture-heavy region without causing harmful ground deformation. As in the Dutch case, InSAR can provide thousands of measurement points as opposed to a few stations throughout the region and thus allows for a much more precise understanding of ground movements throughout a predefined area.

The variety of InSAR applications will lead to a significant portfolio of cases. Its application is very broad and continues to develop as associated benefits increasingly draw attention and become wider-known and better understood. At the time of writing, two other cases (in Italy and Norway)[8] based on the use of InSAR are also being completed.

[7] http://earsc.org/Sebs/wp-content/uploads/2019/03/Infrastructure-monitoring-Netherlands-Full-case.pdf
[8] These cases will be published at http://earsc.org/Sebs/

The ability to measure small movements in the ground surface, or even below ground, on a sustainable and relatively low-cost basis, is becoming recognised as a powerful tool. Depending on the specific use case, some of the applications require relatively frequent updates while others need measurements that are synthesised into a concrete report only a few times during a year, as in this case here. Often, as in this case, the spatial resolution of Sentinel-1 data is sufficient while for instance in the Dutch case, Sentinel-1 data was used first to then trigger a more detailed analysis using commercial, higher resolution satellite data (the typical tip and cue approach).

As we develop the portfolio of cases based on InSAR, the wider picture will be considered to draw conclusions between the different types of application (or use-case).

1.4 More About the Study

Each case study analysed in SEBS, focuses on products and services which use data coming from Sentinel satellites, measuring the impact of that product or service throughout the value chain. The starting point is the primary user of the satellite data, followed by a step-by-step analysis whereby the operations of beneficiaries in each subsequent link of the value chain are analysed, all the way down to citizens and society.

In this process, the main aim is to understand and demonstrate the value which is generated using satellite-based Earth Observations (EO) and particularly the data coming from the Copernicus Sentinel satellites. Each case study thus underlines the causal relationship between the use of Copernicus Sentinel satellite data and benefits resulting from their use, including increased productivity, more efficient and environmentally friendly operations, economic gains and improved quality of life, among others. The evaluated and demonstrated benefits can be used by:

- **Decision makers**: Having access to a portfolio of concrete cases where the benefits from the operational use of Sentinel data in decision making are clearly articulated, helps decision makers not only to justify future investments but also to direct them towards areas that most matter in their country or organisation.
- **Users:** Moving beyond a vague idea of how EO services can support more effective operations requires a concrete understanding of the benefits they can actually bring in similar cases. In this regard, it is both numbers and stories that can resonate with users and attract them to explore further or deeper uses of EO in their operational activities.
- **Service providers:** Solid argumentation around the economic and environmental benefits stemming from the use of EO, coupled with powerful storytelling, can become an effective marketing tool for service providers seeking to promote their solutions and for EARSC to promote the sector.

In the framework of this project, 20 case studies will be developed with reports to be published on each one. The study has started in March 2017 and will end in mid-2021.

1.5 Acknowledgements

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2 Aquifer Management in Spain

2.1 Overview

Aquifers and the groundwater stored in them have, unknowingly, become indispensable for economic activities in many European countries especially in the hot, arid south. Starting from the very basics, the term "aquifer" generally refers to the underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt). Often, the rock holds water-filled pore spaces, and, when linked, these spaces allow water to flow freely through the rocks. Wells can be drilled into the aquifers so that ground-water can be extracted. Precipitation eventually adds water (recharge) into the porous rocks of the aquifer to complete the cycle.[9]

Although deep down in the soil, meters under the surface, aquifers provide a great deal of the existing freshwater on the Earth with a share of around 30%. Only 1.3% is available as surface water (for instance in lakes or rivers) while the rest is "trapped" in glaciers and ice caps. Being readily accessible, the surface water is often limited and demand for it is often high depending on the regional circumstances. This has made groundwater extracted from aquifers an invaluable resource of fresh water throughout the centuries in many parts of the world.[10]

Almost anywhere in the world, demand for aquifers, or better groundwater extraction, is determined by three factors:

1. drinking water and households
2. irrigation for agriculture (predominantly)
3. industry

These three factors often compete for the available surface water and groundwater, and where demand exceeds supply, overexploitation of aquifers has had detrimental effects on the environment and society. In fact, this is the case in 20% of the world's aquifers which often results in serious repercussions such as land subsidence and saltwater intrusion.[11] Furthermore, extensive pollution has resulted in only 1% of all freshwater (i.e. surface and groundwater) being available for direct use.

It is projected that the magnitude of the global groundwater footprint is at present approximately 3.5 times the actual extent of aquifers and that circa 1.7 billion people live in regions where groundwater resources are at great risk. On top of that, 80% of aquifers have a groundwater footprint that is smaller than their area, meaning that the net global value is determined by a few severely overexploited aquifers.[12]

This lets us conclude that effective and appropriate management of aquifers in general, but especially for those extremely overexploited aquifers, is indispensable for sustainable use and long-

[9] https://www.britannica.com/science/aquifer
[10] https://www.usgs.gov/special-topic/water-science-school/science/where-earths-water?qt-science_center_objects=0#qt-science_center_objects
[11] https://www.nature.com/articles/nature11295
[12] Ibid.

term availability of groundwater. Effective aquifer, or groundwater, management therefore has been defined as one whereby a so-called *safe yield* is respected, i.e. a rate of water extraction that does not cause any "undesirable adverse effects"[13]. The safe yield corresponds to an extraction rate equal to the total recharge or 50% of total recharge depending on different scientific studies. Yet, all studies dealing with aquifer management agree that effective aquifer management should entail the objectives of **renewability** of the resources, **practical exploitations** and **consumption rationality**.[14]

2.1.1 Climatic and Geological Conditions in Spain and Murcia

Spain is among the most arid countries in Europe but features a massive hydrogeological potential. The country is thus a perfect case where due to specific climatic and hydrogeologic pre-conditions and therefore **low levels of surface water**, aquifers have traditionally had to be sourced to secure a reliable supply of fresh water. Most aquifers in Spain are scattered throughout the country and it is projected that the annual aquifer recharge amounts to c. 30% of the total water resources available in the country. Like many other southern European countries, most of the water resources that Spain has at its disposal is currently used for irrigation in **agriculture** and, to a lesser extent, in **industry**. In many instances, the majority of the abstracted groundwater is coming from a **few over- or intensively exploited aquifers** in Southern Spain (see Figure 2-1). Against this backdrop and in light of the **increasing demand** observed over the last decades, **effective aquifer management and thus long-term supply of fresh water is crucial**, both for basic needs (i.e. households) and for specific sectors (i.e. agriculture).

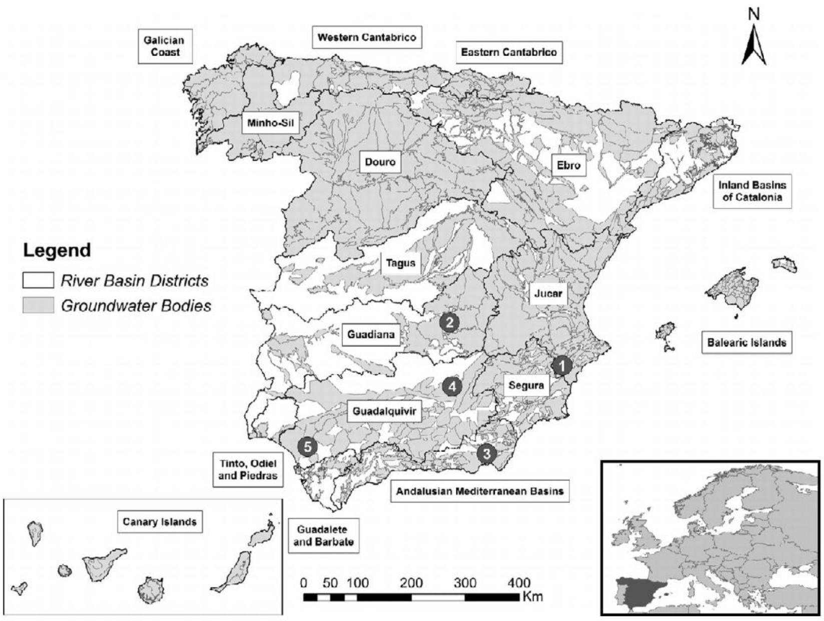

Figure 2-1 Groundwater bodies in Spain. Adapted from De Stefano et al. (2013)

[13] https://www.sciencedirect.com/science/article/pii/B9780128000755000066

[14] Ibid.

One of the most overexploited aquifers in Spain is located in the Segura River Basin in the Southeast of Spain (see location 1 in Figure 2-1) and encompasses the metropolitan area of the city of Murcia, the biggest city in the valley with more than 400,000 inhabitants. The region has developed by occupying the flood plain of the Segura River and extends over 19000 km², a large part of which is cultivated land used for agriculture. Geographically, the river runs from the Southwest to the Northeast through the valley with height changes between 60m and 30m. Overall, this shows the dimension and importance of agriculture in the region for which the river is an important source of fresh water as well.

The aquifer system in the Region of Murcia is composed of two units, a superficial and a deep aquifer. The superficial aquifer comprises the first 5 to 30m of recent clay, silt and sands facies. The lower aquifer system, situated under the aforementioned aquifer, is made up of a sequence of gravels and sands alternating with marls, clay and silts. In the upper part of this aquifer, just under the superficial aquifer, there is a 10 to 30m layer of gravel that has been intensively exploited since the 1990s as it contained a significant water resource.

Most importantly, and this point is crucial to this case study, the **materials that make up the superficial aquifer in the Region are extremely compressible**. They provide a layer of medium to soft sediments that are **vulnerable to suffering from consolidation** due to variations of effective stresses acting upon them. The gravels and sands beneath are, on the contrary, more rigid and are the geotechnical substratum (i.e. basis) of the zone, used as the support level for deep foundations. As soon as groundwater is extracted from the upper gravels of the deep aquifer, a gradient is formed causing the **lowering of the water table**. Consequently, pore pressure in the upper superficial aquifer declines and the aquifer goes through a **consolidation process, often including land subsidence**.[15]

In the past 20 years, two major drought periods occurred in the Region of Murcia 1992–1995 and 2006–2009. In both cases groundwater from aquifers was intensely exploited, initiating and accelerating the aforementioned consolidation processes. In the first period, a lowering of the piezometric level of around 8m (i.e. the liquid or hydrostatic pressure in the aquifer) caused an estimated ground settlement of 8cm! During this period, the consolidation of the aquifer system in the City of Murcia led to damages in buildings and other structures and resulted in great economic loss.[16]

2.1.2 Aquifer Management in the Region of Murcia

Given the crucial importance of effective aquifer management and rational groundwater extraction in Spain, water has been recognised as a public domain resource as of 1985. Thanks to this new legislation, water that is abstracted from wells drilled from 1986 onwards is for public use.

[15] G. Bru, G. Herrera, R. Tomás, J. Duro, R. De la Vega & J. Mulas (2013) Control of deformation of buildings affected by subsidence using persistent scatterer interferometry, Structure and Infrastructure Engineering, 9:2, 188-200, DOI: 10.1080/15732479.2010.519710
[16] https://www.researchgate.net/publication/26641182_Advanced_interpretation_of_subsidence_in_Murcia_SE_Spain_using_A-DInSAR_data_-_Modelling_and_validation

Nevertheless, users that had installed private wells and exploited groundwater before that year were able to keep their water rights private. As a result, most water users opted for the latter alternative which is why most groundwater rights in the Region are still held private until today. This, in turn, has led to situations of high legal complexity since public and private ownership entails different rights and obligations upon users as well as different legal alternatives and restrictions for water authorities.

On top of that, unlicensed groundwater extraction has continued posing a major concern that water authorities often find themselves struggling with. It is projected that the number of illegal wells is more than half a million! 90% of existing wells could be unauthorised or in a legal grey area.[17]

Furthermore, policies related to groundwater management are impacted by the European Water Framework Directive (WFD), which in the Region of Murcia is to be implemented by the respective River Basin Authority CHS. As all EU Member States, Spain is currently in the process of implementing the principles of the WFD, and this process represents a unique opportunity to improve groundwater protection, knowledge diffusion and generally a more effective management of the aquifer. However, to adapt the WFD principles to both the hydro-climatic and socio-economic context of a southern Mediterranean country such as Spain is a highly challenging task.[18]

In the Region of Murcia, CHS as the Segura River Basin Authority, an autonomous organisation of the General State Administration, is responsible for the general management of the water resources, and thus for the aquifers in the Basin. The biggest challenge faced by CHS is the structural water deficit in the Segura River Basin that is characterised by frequent extreme meteorological events like floods and droughts. As a consequence, the various water users in the basin have developed a long history and strong expertise in water culture aiming at optimum use of the available resources for both drinking and irrigation purposes.

A key experience for the operations of CHS was the period from 1992 to 1995 which was characterized by frequent and prolonged droughts across the Mediterranean. The period was one of the driest in the century for the Iberian Peninsula, and especially Spain. The drought had several peaks, with the most extreme period between 1994 and 1995.

For the Region of Murcia, the 1992-1995 drought had disastrous effects since the demand for water rapidly increased. In the wake of the crisis, water demand increased, leading to severe overexploitation of the aquifers. This, in turn, led to extreme water shortages and under-supply for some farmers, resulting in a reduction of cultivated areas due to a lack of irrigation water, reduced productivity of annual crop cultivation as well as a regional shortage of feed/water for livestock[19]. More importantly, the **overexploitation led to a consolidation process of the superficial (upper) aquifer** in the Segura River Basin (as explained above), resulting in severe damages to buildings and infrastructure, ultimately causing economic loss and even risk to human life[20]. More than 300 complaints were received, and more than 150 buildings and other structures (sidewalks, roads,

[17] https://www.nat-hazards-earth-syst-sci.net/9/647/2009/
[18] https://ec.europa.eu/environment/water/water-framework/index_en.html
[19] http://www.geo.uio.no/edc/droughtdb/edr/DroughtEvents/_1991_Event.php
[20] http://www.dfists.ua.es/~juanma/PapersPDF/Journals/rse/tomas05.pdf

walls, etc.) suffered moderate damages. The region faced an economic loss of around 50 million Euros. The severity of the drought period from the 1990s and its consequences led to several investigations into the cause and effect relationship between droughts, aquifer management and land subsidence and how the water resource management of the aquifer system could be improved in the region.

As a reaction to the drought periods 1992-1995 and a second one following in 2006-2009, a **special legal plan for drought periods**[21] was developed, managed and monitored by CHS to prevent future over-exploitation of the aquifers and mitigate potential negative impacts on the environment and economy. Essentially, a 3-step-indicator system was defined that shows the degree of water shortage in the aquifers across the Segura River Basin.

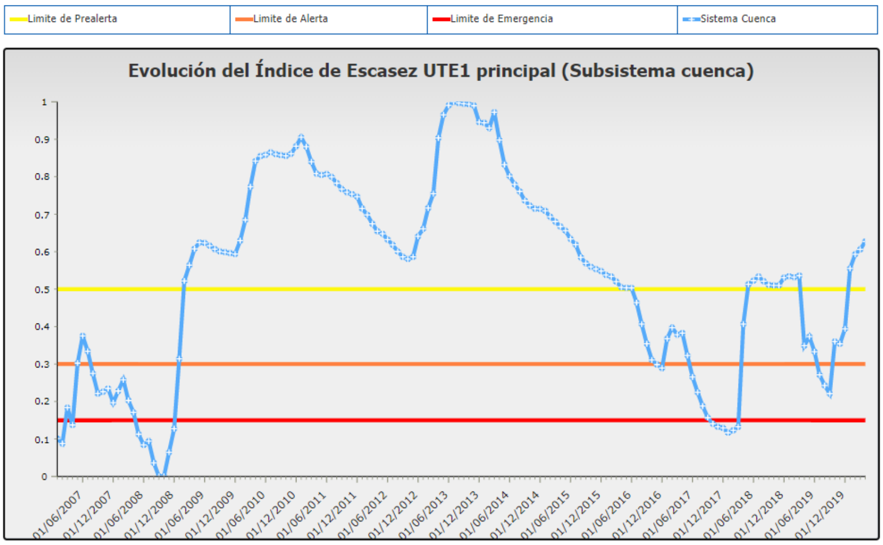

Figure 2-2 Development of the value of the shortage index in UTE I Main (Basin Subsystem I; one of the 4 sub-basins). © CHS

For each of the four sub-basins of the Segura River Basin, there are two important variables defining this index, and which are each calculated once a month: the **amount of precipitation** and the **relation between demand and supply**. Based on three thresholds of severity (yellow = pre-alert, orange = alert, red = emergency), an "official" drought is declared once the index (see Figure 2-2) has overstepped the critical red line ("emergency line") for three consecutive months. If an official drought is declared, the government has to publish a decree that, depending on the severity, releases further budget to CHS to allow special mitigation measures such as the exploitation of further drought wells operated by CHS or increased output by desalination plants that exist since the 1990s in the region.[22]

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[21] https://www.boe.es/diario_boe/txt.php?id=BOE-A-2018-17752

[22] Ibid.

2.1.3 Social, Environmental and Economic Dimension of Aquifer Management

Aquifer and (ground-)water management touch upon and impact crucial social and economic aspects in the Segura River Basin for various reasons. Historically, the region has been the natural home for the cultivation of fruits and vegetables since annual temperatures are high almost throughout the year and the soil in the region is especially fertile. These conditions have been ideal to produce **significant agricultural output with extremely high quality**. As a result, Murcia and the Segura basin have become the main producers of fruits and vegetables in Spain over the last decades: while the region only comprises 4.3% of the Spanish population, it is responsible for between 20 and 30% of the country's exports in this segment and thus owes a considerable part of its economic productivity to the agricultural sector.[23]

The astonishing productivity has been achieved both **thanks to and despite the regional climate since the Segura River Basin suffers from a structural water deficit** which brings us back to the importance of effective water management. The river basin is one of the driest in Europe and, by far, the driest in mainland Spain. The rain throughout the year (365mm annual rainfall on average) falls within just a few days. These conditions, however, have been viewed by farmers as a challenge to meet, and consequently, agriculture has flourished and is the predominant economic activity in the region.[24]

Despite considerable efforts to increase the water supply (through the building of dams or canals providing water from remote basins and desalination plants) as well as a traditional culture of rationalising water use, the **water deficit has remained at a dangerous high up until now**. Essentially, it boils down to the region being inherently dry, and in the foreseeable future, the effects of climate change will only intensify the observed extremes i.e. unreliable rainfall patterns and high average temperatures (see for instance the graphs produced by the Copernicus Climate Change Service[25] as part of the European State of Climate 2017).

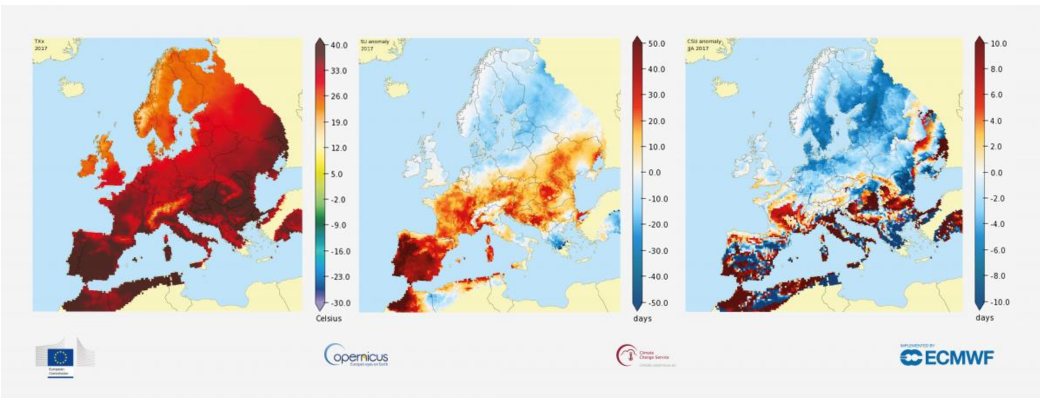

Figure 2-3: Maximum value of daily maximum temperature (credit: C3S/ECMWF/KNMI)

[23] https://murciatoday.com/understanding-water-and-the-drought-in-murcia-and-the-segura-basin_171862-a.html
[24] Ibid.
[25] https://climate.copernicus.eu/climate-2017-focus-region-southwest-europe

Similarly, multiple studies into the effects of climate change in the region are raising the alarm. The 2018 Special Report on Desertification by the European Court of Auditors makes specific mention to the region of Murcia and to the South of Spain[26], and the ensuing soil degradation has even made it into "mainstream" media[27]. Of course, the problem of water scarcity and soil degradation is not confined only to Murcia – a large part of the Mediterraean basin is also suffering from this issue[28].

Currently, CHS estimates an annual demand for fresh water in the whole Segura River Basin of around 1,843 cubic hectometre of which 14% is reserved for urban supply (this includes industrial use and e.g. golf courses) while a **whopping 83.9 % is allocated to agriculture**. On the other hand, a typical hydrological year provides only fresh water through (in hm^3):

- Surface water (reservoirs and rivers): 400
- Groundwater (aquifers or drought wells): 218
- Transfer (canals): 322
- Regenerated or re-used water: 270
- Desalinated water: 193

This shows that the **region is 440 hm^3 short of fresh water**, leading to an **enormous structural water deficit** and ultimately to **competition for water between the various sectors and users of fresh water in the region, but also only amongst agricultural producers**. Naturally, these stakeholders are looking for every bit of additional capacity. However, expanding supply from the mentioned sources is difficult, if not impossible. Surface water is essentially dependent on rainfall which is erratic and extremely low in the area. Transfers from other regions are limited as reservoirs for instance in Cuenca or Teruel are dangerously low. Regenerated water from wastewater is already at maximum capacity and 98% of it is going towards agricultural purposes, leaving **little room for expansion**. Lastly, desalination plants are operating in the region and with more plants, more fresh water could be supplied, yet they are expensive to run and bring about further negative environmental impacts. Moreover, water coming from desalination plants is of poor quality for both urban and agricultural purposes which is why it has to be mixed with other sources.[29]

With these limitations, farmers have sought to expand water supply primarily through the increase of groundwater abstractions from the aquifers of the basin, often clashing with environmental interests and sustainable practices. This is reflected in several protests and demonstrations by farmers and agricultural interest groups in front of the CHS headquarters in Murcia in times when CHS had to limit access to groundwater for environmental protection.[30][31]

[26] https://www.eca.europa.eu/Lists/ECADocuments/SR18_33/SR_DESERTIFICATION_EN.pdf
[27] See for instance https://www.politico.eu/article/farmer-sand-spain-fight-against-desertification-soil-degradation/
[28] https://www.medecc.org/wp-content/uploads/2018/12/MedECC-Booklet_EN_WEB.pdf
[29] https://murciatoday.com/understanding-water-and-the-drought-in-murcia-and-the-segura-basin_171862-a.html
[30] http://www.fruitnet.com/eurofruit/article/174933/madrid-protest-highlights-spanish-water-crisis
[31] https://murciatoday.com/outrage-among-murcia-farmers-as-the-spanish-government-denies-them-water_1243632-a.html

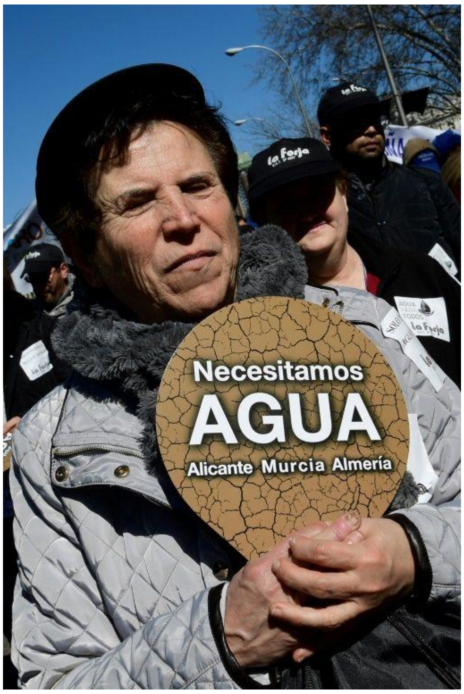

Figure 2-4: "We need water" – farmers protest in 2018 © AFP News

Increasing agricultural cultivation while at the same time implementing a more restrictive policy in terms of access to groundwater on the part of CHS has meant that illegal water use, illegal wells and even the construction of canals leading water to farmers' fields without an official permit have spread throughout the region. It is projected that some 6,500 ha are turned into irrigated farmland each year in the Segura River Basin, highly increasing water demand. Moreover, it is estimated that in the most severely overexploited regions of the Segura River Basin around 40 % of irrigated lands are illegal. This flourishing illegal activity has taken place not only in the Segura River Basin but in numerous Spanish water-stressed regions. The main reason for the rate of illegal groundwater abstraction lies in the enormous profits that can be made and that have incentivised farmers to expand their farmland in the face of ineffective controls by public authorities. As a result, river basin authorities such as CHS are increasingly under huge economic and political pressure which complicates their efforts to tackle illegal water use and aquifer (over)exploitation[32][33]. One important parameter exacerbating the effects of illegal wells is the fact that whilst offenders are known and denounced through administrative channels, the system allows many guarantees, leading to prolonged procedures and eventually causes a situation where illegal wells are not effectively sealed until many years have passed.

Agriculture is not the only economic factor in the region. The **booming tourism** industry has developed exponentially in Spain over the last decades and in the Region of Murcia in particular.

[32] https://www.wwf.eu/?68900/Spain-sucked-dry-by-illegal-water-use

[33] A study of the Ministry for Public Works calculated an increase of 65.400 ha. between 1990 and 2000 of irrigated farmland in the Segura River Basin, although the law forbids to grant new water concessions for irrigation since 1986. The results of that study can be found in Annex II of the report "*Informe de Sostenibilidad Ambiental. Actuaciones Urgentes del Programa Agua en las cuencas mediterráneas*" (Ministerio de Medio Ambiente, 2005).

Water demand has risen not only to satisfy increasing demand due to mass tourism but also due to the **resultant thriving construction industry**. From 2005 to 2015, tourism in the region had roughly doubled and continued to grow over the last years, even outperforming other Spanish regions by far.[34] To meet accommodation needs, it was estimated in 2005 that an additional staggering 114,000 (!) buildings for urban development and tourism were planned while the number of golf courses that consume huge amounts of water for irrigation has more than tripled from 6 to 22 between 2005 and now.[35][36]

What all this shows is that water management and ultimately aquifer management is a highly delicate issue in the Region of Murcia and touches upon almost any aspect of economic and social life. Limiting access to groundwater directly affects the agricultural output of farmers in the region which have the biggest share of GDP regionally. Similarly, for instance, no golf player is eager to play their shots on an arid golf course! This demonstrates that reliable **access to (ground) water is directly related to economic success** in the region – perhaps more than anywhere else in Europe given Murcia's economic structure and characteristics – which in turn points to the economic and social dimension of aquifer management. While water abstraction from aquifers is one of a few potential water resources in the region, it is seemingly the easiest especially for farmers to source from with relatively little to no effective controls. At the same time, effective aquifer management with the perspective of long-term sustainability is crucial in that over-exploitation may lead to a tipping point after which aquifers will not be able to recharge and thus destroy the very basis of economic activities in the region in the long-term: water security.

2.2 Informed decisions, coordinated actions and effective interventions

Preventing, reducing and mitigating the adverse impacts of groundwater exploitation and subsequent land subsidence with an intensity, duration and geographical spread as in the case of the Region of Murcia requires that all actors work seamlessly together and that all available sources of information are effectively used. Thus, having the best possible situational awareness – i.e. where and when groundwater is being extracted, is of utmost importance. Knowing where and when the extraction of groundwater from well-points is possible without harming the area of influence of that well-point and anticipating its effects on the communities living within the area is of utmost importance for CHS and other stakeholders in the region to make informed decisions, effectively execute their mandate and avoid negative unintended effects. Should it indeed be impossible to extract groundwater from the various well-points for instance due to environmental considerations, this knowledge enables CHS to coordinate actions, for instance, with the existing desalination plants to increase the output of fresh water.

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[34] https://murciatoday.com/murcia-out_performs-the-rest-of-spain-in-terms-of-international-tourism-growth_632085-a.html
[35] https://www.wwf.eu/?68900/Spain-sucked-dry-by-illegal-water-use
[36] https://blog.abacoadvisers.com/enjoy-5-of-the-best-murcia-golf-courses/

2.2.1 Collecting the necessary data

To fulfil its mandate, CHS has built up and managed a control network of more than 130 stations throughout the Segura River Basin that measure piezometric levels of water pressure. From this and further modelling, CHS can conclude the current amount of water in the aquifers. The stations are distributed across all the different individual "sub-basins" of the Segura River Basin. According to CHS, the control points at which the measurements are carried out are chosen depending on their significance of reflecting the overall behaviour of the water mass within the sub-basin in question. The spatial density of the piezometers is not completely uniform across the basin. Depending on the geographical extent defined for each water body, measurement stations range from a single piezometer at a smaller surface area to several piezometers over the largest sub-basins with the largest geographic extent.[37] The figure below shows that the measurement points are rather limited given the large extent of the Segura River Basin.

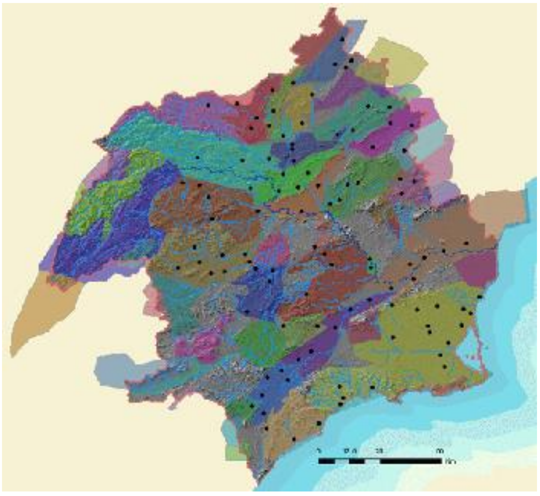

Figure 2-5 Map of the Piezometric Control Network in the Segura River Basin © CHS

2.2.2 Limitations of conventional methods

While this ground control network can be a very useful in-situ tool to measure piezometric data and derive the level of subsidence, it is also bounded by certain limitations. These limitations give rise to important challenges faced by the authorities – especially in large scale, continued drought periods such as the 1992-1995 or 2006-2009 ones:

- **Constructing a broader picture**: The ability to have a region-wide picture of the magnitude of subsidence (and its impact) is crucial for the coordinated extraction of groundwater and thus the allocation of resources. Achieving this with a traditional GNSS surveying technique is extremely difficult and costly, and practically impossible, during a drought period; the build-up, calibration and maintenance of a GNSS station runs into the thousands and, as we heard in interviews with the River Basin Authority, are prone to theft. The data is extremely

[37] https://www.chsegura.es/chs_en/cuenca/redesdecontrol/nivelespiezometricos/

local and only a maximum of 40 to 50 stations can be maintained at the same time whilst Earth observation can provide millions of measurements with millimetre accuracy.

- **Ensuring continuous monitoring**: Maintaining an accurate picture of the evolution of the land subsidence in different areas of the region would require continued and widespread use of GNSS stations and thus is particularly resource-intensive. At the moment, the authority gets two measurements per year through IGME/DARES. While GNSS surveys can give exact current data, they cannot look into longer-term trends or even historical trends. This can be achieved with historical archived satellite data.
- **Facilitating common understanding**: Communicating on the evolution and impacts of the subsidence is highly critical both between the corresponding public authorities but also to the public, media and political hierarchy. This cannot be easily achieved with a limited number of GNSS-derived numbers (i.e. measurements of the piezometric data).

All these limitations can – to a very large extent – be addressed by the use of satellite data. Therefore, a few years ago, CHS started a cooperation with the Geological and Mining Institute of Spain (IGME) and DARES TECHNOLOGY, an Earth observation company from Barcelona, to support them in their monitoring activities related to ground deformation and aquifer management.

We will look into this service in the next chapter, followed by a thorough account of how it was used by the different actors (chapter 4) and the concrete value it brought (chapter 5).

3 The Use of Sentinel Data

In their efforts to conduct effective and sustainable aquifer management and avoid the detrimental effects of land subsidence and ground deformation, CHS was faced with the challenge of coordinating the extraction of groundwater throughout the region and taking into consideration the well-points´ areas of influence – a complex task where a synoptic view with thousands of measurements can facilitate and improve decision-making and coordination between the different well-points. It is therefore vital for CHS to have accurate and updated information, but – more importantly – to have thousands of measurements (and not only 130) on subsidence **throughout the region** and especially **in densely populated urban areas** nearby well-points. This allows CHS and its decision-makers to select which well-points can be sourced, and thus coordinate extractions between the various well-points throughout the region. **This need for continuous and precise subsidence measurements throughout the entire region is met by the use of satellite data**.

In the case of *Aquifer Management in Spain,* this need was addressed by the collaboration between IGME[38] and in particular DARES TECHNOLOGY[39], an Earth observation company specialized in InSAR measurements using Sentinel-1 data from the EU´s Copernicus Programme[40]. While this has been one of the first use cases that a Spanish authority sought to systematically use satellite-based InSAR products, it must be noted that satellite imagery has been used for many years across the globe and in several land subsidence contexts.

Thus, before looking into the specifics of this use case and how CHS integrated the information into their operations, it is important to understand how satellites can capture changes on the surface of the Earth, allowing to construct accurate and regularly updated deformation measurements caused by aquifer exploitation.

3.1 Satellite Data and Ground Deformation

With the advent of radar satellite data, scientists have sought to find ways to purposefully employ them for detecting and monitoring land subsidence and ground deformation. In Europe, the Terrafirma project was a major milestone in the early 2000s; it demonstrated the benefits and advantages of using radar satellite data to detect and measure Earth-surface terrain motion as well as to improve the identification, assessment, understanding and monitoring of ground movements in relation to tectonics, floods and hydrogeology.[41] Radar satellite data has been used for many decades. In the 1990s and 2000s, ERS and Envisat[42] have opened new avenues for researchers and companies. However, their temporal and spatial resolution was not sufficient, whilst commercial radar data was too expensive. This changed dramatically with the availability of Sentinel-1 data from the Copernicus Programme[43] in 2014 and its open data policy. The characteristics of Sentinel

[38] http://www.igme.es/
[39] http://dares.tech/
[40] https://www.copernicus.eu/en
[41] https://www.esa.int/About_Us/ESRIN/Ground_movement_risks_identified_by_Terrafirma
[42] https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat
[43] https://www.copernicus.eu/en

data, the way they improve the understanding of ground motion as well as DARES' utilisation of the data is discussed in this chapter.

The satellite data:

Sentinel-1 is the Copernicus radar mission, providing an all-weather, day-and-night supply of imagery of Earth's surface. The mission consists of two satellites embarking C-band synthetic aperture radars (SARs) in continuity of the ESA's ERS-2 and Envisat missions. the mission images the entire Earth every six days for the benefit of manifold applications such as, for example, monitoring of Arctic sea ice extent, surveillance of the marine environment, monitoring land-surface for motion risks, mapping for forest, water and soil management.

Copernicus Sentinels data are available under an open and free data policy.

Sentinel-2 data can be accessed at https://scihub.copernicus.eu

More info: https://sentinels.copernicus.eu

3.1.1 Sentinel-1 and the InSAR technique

The case of monitoring land subsidence in Murcia relies on data coming from Sentinel-1[44]. Sentinel-1 is the latest SAR mission launched by ESA with the first Sentinel-1A being launched in 2014 followed by Sentinel-1B in 2016. Sentinel-1 carry Synthetic Aperture Radar (SAR) operating in C-band. This enables an **all-weather, day-night** capability to detect and quantify accurately small ground surface deformations. The technique is known as Synthetic Aperture Radar (SAR) Interferometry (**InSAR**) and **uses several observations of the ground at intervals of days, weeks and sometimes months.** Using Multi-Temporal Interferometry (MTI) algorithms, one is able to detect **Earth surface movements of a few mm** which have occurred between the observations. In particular, the technique allows detecting and monitoring millimetric displacements occurring on selected point targets exhibiting coherent radar backscattering properties.

InSAR techniques are attractive for different areas of risk management such as monitoring of subsidence, volcanoes, tectonic movements, urban areas, infrastructure and slope instabilities. Such approaches were previously carried out using the data from the earlier missions ERS-1/2 and ENVISAT (ENV). Using archive data from these missions one can perform ground instability analysis "back in time" almost all over the Earth. This has been the **only tool able to develop a historical map of ground movement** going back to the 1990s when ERS-1 was operational.

Sentinel-1, by offering regular global-scale coverage, free imagery, improved revisit time (up to 6 days) and long wavelengths (5.6 mm) can now guarantee wider and more efficient application of MTI for the global ground deformation monitoring. The two-satellites Sentinel-1A and 1B provide high reliability data with a rapid data dissemination to support operational applications in the priority areas of marine and land monitoring as well as emergency services. To accomplish the above, the satellites' SAR instrument offers medium-to-high-resolution radar imagery.

The use of Sentinel-1 with respect to other existing SAR constellations have the following advantages:

[44] https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1

- it is possible to detect signals from targets with short de-correlation time such as Distributed Scatterers. Using the Sentinel-1 images, and under optimal conditions, it is possible to monitor the ground displacements also on soil, characterized by a mean decorrelation time of about 10 days improving the number of measurable targets;
- the high revisit time of Sentinel-1 mitigates overfitting and motion ambiguity problems on the tracking of non-linear ground surface displacements over time;
- cost-effective SAR images for ground deformation monitoring.

3.1.2 How can Satellites measure Ground Deformation?

The analysis of ground deformations and land subsidence to coordinate the ground water abstraction between the various well-points in the Segura River Basin can benefit from increased exploitation of affordable remote sensing systems. SAR, such as that on Sentinel-1, are playing a crucial and growing role.

A SAR system emits microwave pulses (with a wavelength ranging from few centimeters to few tens of centimeters) and records the echoes from each pulse. The energy that is reflected or scattered back from the ground provides important information on the surface. Since microwave radiation penetrates the atmosphere with negligible absorption, SAR allows for monitoring during all weather conditions and at night. These characteristics for all-weather and night-day acquisitions make this technology very appealing for Earth surface monitoring purposes.

SAR data are intensively used for the measurement of ground and structure deformations and the technique used for the data processing is typically mentioned in literature as Multi-Temporal Interferometry (MTI)[45]. Over the last two decades, MTI has shown strengths and capacities in terms of wide area coverage (several tens of thousands of square kilometers) over long periods (several years). Some Earth observation missions offer high spatial resolution (e.g. 1 m or less with COSMO-SkyMed and TerraSAR-X) and high temporal resolution (e.g. 1 image every 6 days with Sentinel-1A/B).

The basis of MTI (InSAR) is that the radar can measure to high precision when a point on the ground has moved closer or further away from the radar. As the radar signal hits the ground, the intensity of the energy reflected is determined by the nature of the ground surface. If this is strong and stable from one image to another (which may be taken days, months or even years apart), then changes in (the phase of) the signal enable the variations on distance to be measured.

The nature of the ground surface is highly important. If it is covered in vegetation (as in rural areas), then the signal is weak and changes (growth, wind etc.) cause the signal to become decorrelated and not useful (or too noisy) for measurements of ground movement.

[45] J. Wasowski, F. Bovenga, "Chapter 11 - Remote Sensing of Landslide Motion with Emphasis on Satellite Multitemporal Interferometry Applications: An Overview", Science Direct, Landslide Hazards, Risks and Disasters, 2015, Pages 345-403, https://doi.org/10.1016/B978-0-12-396452-6.00011-2

On the other hand, over man-made surfaces such as urban areas in Murcia, a strong reflection can come from single points such as infrastructure-heavy urban areas. These are highly effective to measure ground movement. In some cases, a very strong and dominant reflector (known as a corner reflector) may be placed to help measurements. Otherwise, buildings, road signs and other metal objects found in urban infrastructures will provide good measurement conditions – which is often the case in urban areas.

The ground resolution and the frequency of observations are both important characteristics in determining where the InSAR ground deformation monitoring may be used for effective land subsidence and ultimately aquifer management.

- Ground resolution basically determines how far apart points on the ground may be detected. The nature of the ground is very important so that built up areas, with many reflectors in close proximity, require much higher resolution in order to identify which point has moved. If too many reflectors are present in the same measurement cell (pixel), then the measurement becomes confused and only an average movement can be measured. Higher resolution images help solve this problem but are generally commercial compared to the Sentinel-1 data which is free.
- The frequency of the observations depends on how often the satellite passes overhead and if images are being collected. High resolution satellites generally are imaging smaller "swaths" i.e. smaller areas on the ground, and hence will observe the target less frequently. Sentinel-1 has a larger swath width and can provide images every 3 to 6 days over Spain. There is a direct trade-off between the ability to measure single points on the ground compared to taking measurements on a regular basis based on MTI (which requires same orbital passes).

The availability of images from many satellites increases the ability to measure movements either in a closely-spaced grid (high spatial resolution) or with a shorter delay between each measurement. Moreover, only images taken with the same satellite may be used in MTI processing to generate ground movement maps.

Generally, current capability does not allow near-real time monitoring and ground movements can be detected over periods of weeks or months. This is however sufficient for many applications associated with land subsidence where the rate of movement is generally slow.

The use of InSAR to monitor land subsidence induced by aquifer over-exploitation has been the subject of various research projects and studies. In fact, the number of studies related to InSAR and aquifer management has grown exponentially over the last years and uncovered not only the causes of severe infrastructure problems in the Region of Murcia, but also for instance in the

Montellano aquifer[46] in the Southwest of Spain or also in major cities in central Mexico[47] and various other regions all over the world where ground water extraction has reached a dangerous level.

3.2 The DARES InSAR Service

DARES Technology[48] is a fast-growing technology company based in Barcelona, Spain, that has specialised on the provision of ground deformation maps and surface displacement information with radar technology. Focusing on InSAR measurements and ground deformation, DARES is providing its InSAR services to a multitude of application areas including mining, infrastructure and the oil & gas sector.

In the particular use case of Murcia, DARES provides InSAR measurements over the Segura River Basin every six months and provides these measurements in the form of subsidence maps as shape files to IGME, the Geological Survey of Spain.[49] Having received the subsidence measurements over the Segura River Basin from DARES, IGME functions as an intermediate user in that they do the "forensic analysis", interpret the data and add value by imposing another layer of information by correlating it with other available (hydro)geological data. DARES does a pre-validation and correlates the InSAR measurements with other data, but does not do any risk evaluation. As an example, DARES provides subsidence measures, yet does not assess whether for instance a house in Murcia is at the risk of collapse since the company has no knowledge of geological pre-conditions or the characteristics of the building. However, IGME – with its geological expert knowledge on exactly this kind of information – can add this extra-layer of information. It is the combined product in the form of graphical maps, GIS representations and documented reports that provide CHS with overall useful and actionable insights.

The DARES service ultimately enables CHS not only to have a synoptic overview of land subsidence over the Segura River Basin, but – thanks to the good geolocation characteristics of Sentinel-1 – to precisely locate specific measurement points. For this application the precision of measurements provided by DARES is at the millimetre level, making it more than adequate for CHS who need to observe subsidence at the centimetre level. In practice, this enables CHS to carry out on-site inspections more precisely. Theoretically, many of the illegal activities such as illegal wells (drills) in the Basin can be inferred from InSAR measurements as they detect land subsidence and thus – in principle – can uncover illegal wells with high probability.

The DARES InSAR service also benefits from the reliability of Copernicus data provision in that the satellites follow a consistent programme of overpasses which allows the collection of regular data over the same point without the need to task them to do so[50]. This, in turn, means that data

46 Ruiz-Constán, A., Ruiz-Armenteros, A.M., Lamas-Fernández, F. *et al.* Multi-temporal InSAR evidence of ground subsidence induced by groundwater withdrawal: the Montellano aquifer (SW Spain). *Environ Earth Sci* **75,** 242 (2016). https://doi.org/10.1007/s12665-015-5051-x

47 https://www.sciencedirect.com/science/article/abs/pii/S0303243415300672

48 http://dares.tech/

49 http://www.igme.es/

50 According to https://sentinels.copernicus.eu/documents/247904/685154/Sentinel_High_Level_Operations_Plan

processing within DARES is stable and big adaptations are not needed. Furthermore, the service benefits from a great history and archive of Sentinel-1 data by now as Sentinel-1A has been providing data since 2014. This is crucial for time-series and multi-temporal interferometry. Thanks to this archive and complementary data of preceding radar satellites such as ERS-1 and -2 as well as ENVISAT, companies for instance from the construction industry have turned to the DARES InSAR service in the past to show evidence and demonstrate that subsidence has happened before constructions started. Moreover, the DARES InSAR service is available to a multitude of application sectors such as mining and urban infrastructures given Sentinel-1's C-band which performs well in all forms of sectors.

3.2.1 Future Evolution of the Service

Currently and in parallel with its InSAR service, DARES is developing its own drones mounted with radar sensors. In the future, using a tip and cue approach, these drones will be able to fly over specific areas of interest detected by Sentinel-1 to provide even more precise SAR measurements over these spots and develop overall a better and more precise service to its clients.

Recently, DARES won funding from the Horizon 2020 SME instrument to develop further its InSAR service with a focus on the mining industry. The project MOTIONMAPPERTM will develop a real-time slope stability and subsidence monitoring service to improve productivity and prevent catastrophic events in the mining industry. Having started in 2018 to develop disruptive solutions to control slope stability and ground settlements for geotechnical early-warnings for the mining industry, it will certainly positively impact the overall DARES InSAR service.

4 Understanding the Value Chain

4.1 Description of the Value-Chain

The use of satellite data for the development of services supporting more efficient aquifer management gives rise to a concrete value chain. In this particular case, DARES makes use of Sentinel-1 data to provide IGME with accurate and continuous monitoring of ground deformation over the Segura River Basin. In turn, IGME combines this data with complementary piezometric measurements, to provide a complete analysis of the impact of pumping activity on land subsidence. This is of key importance for CHS, which thanks to this enhanced situational awareness can make informed decisions with regards to the exploitation of groundwater resources.

Thus, the use of Satellite data at the entry point of the value chain results in enhanced information or improved operations that bring value for each link further down the chain. Ultimately, the implementation of more sustainable aquifer exploitation (both from an economic and an environmental point of view), results in benefits experienced by citizens and other governmental agencies at the far end of the value chain. But before we dive into the individual links and attempt to quantify the benefits (this is done in chapter 5) it is instructive to understand how the use of satellite data helps actors along the value chain to address the challenges that shape their own operational reality. Thus, in the following sections, we provide details on the interests and responsibilities of the stakeholders in each tier.

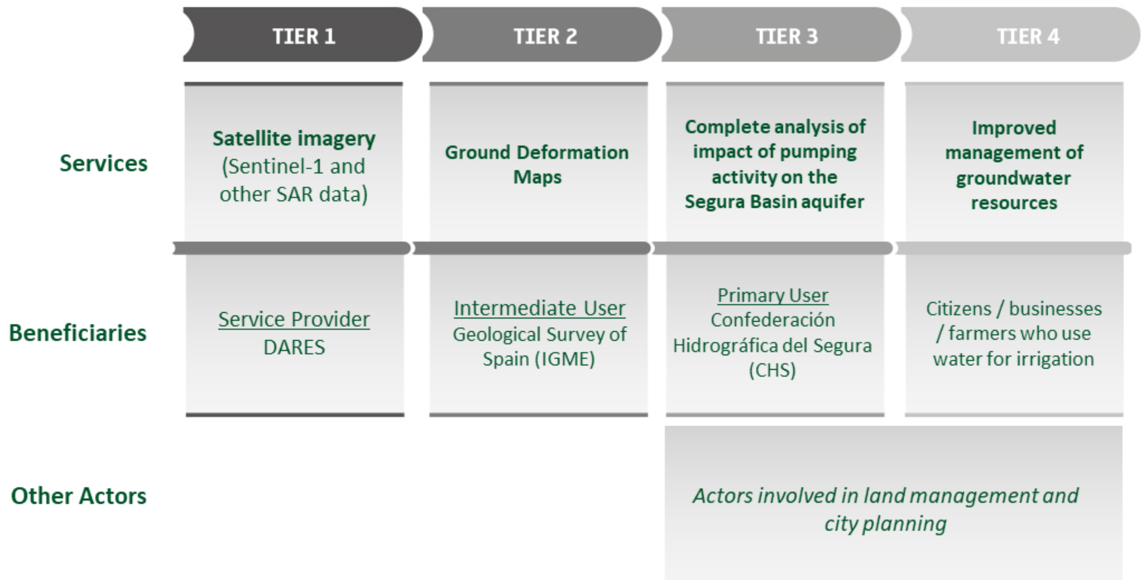

Figure 4-1: The value chain for Aquifer Management in Murcia

4.2 The Actors

4.2.1 Tier 1: Service Provider – DARES

DARES is a prime example of an innovative company that was created on the basis of proven technical excellence, a solid understanding of the market that can benefit from the technical value proposition, and a fresh opportunity that arose with the advent of the Copernicus Sentinel era. “*Without Copernicus, I would have never created DARES”*. The words of Javier Duro – CEO and founder of DARES – echo the critical role of Copernicus free, full and open data policy, in enabling him to take the big step and leave an established market player to start a new venture. But to grasp this opportunity, Javier capitalised on his extensive experience in SAR applications and the associated business network, developed over 13 years as Director of R&D at Altamira. Founded in 2015, the company is hosted at the ESA BIC facilities in Barcelona. Starting up with 1 employee and with proprietary software developed at the Remote Sensing Laboratory (RSLab) of the Polytechnic University of Catalunya (UPC), DARES has grown steadily to 25 employees.

Figure 4-2: With some of the members of the DARES team during our visit to the Barcelona HQ

DARES’ mission is to detect and monitor ground surface anomalies (e.g. subsidence, ground heave, active slopes, rock falls, land cover and land cover changes, water bodies) based on radar satellites (InSAR technology). It is pioneering novel approaches in electromagnetic signal and image data processing, mainly in the field of radar signal and interferometry and derived products/services. Beyond exploiting SAR satellites, DARES is developing proprietary solutions based on drones.

Today, DARES is already serving multiple clients across the world in the sectors of mining, oil & gas and infrastructure. This latter sector is where aquifer management in Murcia falls under. This case is a prime example of the result of strategic partnerships and collaborations that DARES has developed with universities and research institutes. Thus, beyond IGME with whom DARES collaborates in the case of Murcia, additional collaborations exist in Spain (e.g. TSC/UPC, CSIC) and beyond (e.g. CNR in Italy and DLR in Germany).

The company has been profitable from the very beginning and has managed over the years to do work for prominent clients across the globe. In that regard, **the "internationalisation" of DARES is particularly interesting as it directly tied to the global reach of Copernicus Sentinels**. Thus, DARES is strongly developing business in Latin America (it has established a subsidiary in Chile with 2 people working there and has inroads in Peru too), Australia and North America.

4.2.2 Tier 2: Intermediate User – Geological and Mining Institute of Spain (IGME)

The Geological and Mining Institute of Spain (IGME) is a Public Research Organization attached to the General Secretariat for the Coordination of Scientific Policy of the Ministry of Science, Innovation and Universities[51]. IGME has a rich tradition dating as far back as 1849, when Isabel the 2nd of Spain founded the *Comisión para la Carta Geológica de Madrid y General del Reino*[52], a commission to form the Geological Map of Madrid and Spain in general. Over the years it was operating under different names and legal frameworks, but its mission has remained to a large extent unaltered. This is best captured – in a rather prophetic way – in the prologue of the first edition of the bulletin that IGME produces since 1874. It reads: "*... so that the men of science and the industrialists could take advantage of the data contained in these valuable documents ... There will hardly be a mining engineer, professor of geology or naturalist, who does not possess a wealth of observations to which he would readily give body, with obvious utility to the sciences, if they were provided with the means of publishing them as they were doing them.*"[53] So, **IGME has been committed to helping public administrations, economic operators and society at large by creating and sharing knowledge on various geological subjects (geoscience, hydrogeology, mineral resources, risks, geodiversity, etc.).**

In modern times, this mission statement could not have found a better fit than in the work performed by the *Geohazards InSAR laboratory and Modeling Group*. This is a laboratory that conducts multidisciplinary research, development and innovation activities, under the aegis of IGME, and with the support and contribution of several research centres, universities and companies at national and international level. The main focus of the InSARlab is the integration of Earth surface displacement data obtained from radar satellite images, with geo-thematic layers, in situ observations and numerical models, allowing them to advance the knowledge of the mechanisms that control earthquakes, landslides and subsidence, quantify their impact and assess the associated risks.

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[51] http://www.ciencia.gob.es/portal/site/MICINN/

[52] Interestingly the official document for this can be found here https://boe.es/datos/pdfs/BOE//1849/5424/A00001-00002.pdf

[53] Translated from Spanish: https://www.igme.es/Boletin/historia.htm

A perfect case in point for this is the collaboration between IGME and DARES for the provision of support to CHS towards more sustainable aquifer management in Murcia. Thus, Gerardo Herrera and Marta Béjar Pizarro have been studying subsidence in the Murcia region and in particular on the Segura River Basin already since 2005, publishing multiple scientific papers on the subject[54]. These papers capture the findings around the application of differential InSAR using different satellites (from ERS and Envisat in the 00's to Sentinel 1 since 2014), as well as other ground measurements (piezometric). In this process, the arrival of Sentinel-1 has brought a revolution not only due to the sheer amount of data collected but also thanks to its technical quality (see chapter 3). **Moreover, as Sentinels triggered the emergence of DARES, IGME found the perfect partner to provide them with automated ground deformation monitoring capabilities using advanced algorithms**. This collaboration has greatly facilitated IGME's mission to support CHS.

4.2.3 Tier 3: Primary User – Segura River Basin Authority

Founded in 1926 by a Royal Decree-Law[55], the Segura River Basin Authority (CHS) is the main public sector organisation responsible for the management of water resources in the Segura River Basin, overseen by the Directorate-General for Water of the Spanish Ministry for Ecological Transition and Demographic Challenges. Given the extent of the Segura River Basin, the CHS manages the water resources in South-Eastern Spain and seeks to reconcile the water rights of public and private users from the four autonomous communities within the basin (Andalucia, Castilla-La Mancha, Comunidad Valenciana and Murcia) with the protection of the environment. This overarching, trans-regional approach to managing water resources has proven mostly effective and successful in the past. Whilst its centre of attention is the Segura River Basin, the operations of the CHS have a strong European dimension and are also governed by the introduction of the EU Water Framework Directive that sets common criteria for the protection of European water resources.[56] To that end, the CHS has been involved in a number of European LIFE projects to foster the protection and improved use of water resources in the Segura River Basin through international exchange and collaboration.[57][58][59]

All these elements underpin the CHS' main mission. Its **main objective and priority is the sufficient supply of water in urban areas** for the general public, as specified under the Spanish Water Law. **Secondly, the CHS seeks to guarantee the sufficient supply of water to the agricultural sector and**

[54] See publications for both of them here: https://www.igme.es/InSARLAB/equipo.htm
[55] https://www.chsegura.es/chs_en/informaciongeneral/80_aniversario/
[56] https://ec.europa.eu/environment/water/water-framework/index_en.html
[57] https://www.chsegura.es/chs/cuenca/segurariverlink/riverlink/
[58] https://www.chsegura.es/chs/cuenca/segurariverphy/
[59] https://www.chsegura.es/chs/cuenca/seguraripisilvanatura/

related industries. This is oftentimes posing a difficult challenge given that agriculture constitutes a core economic activity within the region and requires a high supply of water for irrigation.[60]

Given these circumstances, the CHS sits on the fence between guaranteeing sufficient amount of water in response to different streams of demand and protecting the environment through the prevention of the overexploitation of aquifers and other water resources. Often, this challenge is amplified even further by extreme weather events such as droughts and floods as well as a structural water deficit throughout the region. Although providing sufficient water supplies to farmers is important for the continuity of agricultural activities, avoiding land subsidence through an over-use of groundwaters is paramount and reflects a balancing act that is often hard to achieve as frequent protests from farmers in front of the CHS demonstrate.[61]Such events occur in particular when there is additional strain on the water reservoir due to prolonged droughts. Murcia and the greater Segura Basin region are no strangers to such events; in fact, **Segura is considered the driest river basin located in mainland, with rainfall accounting on average to 1mm for each day of the year.** The case of the drought period spanning essentially 2014-2020 serves as a perfect example and illustrates the direness of the situation and the importance of informed decisions and solid planning when it comes to managing water resources. On that occasion[62], the Segura Basin water reservoirs have been reaching levels as low as 15%, prompting the CHS to (i) take strict measures with regards to distribution of water to households and farmers alike, (ii) seek the mobilisation of all tools available in order to monitor the situation.

It is within this context, that the **CHS sought professional advice from IGME and DARES, incorporated within regular reports on the levels of land subsidence around the wells and associated analyses on the state of the aquifer and its exploitation**. This advice has been delivered using the Sentinel-enabled InSAR service of DARES.

4.2.4 Tier 4: Citizens and Society

Citizens and the wider public are by nature dependent on the reliable and safe supply of water. First of all, the supply of drinking water is obviously the most important aspect of water and aquifer management in the region. Secondly, the proper and sustainable management of the water resources and ground water in particular is indispensable for the wider economy in the region since agriculture forms a central part of the region's economic activities that heavily relies on a stable water supply for irrigation purposes.

On top of that, citizens and the wider public have an interest in the sustainable management of the aquifers since land subsidence and ground deformation associated to aquifer over-exploitation have caused considerable economic damage to the inhabitants of the Region of Murcia in the past. It is estimated that ground water extraction and associated land subsidence during the 1992-1995

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[60] https://www.chsegura.es/chs_en/informaciongeneral/bienvenida/

[61] Reference to protests

[62] https://murciatoday.com/understanding-water-and-the-drought-in-murcia-and-the-segura-basin_171862-a.html

for instance resulted in an economic loss of about 55 million Euros through damages in public infrastructures and private homes.

4.2.5 Other Beneficiaries

The **Department of Development and Infrastructures**[63] of the Autonomous Community of the Region of Murcia responsible for land and territorial management has a major interest in sustainable aquifer management practices. Mandated with urban planning, the allocation and permitting of new settlement areas or the granting of infrastructure projects as well as the exact type of settlements that can be built in a certain zone, decision-makers of the authority are aware of the risks of aquifer over-exploitation and associated ground deformation. Their work and strategic urban planning is thus directly related to the way aquifers are being managed in the region.

Against this background, the Department has been studying subsidence with InSAR since 1995[64]. Thus, the problem of land subsidence in the region was identified using InSAR and the criticality of both soils and the correct distribution of infrastructures and settlement zones across the region, taking into account the varying degrees of land subsidence across the region, was described. Given the Department's responsibility for the design and oversight of the material requirements for new constructions, a new urban plan was developed after the study that introduced new requirements for new infrastructures to take the risks of land subsidence in the region into account.

63 https://www.carm.es/web/pagina?IDCONTENIDO=67&IDTIPO=200&__PLANT_PERSONALIZADA=/JSP/CARM/carm2018/organigramas/plantillaDetalleOrganigrama.jsp&IDESTRUCTURAJERARQUICA=257&RASTRO=c$m22660,121

64 See De La Pena, et al. 1995, La subsidencia del terreno en la ciudad y área metropolitana de Murcia

5 Assessing the Benefits

Now that we know which effects the Sentinel-enableδ InSAR service is causing in the subsequent tiers of the value chain, we can establish the different types of benefits that are generated through its use. Which financial value can we attribute to the availability of the service? Which environmental or regulatory benefits can we identify? Are there any other social or scientific impacts that we can track? These are the questions we are addressing in this chapter. In this regard, it is useful to recall our value chain picture whilst adding the last two layers to it.

	TIER 1	TIER 2	TIER 3	TIER 4
Services	**Satellite imagery** (Sentinel-1 and other SAR data)	**Ground Deformation Maps**	**Complete analysis of impact of pumping activity on the Segura Basin aquifer**	**Improved management of groundwater resources**
Beneficiaries	Service Provider DARES	Intermediate User Geological Survey of Spain (IGME)	Primary User Confederación Hidrográfica del Segura (CHS)	Citizens / businesses / farmers who use water for irrigation
Other Actors			*Actors involved in land management and city planning*	
Type of Benefit	Access to free and high-quality datasets allowing the delivery of valuable services	Enhanced ability to (i) deliver **added value services**; (ii) conduct **solid scientific analyses**	(i) **Safer operation** of extraction wells; (ii) better **compliance with regulation;** (iii) less reliance on alternative solutions	(i) **Reduced damages** risk; (ii) increased **trust** in authorities; (iii) **environmental protection**
Manifestation of value	Savings and simplicity in sourcing data enable profitable **business model (revenues)**	Access to high-quality, continuous InSAR measurements enables **accurate reports and generates revenues**	(i) Protection of property, (ii) Sustainable Aquifer Management, (iii) **Savings**	Lesser strain on the aquifer, increased visibility on economic prospects, improved urban planning

Figure 5-1: Benefits along the value chain

5.1 Overview

Before we dive into the discussion for each of the tiers it is instructive to make some high-level observations:

1. The value generated in this case arises during drought periods

The CHS requires the ground subsidence reports provided by IGME (using InSAR measurements from DARES) only during the drought periods. It is in these conditions that CHS activates the operation of extraction wells and thus triggers the Sentinel-based service. As a result, the discussion of benefits in the following sections is conducted within this framework of drought periods.

2. All tiers in the value chain experience direct benefits

In a rather exceptional manner (when compared to previous cases) the case of aquifer management presents benefits for actors across all four tiers that are directly tied to the use of Sentinels. As will be discussed below, the main actors in the first two tiers (DARES and IGME respectively) generate revenues associated with the provision of the service. These are directly tied to using Sentinel-1 data as without it they wouldn't be able to tackle the issues of CHS. In turn, CHS is able to fulfil regulatory obligations thanks to the fact that Sentinel-enabled InSAR services provide the required situational awareness. Finally, by ensuring ground deformation remains within acceptable limits, damages in buildings close to the extraction wells are fully avoided. This, again, is directly connected to the use of the Sentinel-based InSAR service.

3. Winners and losers

In our study – as we did in previous ones and will do in future ones – we are concentrating on the positive effects brought about by the availability and subsequent usage of the Sentinel data in the value chain. That being said, one needs to realize: where there are winners, there must also be some losers. Put differently, innovation and subsequent benefits will partly come at the expense of existing stakeholders. In this case, farmers relying on water extracted from illegal wells are more "exposed", since subsidence associated with their activities is more easily observed. Nonetheless, this impact can be very well seen as a positive one when viewed from the perspective of CHS and the greater good of sustainable aquifer management. More generally, recent studies demonstrate that 'on balance' and at macro level, there is a distinct positive effect. Annex 3 holds some further observations on this subject.

All that said, the next section presents a systematic analysis of the economic value ("adding a price tag") and other types of benefits arising from the use of Sentinel data in each Tier.

5.2 Benefits along the Value-Chain

5.2.1 Tier 1: Service Provider – DARES

The ability of DARES to develop and deliver a service that meets the needs of actors in subsequent tiers is directly tied to the availability of Sentinel data. As Javier clearly put it: "*DARES would not exist if it weren't for the free, full and open access to such high quality data as that provided by Copernicus Sentinels*". Thus, the first benefit experienced by DARES is that of enabled **entrepreneurship and innovation**. This can be better understood when we recall the advantages of Sentinel-1 data discussed in section 3.1.4. Thus, DARES benefits from the three key parameters:

- **Continuity resulting in richness of measurements**: For the purpose of aquifer management, DARES needs to support IGME in producing accurate reports on the progress of ground deformation. These reports cover typically 3-monthly periods and use time-series generated using Sentinel-1. Thanks to the revisit time of Sentinel-1, DARES can provide IGME with a large volume of InSAR measurements over the same region every 5 days, irrespective of weather conditions and without having to task the satellites (as would be the case for commercial satellite missions). This frequency is suitable for the monitoring of displacements around the aquifer exploitation wells as acceleration can be steadily monitored. Moreover, by having access to a rich archive of reliable data, DARES can build projections and forecasts, which is of critical importance for such analyses.

- **Suitable performance:** The other key factor when producing ground deformation maps is connected to the overall quality of the measurements. Using the C-Band Sentinel-1 data (which perform well on all environments and not only in urban areas as the X-Band) and its proprietary algorithms, DARES can perform multi-temporal or differential InSAR analysis (MT-InSAR and DInSAR respectively) to measure displacements to millimetric accuracy. The resolution of 3x20m in Interferometric wide swath mode and the point spacing of the measurements at approx. 30m, may not be as good as some of the commercial satellites but is sufficient for aquifer exploitation monitoring.
- **Zero-marginal cost per ha for an automated solution:** The cost of the necessary imagery is critical for the viability of the business model. The free, full and open policy of Copernicus ensures that zero marginal costs are required for every additional km^2. This is not the case of commercial providers' imagery who are typically charging by the size of the area of interest. Thus, for a scalable, automated solution such as the DARES InSAR, the availability of Sentinel-1 imagery is critical. Of course, higher-tier customers may ask and receive ground deformation maps that combine S-1 with higher resolution data sourced from commercial providers, but, as Javier pointed out, this happens rarely if at all. It can be strongly argued however, that even in this case, the availability of Sentinel data is driving the cost of this data down, making it more profitable for companies such as DARES to roll their services out.

These key parameters and the fact that Javier was bringing very extensive experience in the field from his previous work, allowed the successful launch of DARES from the outset. As discussed in section 4.2.1, DARES quickly grew from a single employee and a few students working part-time, to a **25-people highly-skilled and talented team** with a global presence. **This growth, reflected both on the <u>employment</u> and <u>revenue</u> figures of the company, is to a very large extent thanks to Copernicus Sentinels** (Javier himself attributes about 85%). Thus, DARES has been exploiting Sentinel data to serve customers in the mining, infrastructure and Oil & Gas sectors for a total of approximately **1 Million Euros in revenues per year**. The ability of DARES to quickly scale and attract local but also international talent should not be underestimated. As Javier underlined "*If we couldn't build a strong value proposition based on continuous innovation and a disruptive business model, our people would have gone to work to other European countries or to public institutions*".

Of the total 1M€ annual revenue, around 5% can be attributed to work done in Spain for aquifer monitoring, which would amount to 50,000 € per year. At this point, it is worth to further precise this figure by looking into the specifics of the case in Murcia. This will eventually allow us to project not only the current but also the potential economic benefits for DARES.

DARES provides IGME with InSAR measurements over an area of approximately 500km^2. To do so the actual area that is being monitored and processed corresponds to 1200km^2. The provision of the service (including the additional analysis carried out by IGME and discussed in the next tier) costs approx. 42 € per monitored and processed km^2; this translates into 50,000 € per cycle. **Over the period 2014-2020, four monitoring cycles have been concluded amounting to a total of 200,000€.** This figure corresponds to the revenue generated by DARES and IGME combined for the case of the Segura River Basin and it relies fully on the exploitation of Sentinel-1 data. The actual split between DARES and IGME is close to 40-60%, which again checks out with the above calculation of 50k€ per year (in terms of order of magnitude).

Figure 5-2: Map of Spanish River Basin districts

At this point it is instructive to project the potential economic benefit for DARES, if it were to support aquifer management activities across Spain[65]. The scarcity of water and its importance to the local communities (households, businesses and agriculture) are both applicable to other basins in Spain too. For instance, as reported by the European Environment Agency[66], water supply problems – that could lead to overexploitation and thus damage-threatening ground subsidence – are found also in Guadiana, Guadalquivir and Sur Basins. Other sources[67] include in this category Jucar as an additional area which is heavily irrigated and suffers from droughts. Additional river basin districts that can be justifiably considered[68] are the Upper Tajo, where significant subsidence due to groundwater extraction in Madrid has been detected; the internal Catalonian basins,

[65] A discussion on wider scalability perspectives (i.e. other areas in the world with similar conditions) is provided in section 6.3.
[66] See here: https://www.eea.europa.eu/publications/92-9167-056-1/page003.html
[67] See Schwabe, "Drought in Arid and Semi-Arid Regions", (2009)
[68] This is based on direct inputs by IGME

especially Girona, Barcelona and Cambrils which also present subsidence; the Ebro basin, which is in danger of presenting subsidence due to large arid areas with intensive agricultural use.

Considering that DARES is already serving 7% of the area of the Segura basin, we could produce a low and high scenario of expansion representing 10% or 20% of the area in these other basins. Such an expansion seems feasible given the ability of DARES to process – in virtually an end-to-end automated workflow – Sentinel-1 data, and produce InSAR measurements or more advanced products for clients across the globe. Such a scaling factor could also be justified especially inside Spain by the prestigious position that IGME holds as the organisation advising the counterparts of CHS in other regions too. The results of this exercise are presented at the end of Tier 2 as they also include the projections for IGME.

5.2.2 Tier 2: Intermediate User – IGME

The role of IGME in the case of Aquifer Management in Spain brings to light a very interesting aspect: **Acting as the intermediate user, IGME is (i) opening the door for an innovative company (such as DARES) to a public sector client (such as CHS), (ii) adding value to the product delivered by DARES so that it fully meets the scope of the assignment tasked by CHS**. These two points combined act as a catalyst for this case to be materialised. IGME has a prestigious and long-established role in the Spanish ecosystem – similar to many other geological societies/surveys/institutes in other countries around the world. Thanks to that, IGME is in close contact with public sector organisations which it helps understand and analyse different phenomena and processes. In the case of ground deformation monitoring, through the use of InSAR, IGME has developed strong expertise and long experience over many years of scientific and R&D work, often honed through key European projects (e.g. Terrafirma, PANGEO). Therefore, with strong existing ties to the public sector in Spain and a proven track record, IGME was able to "vouch" for the advanced capabilities of DARES. This is not to say that without IGME, DARES would not have the possibility to serve CHS as a client – but it certainly helps! In fact, the combined strengths of IGME and DARES create a win-win-win situation. DARES provides its excellent products generating revenue, IGME fulfils its mission and adds scientific know-how on the InSAR measurements and CHS receives the support it needs. But let's dive a bit deeper into this dynamic as seen from the perspective of IGME.

The main "engine" for IGME, in this case, are the researchers working within the InSARlab. As discussed in section 4.2.2, this is a laboratory that conducts multidisciplinary research, combining different streams of data (i.e. satellite and in situ measurements) and produces models and analysis that describe ground movement associated with different phenomena (earthquakes, landslides, subsidence due to aquifer exploitation, etc.). In this capacity, IGME produces both frontline research but also technical consultancy such as the one requested by CHS for the Segura River Basin. In this case, IGME was contracted by CHS in two subsequent contracts covering the period 2014-2020. As this was a period characterised by persistent droughts, the need to ensure a stable flow of water for both irrigation purposes and household consumption, was great. To that end, CHS sought to extract groundwater through the operation of pumping wells in the Vega Media and Baja del Segura areas (see figure below). However, as intensive extraction of water from the aquifer can result in significant land subsidence and consequently structural damages in buildings, CHS tasked IGME with the monitoring and reporting of ground deformation over the area in which the extraction operation took place.

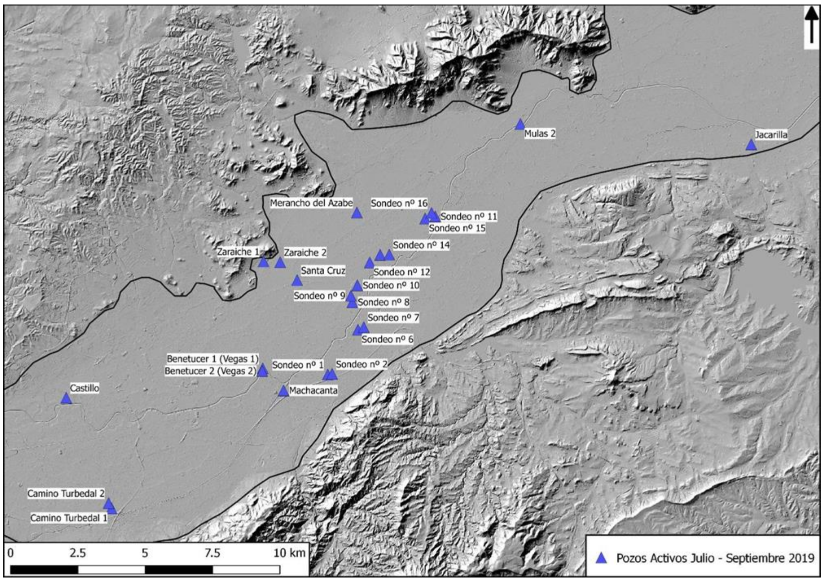

Figure 5-3: Locations of the pumping wells in the Vega Media and Baja del Segura areas

To carry out this task, IGME relied on the use of InSAR techniques for the analysis of images provided by Sentinel-1 in Interferometric Wide Swath (IW) mode. Thanks to its wide spatial coverage and high density of measurements, Sentinel-1 (freshly operating at the time the study started in 2014) proved an invaluable asset for this type of analysis. Thus, with the help of DARES who performed the processing of the imagery using the Coherent Pixels Technique software (CPT)[69], IGME has been able to analyse hundreds of images on an annual basis (e.g. 146 between March 2015-August 2018 and 63 between August 2018-September 2019) and, literally, millions of measuring points (817k and 424k for the respective periods). Comparing the Sentinel-1 based InSAR extracted measurements with those of piezometric readings, IGME was able to monitor the extraction areas and evaluate their response to the pumping actions to provide CHS with advice on the status and optimisation of aquifer management. This was done within regular reports provided to CHS; these reports contained a thorough analysis of the evolution of displacements/ground deformation in the proximity of the wells (see example in the figure below).

[69] Developed by the Remote Sensing Laboratory (RSLab) of the Polytechnic University of Catalunya (UPC), maintained and updated by the company DARES Technology (Blanco-Sánchez et al., 2008; Centolanza et al., 2017).

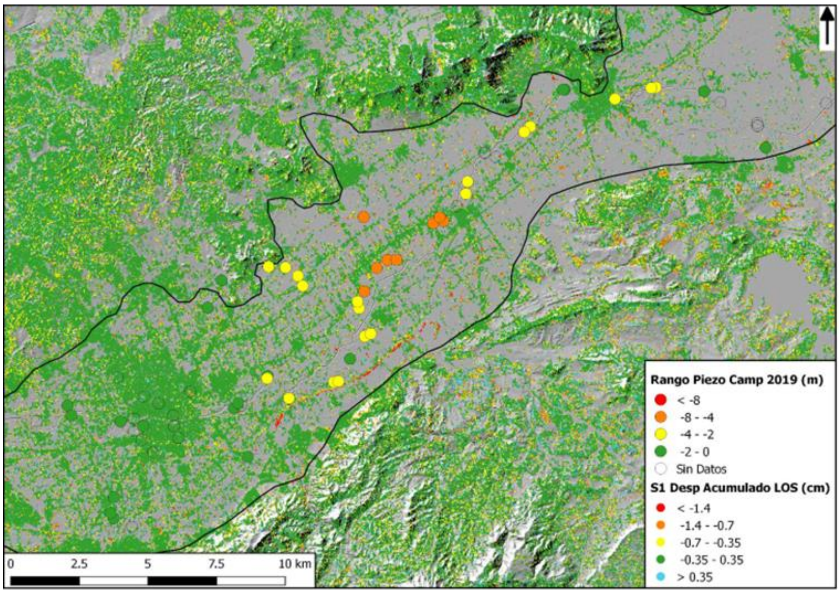

Figure 5-4: Actual example of map presenting accumulated deformation around the wells

Thanks to the quality of the input Sentinel-1 data, the technical excellence of the measurements provided by DARES and the scientific expertise of IGME, deformations even below 5mm were monitored. This was also due to the ability of IGME to showcase remarkable correlation between InSAR and piezometric data. Such correlation is fundamental to explain the ultimate influence of the pumping campaign in the general trend of the exploitation of the aquifer and project longer-term effects and forecasts. In that regard, what is particularly interesting is that deformations of even a few millimetres can cause instabilities for a few hundreds of meters away from wells. This information is crucial for both the CHS – and as we will see further in this report – for authorities dealing with urban planning.

In carrying out this contract with CHS, IGME experiences a multitude of benefits that can be directly associated with the availability of Sentinel data. Firstly, the execution of these contracts has **directly resulted in job creation**. Thus, in the first contract, IGME hired a technical expert to assist with the analysis and interpretation of the data, whereas for the second contract the expert was hired directly by CHS. Secondly, the **economic** perspectives of these contracts allowed IGME to exploit the scientific expertise of the InSARlab and sustain its operation. Thirdly, and very importantly, the availability of the data allowed IGME to perform its fundamental mission of **providing a high-quality geological service for the safety and wellbeing of the society and the environment**. Finally, by combining piezometric data with Sentinel-1 measurements, IGME is empowered to **do better science**. In simple terms, thanks to wealth and quality of collected data, IGME is able to; understand better the processes involved in aquifer exploitation, model with greater accuracy the aquifer's response behaviour and create forecasts for the future. This is a "transferrable" benefit as the insights generated and the lessons learned can be transferred to other monitoring areas in subsequent contracts.

In that regard, and following the same logic as the one presented for Tier-1/DARES, we can project potential economic benefits for IGME if it were to partner with DARES and serve counterparts of CHS in other basins. The result of such exercise yields the following outcomes[70].

		Monitored Area (Potential)		Potential Annual Revenue for DARES		Potential Annual Revenue for IGME	
River Basin	Total Basin Area	Low	High	Low	High	Low	High
Segura	19033	1903	3807	€ 31,975	€ 63,951	€ 47,963	€ 95,926
Guadiana	55498	5550	11100	€ 93,237	€ 186,473	€ 139,855	€ 279,710
Guadalquivir	57196	5720	11439	€ 96,089	€ 192,179	€ 144,134	€ 288,268
Sur	18000	1800	3600	€ 30,240	€ 60,480	€ 45,360	€ 90,720
Jucar	42737	4274	8547	€ 71,798	€ 143,596	€ 107,697	€ 215,394
Tajo (Madrid)	8000	800	1600	€ 13,440	€ 26,880	€ 20,160	€ 40,320
Catalonia	16441	1644	3288	€ 27,621	€ 55,242	€ 41,431	€ 82,863
Total	**216905**	**21691**	**43381**	**€ 364,400**	**€ 728,801**	**€ 546,601**	**€ 1,093,201**

Table 5-1: Potential Annual Revenues for DARES and IGME for extrapolation in Spain

5.2.3 Tier 3: Segura River Basin Authority

At first sight, the mission of the Segura River Basin Authority might seem simple enough: ensure the provision of enough water to the different stakeholder groups (farmers, households, businesses) whilst observing compliance with environmental regulation. Yet, one doesn't need to dig as deep as the aquifer exploitation wells, to understand the scale and complexity of such an endeavour. This is directly tied to two key parameters:

1. **Economic output:** Murcia and the Segura basin, whilst accounting for just 4.3% of Spain's population, are responsible for between 20-30% of the country's fruit and vegetable exports. This makes agriculture the key economic activity in the region.
2. **Climate:** Ironically, perhaps, this is one of the driest (if not THE driest) river basin on the whole of continental Europe. Droughts often last for multiple consecutive years as was the case during the period 1992-1995 and, more recently, during 2014-2020.

The common denominator connecting these two parameters and the silent protagonist of our story overall is water. Farmers rely on constant access to an adequate flow of water for irrigation purposes (with most of it coming from the aquifer[71]). In fact, 85% of the available water resources are used for the irrigation of almost 300,000 ha of crop land. The source of this water depends on the hydrological conditions every year, but, on average, it corresponds to 29% rainfall-runoff (superficial water), 20% interbasin water transfer, 38% groundwater, 7% treated wastewater and 6% desalinated seawater[72]. Of course, during drought periods, the demand for groundwater increases. Similarly, households and businesses in the region need drinking and washing water. The significant increase of the population in the region has further strained water resources; for instance, the permanent population (registered individuals) in the Murcia region was 1.2M in 2001, growing to 1.49M in 2019. This corresponds to a 25% growth in less than 20 years!

[70] The size of the basins is sourced from the "Summary of Spanish River Basin Management Plans" accessible here: https://www.miteco.gob.es/es/agua/temas/planificacion-hidrologica/summaryrbmp2ndcycledraft_tcm30-379040.pdf
[71] A very detailed presentation of water usage in the region can be accessed (in Spanish) here: https://www.chsegura.es/static/plan-15-21/A03_usos_y_demandas.zip
[72] Data from Martinez-Paz et al. 2018 https://doi.org/10.1371/journal.pone.0206852

Keeping a balance between the different uses and stakeholder groups is a very complex process, which entails environmental, societal, economic and political dimensions. Therefore, the CHS and other stakeholders involved in decision-making, have considered, piloted or adopted multiple different water management schemes that would on one hand meet the needs of different users and, on the other, respect environmental considerations and economic limitations[73]. Thus, measures such as imposing environmental tax on groundwater pumping; purchasing water rights (deemed as "buyback") to reduce pressure on the aquifer; establishing pumping quotas, are used in different areas of the world – and so, too, in Segura – to solve this difficult equation. It is important to note, that such measures are effectively guided by the EU Water Framework Directive[74], which for the purposes of our discussion here seeks to achieve good water status for all water bodies (surface, underground, transition, coastal), whilst protecting the ecosystems that depend on them. This high-level mission is then transposed through regulations and instructions that are, in principle, included in the national/regional plans[75]. In the case of Segura, this is reflected in the Hydrological plan for 2015-2021[76]. It should be noted already at this stage, however, that due to the importance of agriculture in the region, the goals that should have been achieved in previous years have been moved in the future; progress has been reported in Segura with regards to meeting these goals and best practices but more can be done[77].

Whatever the economic instrument considered, one of the prerequisites for successful implementation is the monitoring of groundwater withdrawals to assure that sustainable pumping rates are respected. And it is precisely at this point that the use of Sentinel-powered, InSAR-based, aquifer exploitation monitoring comes into the picture. By using the reports provided by IGME (with the help of DARES), CHS is in a good position to **(i)** ensure the **safe operation** of the extraction wells thus avoiding damages in buildings due to excessive land subsidence, **(ii)** compose well-informed **environmental impact analyses**, **(iii) optimise the exploitation** of the aquifer within the limits imposed by regulation, **(iv) inform longer-term strategies** for the exploitation of the aquifer. Let us now investigate each of these points individually.

Safer operation of extraction wells

In the previous intensive drought period, extending over 1992-1995, the aquifer exploitation wells were located much closer to the densely inhabited part of Murcia. At the time, there was no system in place monitoring ground deformation around the wells, at least none with an accuracy and regularity measurement such as this provided by Sentinel-enabled InSAR. As a result of the exploitation of the aquifer, significant damages on buildings occurred. Whilst an extensive study on the economic impact has not been conducted for that occasion, IGME has been informally provided by the Regional government of Murcia with a figure amounting to 50 Million Euros direct costs

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[73] There is rich literature on that subject. Indicatively we suggest looking into Calatrava and Martinez-Granados (2019) - https://doi.org/10.1080/07900627.2018.1504756 and the reference on the previous footnote.
[74] https://ec.europa.eu/environment/water/water-framework/index_en.html
[75] See for instance the 2016 European Parliament Study on River Basins and Water Management in Spain https://www.europarl.europa.eu/RegData/etudes/STUD/2016/536491/IPOL_STU(2016)536491_EN.pdf
[76] https://www.chsegura.es/chs/planificacionydma/planificacion15-21/index.html
[77] See for instance here https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2019:0042:FIN:EN:PDF

incurred in association with the building damages[78]. An immediate outcome of this was the moving of exploitation wells further away from the city.

Today, with multiple wells scattered around the basin, it is important – and required by law – to monitor their operation and ensure that the associated land subsidence does not exceed a cumulative displacement of 2cm. It is interesting to note at this stage that none of the involved stakeholders knows how this figure has been calculated. Thanks to the InSAR measurements (by DARES) and their interpretation (by IGME), CHS is able to monitor land subsidence around each well with millimetric accuracy. In practice, this means that if a certain well seems to produce too much displacement, it is shut down. This means that CHS ensures that no damages occur in buildings – a benefit enabled in Tier 3 with the help of the InSAR service but "felt" in Tier 4 (Citizens and Society). Since the wells are not located in the most densely built parts of the basin, we cannot assume potential avoided costs at the order of the previously estimated total of 50M€[79]. If we take the population density ratio (city[80] vs region[81]: 500 vs 130 inhabitants per square kilometre) we conclude that **thanks to the close monitoring of the operations, with Sentinel-based InSAR, potential building damages amounting to a maximum of 13M€ are avoided**. It should be noted that this figure is based on the 1992-1995 event, occurring over 4 years. The service provided by DARES/IGME to CHS has been running for 7 years. Thus, making the necessary adjustment (i.e. it would have been 22.75M€ over 7 years) we find that the annual benefit associated with avoided damages may rise up to 3.25M€ for the case of the Segura basin.

Following the same extrapolation approach, that is projecting the scenario where DARES/IGME serve a selection of other river basins with similar characteristics and using the same scaling factor (10% and 20% for the low and high scenarios respectively) we construct the following table:

[78] This figure has been included in Martínez, M., Mulas, J., Herrera, G., & Aragón, R. (2004, October). "Efectos de una subsidencia moderada por extracción de agua subterránea en Murcia, España". In Proc. XXIII Congress of IAH-ALHSUD, Zacatecas, Mexico. Conference on Groundwater Flow Understanding from local to regional scales (pp. 249-252).

[79] We assume that this figure corresponds to the estimation of the 1992-1995 costs in today's values.

[80] Different sources quote between 450 and 510 – we take it as 500. https://en.wikipedia.org/wiki/Murcia

[81] See here: https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/base-profile/region-murcia

Damage extrapolation Spain	Damage per area	Scaling factor Low	Scaling factor High	Damage associated to well extraction
	€ 2,708.33	0.1	0.2	0.5

		Monitored Area (Potential)		Potential Savings (Building Damages)	
River Basin	Total Basin Area	Low	High	Low	High
Segura	19033	1903	3807	€ 2,577,385	€ 5,154,771
Guadiana	55498	5550	11100	€ 7,515,354	€ 15,030,708
Guadalquivir	57196	5720	11439	€ 7,745,292	€ 15,490,583
Sur	18000	1800	3600	€ 2,437,500	€ 4,875,000
Jucar	42737	4274	8547	€ 5,787,302	€ 11,574,604
Tajo (Madrid)	8000	800	1600	€ 1,083,333	€ 2,166,667
Catalonia	16441	1644	3288	€ 2,226,385	€ 4,452,771
Total	**216905**	**21691**	**43381**	**€ 29,372,552**	**€ 58,745,104**

Table 5-2: Potential savings from avoided damages over selected river basins in Spain

What this table tells us is the following: if CHS and its counterparts in the selected river basins (where it would make sense to deploy InSAR monitoring for aquifer management) were not using the service, the overexploitation of the aquifer could generate ground subsidence that could lead to **damages in buildings reaching annual values of 29.4 to 58.7 Million Euros.** It should be noted that in this calculation we considered that only 50% of the reported damages would really be associated with the water extraction activities in the aquifer; the other 50% would be claims related to other causes of building damages. This shows that whilst our projection is very modest, it still yields significant benefits thanks to Sentinel 1-based InSAR.

Environmental Impact Analyses

The execution of aquifer exploitation activities in the Segura River Basin is governed by the Resolution of October 2011[82]. This formulates an Environmental Impact Assessment for aquifer exploitation in the Vega Media region. This sets the objectives, overall framework (and boundary conditions) and technical details for the operation. Very importantly it explicitly refers to subsidence-related matters following the 1992-1995 experience. To carry out this approach, CHS contracted IGME and DARES to produce reports using InSAR powered by Sentinel-1. In that sense, **the service by DARES/IGME allows CHS to fulfil its obligations as per the Environmental Impact Assessment**.

To obtain the knowledge required in connection to land subsidence, CHS relies on the reports provided by IGME using the Sentinel-1 enabled InSAR measurements of DARES. But what if these measurements were not available? How would CHS fulfil its obligation? In developing such a hypothetical scenario (counterfactual), it quickly becomes apparent that the associated costs would grow out of proportion.

[82] https://www.boe.es/diario_boe/txt.php?id=BOE-A-2011-16725

GNSS Total Stations cost between 10-20k€[83] and would need to be placed[84] – at minima – on every well in operation. Even when we take only the 25 active wells included in IGME's reports to CHS (see figure 5.1), we quickly see that merely the capital cost rises to between 250-500k€. Moreover, as CHS relayed, these stations are often targeted by thieves. Over the 7 years of monitoring done by DARES/IGME, several of these stations could be stolen.

Cost of Total Station (CAPEX)			
Low		High	
10000		20000	
Number of Stations			
Low (no theft)		High (with thefts)	
25		30	
Total Cost (CAPEX)			
€	250,000.00	€	600,000.00
Maintenance and operating costs			
Half the CAPEX			
Grand Total Cost			
€	375,000.00	€	900,000.00

Table 5-3: "Savings" from Total Station costs - CHS

As a result, additional costs for either purchase of new stations or better security are needed. Together with other operational costs associated with storage and processing of the collected data we can assume that the total cost is 1.5 times the CAPEX. Which means that **CHS would have to invest between 375k** (taking the low/low combination) **and 900k** (taking the high/high combination) **€ in GNSS Total Stations, over the same period (2014-2020) and across the same area.** The results of this assessment are shown in the table above. It should be noted that over and above the financial considerations, the use of GNSS Total Stations wouldn't reach the quality of measurement achieved by InSAR[85].

The use of GNSS Total Stations in the Segura basin and the associated savings experienced when using InSAR instead can be extrapolated in Spain, for the basin areas discussed in the previous tier. To do such an extrapolation we can assume that the spread of stations in order to cover the area that has to be monitored follows the same logic as in Segura. In practice, we take the same number of stations to cover 500 km^2, and calculate the annual price (cost) per square kilometre to be between 107 and 300 € (low-high). This yields the following table.

[83] For instance: https://globalgpssystems.com/total-stations/robotic-total-stations/

[84] The required measurement accuracy can only be obtained by using GNSS augmentation services. This would typically entail a subscription to an Real Time Kinematic (RTK) network which, however, costs approximately 1000€ per year thus not affecting the calculations significantly.

[85] A comprehensive review including cost-benefits is presented here: https://mtri.org/geoasset/media/doc/deliverable_Deliverable%206A.pdf

Counterfactual extrapolation Spain	price per sqkm- Low	price per sqkm - High	Scaling factor Low	Scaling factor High
	€ 107.14	€ 300.00	0.1	0.2

		Monitored Area (Potential)		Potential Savings (Counterfactual)	
River Basin	Total Basin Area	Low	High	Low	High
Segura	19033	1903	3807	€ 203,925	€ 1,141,980
Guadiana	55498	5550	11100	€ 594,621	€ 3,329,880
Guadalquivir	57196	5720	11439	€ 612,814	€ 3,431,760
Sur	18000	1800	3600	€ 192,857	€ 1,080,000
Jucar	42737	4274	8547	€ 457,896	€ 2,564,220
Tajo (Madrid)	8000	800	1600	€ 85,714	€ 480,000
Catalonia	16441	1644	3288	€ 176,154	€ 986,460
Total	**216905**	**21691**	**43381**	**€ 2,323,982**	**€ 13,014,300**

Table 5-4: "Savings" from GNSS Total Stations costs – selected river basins across Spain

In other words, thanks to the use of the – anyway technically superior – InSAR solution, **CHS and its counterparts can be saving on an annual basis between 2.3 and 13 Million Euros.**

Another important aspect related to the Environmental Impact Analyses is the notion of ensuring sustainable aquifer exploitation, safeguarding an ecological flow in the river itself and, reducing the non-renewable groundwater withdrawal. Both these elements are aided by the ability to have continuous monitoring of the extraction operations (with both InSAR and piezometric measurements).

Optimising exploitation

Here we are looking only into the aquifer exploitation operations as they happen, not the longer-term picture (this is covered next). In that context, CHS looks to make available the optimal amount of water taken into account different, conflicting parameters: the needs of the different stakeholder groups, the overall state of the different water resources and the balance between them (i.e. groundwater, surface water, treated wastewater, etc.), the boundaries associated with subsidence risk. In that regard, by **having a clear picture of the state-of-play around each exploitation well, CHS is able to stop or start the operation of the right wells.** This can only be achieved by continuously monitoring ground deformation (with Sentinel-enabled InSAR) and by having a clear image of depletion levels for which ground deformation is certainly a good proxy. To explain this last point: The more the groundwater level is depleted, the more the pore pressure declines and consequently the more the ground subsides. Moreover, the deeper the water is in the aquifer (due to overexploitation) the more expensive the extraction operation[86]. This has a very direct economic impact in the overall operation as, in principle, the excessive cost of groundwater extraction translates into the price of water itself.

[86] In practice, extraction pumps require more energy to "lift" the water from the greater depths. This translates into increased "variable costs" for the operation of the pumps. But capital costs may significantly increase too if one needs to go much deeper to find water. A nice overview can be found here: http://www.clw.csiro.au/publications/technical2002/tr20-02.pdf

This optimisation exercise has another very practical repercussion. If the operation of certain wells is put on hold, the communities in their proximity need to get water from elsewhere. Extrapolating this to the bigger picture, it means CHS has to make decisions on where this water may come from (which may be more costly).

Informing longer-term strategies

The previously discussed economic, public safety, environmental and operational aspects are crucial when considering longer-term strategies around the exploitation of the aquifer in the Segura River Basin. In that regard, the ability to continuously monitor ground deformation around exploitation wells during their operation has a significant direct and indirect impact. Thus, by constructing a comprehensive picture with rich time series, IGME can directly inform CHS on the limits of aquifer exploitation. In practice, this means re-assessing the 2cm of allowed subsidence we discussed earlier and, possibly, amending the limit for future use. Such a process has essentially already taken place; this was the legacy of the Terrafirma project. **CHS was exposed to the possibilities of InSAR and incorporated it to its operational workflow – a very significant step for any Water Management Authority to take**! Similarly, with solid scientific evidence backed by superior capability provided by Sentinel-1 InSAR measurements, CHS can extend the use of InSAR as and where needed, even to the possible extent of informing regulation. Indirect impacts arise in connection to both regulation and economics. In the first instance, the longer-term achievement of environmental goals can certainly benefit from a solid knowledge of the aquifer exploitation operations. Secondly, with the "reality check" over a long period of time provided by InSAR, CHS may inform its strategy vis-à-vis water balance, i.e. where the water comes from and what economic ramifications this strategy entails (e.g. investment in desalination, implementation of different costing schemes to recover groundwater extractions costs, etc.).

5.2.4 Tier 4: Citizens and Society

The key stakeholders in this tier are citizens who need water for daily life uses and farmers who use it for irrigation. Whilst both these stakeholder groups are completely unaware of the techniques and methods used by the competent authorities to manage the aquifer, they both have a strong stake in this case.

Citizens

The memory of building damages that occurred in the period 1992-1995, directly connected to land subsidence due to overexploitation of the aquifer, has led many citizens to be extra cautious about the state of the building they occupy. Often landlords perform *ad hoc* checks of structural damages and measurements of subsidence. In that regard, **the Sentinel-enabled InSAR monitoring of the extraction operations allows quick reactions to potential excessive subsidence (for CHS), thus protecting homes or business buildings** – as shown on table 5-2 in the previous section this benefit ranges between 29.3 and 58.7 Million Euros annually. Indirectly, this also allows a more sustainable exploitation of the aquifer with positive environmental impacts (from avoided depletion to quality of water) and mixed economic impacts. The reason they are mixed is that if groundwater extraction is to be put on hold this needs to be compensated by other sources (provided the same amount of water is still to be supplied to all interested parties – i.e. agriculture). This compensation may translate into additional costs in the water price or in infrastructure development (e.g. for the Tajo-Segura supply canal or for desalination plants). In that regard, it is interesting to note that in recent years dedicated communities of water users have been created in the region exercising tight control on management plans in the respective aquifers[87].

Last, but by no means least, the **increased trust of the public into the work of a competent public authority (CHS), who uses cutting edge technologies (InSAR) to supervise its operations**, is also noteworthy. Whilst this trust can not be quantified, it plays an important role in social cohesion.

Farmers

As discussed earlier, agriculture is the key economic activity in the region. In turn, irrigation accounts for more than 80%[88] of the annual demand for water in the Segura basin. In that regard, irrigation puts the biggest strain on the inherent water deficit in the region (up to 20% less supply than demand[89]). Given the lack of adequate alternative sources (e.g. water transfer from other basins, desalination) to fill in this gap, different challenges arise. On one hand, farmers are called to adopt cutting-edge irrigation solutions in this region, including even water deficit-based practices[90]. One the other, CHS is called to put economic policy measures in place that (i) protect the livelihood of farmers, (ii) reduce or, ideally, eliminate non-renewable extraction of groundwater, (iii) do not overburden the public budgets. As can be seen in dedicated research in this subject[91], this is a very complex problem to solve. Eventually, some mix of water buybacks (i.e. purchasing water rights back from farmers in periods of drought) and public spending seems to be the best scenario. Depending on the mix, different impacts on farm's net margin are observed.

In all this, InSAR-based monitoring enabled by Sentinel-1 observations does not have a direct impact. However, given its contribution to longer-term sustainability of aquifer exploitation, it may be seen as a tool that helps CHS make the right decisions and, ultimately, allow fair water policies.

5.2.5 Other Beneficiaries

When we met with CHS and IGME in Murcia, we were also pleased to be joined by representatives of the Region of Murcia and in particular the department responsible for Urban Planning. They were very keen to better understand both the contours of this particular case, i.e. aquifer management, but also the capabilities of InSAR monitoring in a broader sense. The reason is fairly straightforward: effective urban planning can only be carried out when you have as much information in hand as possible. And even if more than 20 years have passed since 1992-1995 when significant damages

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[87] For instance, Rodríguez–Estrella, T. (2014) mentions the role of such community for the management of the Ascoy-Sopalmo aquifer, Spain's most overexploited one.
[88] https://murciatoday.com/understanding-water-and-the-drought-in-murcia-and-the-segura-basin_171862-a.html
[89] Ditto
[90] See the review done by Ruiz-Sanchez et al (2019): https://www.researchgate.net/publication/49292093_Review_Deficit_irrigation_in_fruit_trees_and_vines_in_Spain
[91] See Javier Calatrava & David Martínez-Granados (2019), 10.1080/07900627.2018.1504756

occurred in buildings across Murcia due to overexploitation of the aquifer, the lessons learned on that occasion are still very vivid. Thus, the first element of interest for the Region of Murcia is to be informed of the findings on the area studied by IGME with InSAR measurements and in particular the overall ground displacement. The aftermath of 1992-1995 was to move the operation of wells further from the city; similarly, now by monitoring the progress of the extraction, CHS can inform the Region of Murcia if something is wrong. Eventually, this information is transformed into subsidence hazard assessments which can inform land plans; where to put structures and more importantly how to build them (foundations). Of course, in some cases the Region of Murcia does not have the luxury of selecting where to put structures – it has to place them in a "bad" place. But with the InSAR information, they can know better where to establish more solid structures.

Aside from this direct interest, the engagement of IGME with CHS has yielded significant momentum around the use of InSAR across the region. Thus, **IGME, CHS and other stakeholders are currently in discussions for the extension of the Sentinel-based InSAR monitoring, to cover mine waste dumps, dams and other areas**. **This may culminate in a one-of-a-kind region-wide InSAR monitoring system powered by Sentinel-1 and the processing prowess of DARES/IGME**.

5.3 Summary of Benefits

In this chapter, we draw together the different benefits to the stakeholders identified along the value chain, grouping them by six dimensions of value-chain analysis.

5.3.1 Economic

The use of Sentinel-1 enabled InSAR measurements for more sustainable aquifer management yields both direct and indirect economic benefits. The former is associated with the **revenues made by DARES and IGME in providing the service to CHS**. We have also analysed the potential benefits for DARES and IGME in a low and high extrapolation scenario; in this case they would be providing the service to other authorities responsible for aquifer management in areas around Spain with similar water scarcity/water demand and associated subsidence conditions.

Tier	Benefits identified	Annual economic value stemming from the provision of Sentinel-enabled INSAR services (in €)	
		Low	High
Tier 1 (DARES)	Generation of revenue from the delivery of INSAR products	€ 364,400	€ 728,801
Tier 2 (IGME)	Generation of revenue from the delivery of reports on ground deformation around extraction wells	€ 546,601	€ 1,093,201
TOTALS		**€ 911,001**	**€ 1,822,002**

Table 5-5: Direct economic benefits for the service provider and the intermediate user

Indirect economic benefits include **avoided costs from investment in alternative solutions** (i.e. GNSS Total Stations) and **avoided costs from building damages**. This last one makes up the largest part of economic benefits; which is no surprise as this is what triggers the use of InSAR-based services in the first place. Here, too, we extrapolated over the selected river basins across Spain.

Tier	Benefits identified	Annual economic value stemming from the use of Sentinel-enabled InSAR services (in €)	
		Low	High
Tier 3 (CHS and counterparts)	Avoided costs from investment in alternative solutions	€ 2,323,982	€ 13,014,300
Tier 4 (Citizens and Society)	Avoided costs from damages on buildings	€ 29,372,552	€ 58,745,104
TOTALS		**€ 31,696,534**	**€ 71,759,404**

Table 5-6: Summary of economic benefits

Thus, as seen in the table above, the **total economic benefit associated with the use of Sentinel-enabled InSAR services for sustainable aquifer management is between 31.7 and 71.8 Million Euros per year.**

5.3.2 Environmental

Using Sentinel-enabled InSAR monitoring, CHS is able to promote a more sustainable management of the aquifer. This has an important, albeit indirect, environmental impact. Thus, the environmental benefits, in this case, come from the reduction of the impact of extensive aquifer water extraction on the surrounding environment. This manifests, as extensively discussed in the previous chapters, in ground subsidence. In practice, by optimising the use of wells and also by having the capability for longer-term monitoring, CHS can promote better use of groundwater and – in principle – avoid or reduce **aquifer depletion**. In turn, the occurrence of effects such as ground erosion and the appearance of gullies can be reduced.

Figure 5-5: Erosion gullies and aligned piping in the case of the Guadalentín Valley[92]

[92] Photo taken from Rodríguez–Estrella, T. 2014 (see next footnote)

Sustainable aquifer management may yield additional environmental benefits. For instance, it helps to maintain river levels of certain thresholds that would **impact ecosystems and protected natural spaces** in the basin[93]. It also prevents saltwater infiltration in the aquifer, on the side closer to the sea, which would **degrade the quality of the water and affect agricultural soils**[94]. These, however, are not directly linked to the use of InSAR-based services.

Nonetheless, InSAR-based services may give rise to other significant environmental benefits (beyond aquifer exploitation and hence beyond the scope of this study) in the context of monitoring of the mining waste dumps stability and potential prevention of chemicals getting into the groundwater[95].

5.3.3 Societal

The ability to sustainably exploit the aquifer – strengthened thanks to InSAR services – has significant societal impact. Beyond the environmental considerations mentioned above, the fact that CHS follows an evidence-based approach, helps to (i) **protect public and private property from damages due to aquifer exploitation-related subsidence,** (ii) **build trust between key stakeholder groups (citizens, farmers, government)**, (iii) **inform longer-term strategies with the potential to make better use of public investment dedicated to overcoming critical challenges such as water scarcity**.

5.3.4 Regulatory

The increased situational awareness achieved thanks to the continuous and accurate monitoring of subsidence with Sentinel-based InSAR measurements, lends **significant direct support to the drafting and implementation of regulations**. In the first case, the ability to establish with solid scientific evidence what are the thresholds for the safe operation of wells can be directly imprinted into the relevant regulation (which currently and rather arbitrarily sets a 2cm accumulated subsidence as the limit). Similarly, as discussed in 5.2.3. the **ability of CHS to observe the provisions of regulation and associated Environmental Impact Assessments** as reflected onto the Resolution of October 2011[96] is significantly improved.

Indirectly, the InSAR services provided by DARES and IGME, help the CHS in the context of the River Basin Management Plan, which in turn, is reflecting the regulatory provisions of the Water Framework Directive (WFD). The achievement of the environmental objectives described in the WFD is to impose a legal requirement connected to the sustainable use of water. This is not a trivial issue as it eventually boils down to finding a meaningful mix of water resources so that (i) the

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93 Ministry of environment, and rural and marine environment of Spain. Newsletter Oficial del Estado, Tuesday, October 25, 2011 (in Spanish).

94 See Rodríguez–Estrella, T. 2014. The problems of overexploitation of aquifers in semi-arid areas: characteristics and proposals for mitigation.

95 Based on direct inputs from IGME this is something currently being explored in the Murcia region

96 https://www.boe.es/diario_boe/txt.php?id=BOE-A-2011-16725

demand side needs are satisfied (i.e. citizens, farmers, businesses) and their livelihoods preserved, (ii) the supply side is optimised (i.e. ensuring no aquifer depletion). All this requires well-thought policies, incentives and investments so as to preserve the natural environment and support local communities.

5.3.5 Entrepreneurship & Innovation

As with many other cases studied under the *Sentinel Benefits Study*, **the use of Sentinel-1 data for aquifer management gives rise to significant entrepreneurship and innovation benefits**. Firstly, it allows a company like DARES to build a **viable business model** around the delivery of **innovative products**, grow fast (**market expansion**) and provide quality services to clients across the globe (**internationalisation**). Secondly, **it allows a public organisation such as CHS to introduce innovative technologies into its workflow with the help of another public institution (IGME).**

5.3.6 Science and Technology

This case has a strong S&T component: thanks to the use of Sentinel-1 InSAR services, IGME can (i) **enhance its scientific output** (with regards to geological studies and modelling), (ii) transform – with the help of DARES – its **applied science to operational services**.

In the first case, IGME observes a "science benefit delta" that can be directly attributed to the use of Sentinel data for InSAR measurements:

- InSAR enables millions of reference points as opposed to GNSS surveying
- InSAR makes possible the modelling of influence areas of well-points which is also critical for territorial/land management
- Accuracy of deformation measurements through InSAR is extremely high and not possible with GNSS (GNSS stations need years of calibration before operational use)
- InSAR measurements have very high correlation (even better than the theoretical value) with piezometric data – thanks to the DARES analysis – allowing for measurement of the deformation below 5mm.

5.4 Synoptic Overview

Having looked at the different types of benefits and before proceeding to the conclusions extracted in this study it is instructive to provide a synoptic overview in the table below.

Tier	Benefits identified	Type	Value where **economic** (annual)
Tier 1 (DARES)	**Viable business model** based on the exploitation of Sentinel-1	Entrepreneurship and innovation	
	Market expansion enabled by exploitation of Sentinel-1	Entrepreneurship and innovation	
	Internationalisation enabled by exploitation of Sentinel-1	Entrepreneurship and innovation	
Tier 2 (IGME)	**Enhanced scientific output**	Science and Technology	
	Transformation of **applied science to operational services**	Science and Technology	
Tier 3 (CHS and counterparts)	**Avoided costs** from investment in alternative solutions	Economic	€ 2.3 - 13 Million
	(Indirect/Longer term) Ability for **sustainable groundwater use**	Environmental	
	Ability to **observe regulatory provisions** and associated Environmental Impact Assessments	Regulatory	
	Ability to **draft regulations** based on solid scientific evidence	Regulatory	
	Innovation in operational workflow	Entrepreneurship and innovation	
Tier 4 (Citizens and Society)	**Avoided costs** from damages on buildings	Economic	€ 29.3 – 58.7 Million
	(Indirect/Long term) Reduced **impact on ecosystems and protected natural spaces**	Environmental	
	(Indirect/Long term) Reduced **soil and water quality degradation**	Environmental	
	Increased trust between key stakeholder groups (farmers, citizens, government)	Societal	
	Informed **long-term strategies for public investment**	Societal	
TOTALS			**€ 31.7 – 71.8 Million**

Table 5-7: Summary of benefits for each Tier

Note: The economic benefits associated with the generation of revenue from the provision of InSAR based services (or equivalently in the case of DARES with increased employment) are not listed here as they would introduce a "double-counting", since they are a cost for CHS.

6 Key Findings and Final Thoughts

6.1 Key Findings

The case of aquifer management in Spain provides a perfect example of how Sentinel-1 data can enable innovative solutions (InSAR services) that meet direct user needs. Thus, using the ground subsidence reports provided by IGME (developed with Sentinel-1 enabled InSAR measurements by DARES), CHS is able to perform more sustainable aquifer management. This is of critical importance, as the region of Murcia – a semi-arid region, with frequent droughts and inherent water scarcity, relies strongly on the economic output of agricultural activity. CHS can meet the regulatory provisions related to groundwater extraction, protect the property of citizens and businesses and safeguard the status of the aquifer, an important environmental asset for the wellbeing of the community.

Similar climatic, geological and economic conditions apply in multiple other areas in Spain and beyond. This means that the strong proposition of Sentinel-enabled InSAR services can create value for aquifer management authorities at a much larger scale (see discussion in 6.3 below). Thus, **when projecting the use of the Sentinel-based InSAR service for sustainable aquifer management in selected river basins in Spain, we find a very significant annual benefit: between 31.7 and 71.8 Million Euros per year, associated with savings from avoided damages to buildings and avoided investments in alternative solutions.**

A summary of the degree of the benefits as applicable to this case, taking into account previously studied cases, is shown below. The assessment is subjective; the basis for it is given in Annex A2.

Economic	Environmental	Societal	Regulatory	Innovation & Entrepreneurship	Scientific & Technological
★★★★	★★	★	★★★	★★	★★

Table 6-1: Benefits Assessment by Category

This case also presents an excellent example of three very different organisations working together in harmony in a very well-knit value chain. DARES, an innovative privately-owned company in Barcelona who has built its business model around the exploitation of freely available Copernicus Sentinel data, provides the key input (InSAR measurements) for IGME, a prestigious public research organisation. With this input, IGME can fulfil its mission - to *help public administrations, economic operators and society at large by creating and sharing knowledge on various geological subjects*. In turn, IGME helps CHS to innovate, using cutting-edge EO-based products and provide value to citizens, farmers, businesses and even other governmental organisations (i.e. the Department of Development and Infrastructures).

Thus, the benefits experienced even further down the value chain, have a strong direct or indirect connection to the use of Sentinel data. This is discussed below.

6.2 The Impact of Sentinel Data

In most cases analysed under the *Sentinel Benefits Study* the question of attribution arises, i.e. what percentage of the produced benefit can be attributed to the use of Sentinel data? In this case, however, this question can be very easily answered: 100%. The ability of IGME to produce reports that meet the requirements of CHS is fully tied to the quality of InSAR measurements generated by DARES using Sentinel-1 data. In essence, the whole value chain is formed thanks to the free, full and open availability of Sentinel data. DARES has strongly underlined that without it they would not have ventured into creating the company; IGME would not be able to produce similar reports using GNSS total stations; subsequently, CHS would not be able to monitor the operation of extraction wells and promote sustainable aquifer management in the same way it does now.

Of course, there are certain benefits, for instance, the environmental ones, which do not directly rely on the use of Sentinel-1 data. Instead, they rely on the decisions made and practices exercised by the stakeholders who do use Sentinel-enabled products. In other words, avoiding aquifer depletion relies on the decisions made by CHS once they form a complete picture defined by multiple parameters (economic, safety, etc.). But in forming a complete picture, CHS certainly benefits from Sentinel-1 InSAR services provided by DARES and IGME.

6.3 Widening the Perspective

The main focus of this case has been Murcia and the use of InSAR measurements to monitor ground subsidence around wells operating along the Segura River Basin. The application, however, of the technique used is by no means specific to this region. Instead, it has a wider perspective. This can be studied along three dimensions: (i) geographic extension, (ii) increased market penetration and (iii) improved technological maturity. The first point has been already discussed earlier where we have attempted to project the benefits on a number of selected river basins across Spain. Below we discuss the geographic extension beyond Spain and cover the other two dimensions too.

- **Geographic Extension**

Subsidence affects sedimentary basins where unconsolidated sediments lay, subjected to intense groundwater extraction due to irrigation and climates characterized by prolonged drought periods. As with the case of Segura, the aquifers of these areas are usually overstressed (or in danger of being so): groundwater extraction outpaces natural groundwater recharge, the groundwater level drops triggering soil consolidation and land subsidence. These conditions affect the whole Mediterranean basin countries, especially those countries with intensive use of groundwater for agriculture, such as Spain, Italy, Greece, Turkey, Israel, Jordan, Egypt, Morocco, etc.

In that regard, the use of Sentinel-1 data to produce InSAR measurements and generate ground subsidence reports can power solutions across all of these countries. In fact, DARES and IGME are already active in doing so. DARES serve clients in similar settings in other geographies – see for instance a product for Mexico City where overexploitation of the aquifer has caused significant ground subsidence. Similarly, IGME is involved in key European projects (most recently e-shape and RESERVOIR) showcasing and extending the capabilities of InSAR. Through these contracts and projects, both DARES and IGME will further the use of Sentinel-1 in InSAR measurements, build relationships with local actors and extend their reach in other geographies.

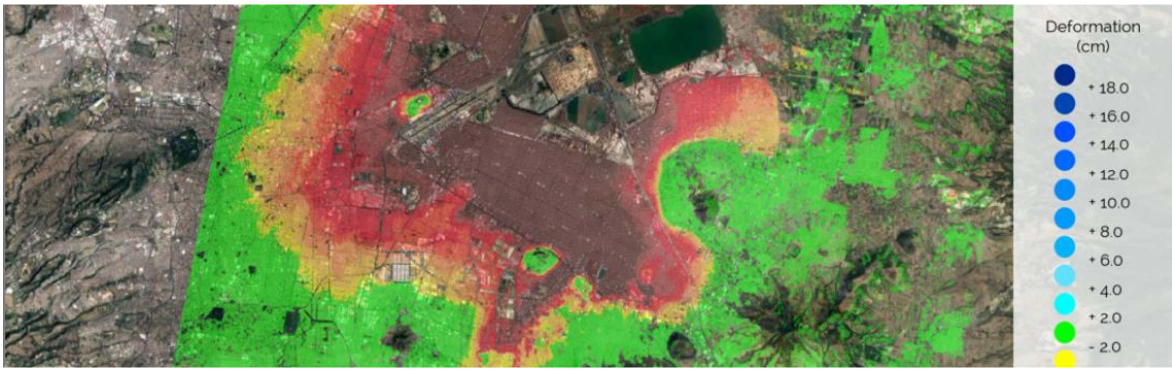

Figure 6-1: DARES serves clients across the globe – the case of subsidence in Mexico City

- **Increased Market Penetration**

Whilst the potential for wider geographical coverage is undeniable, the question of increased market penetration is a prevalent one. In the case of Murcia, the long-term study of the area by IGME has certainly eased market entry. This dynamic, i.e. strong presence of IGME and reputation of DARES, is definitely applicable to Spain. This allowed us to make a projection of market penetration in other areas of Spain which have similar climatic and economic conditions (see sections 5.2.2 and 5.2.3). Even there, additional research is required to establish a model of extrapolation that looks closer into technical characteristics (i.e. subsidence susceptibility, percentage of flat lands along the basin, etc.).

Outside of Spain, the involvement of IGME in international research projects could result in pilot studies, that – over time – turn into operational services potentially supported by DARES. In general, the role of an organisation such as IGME (i.e. a geological survey or geological institute) seems to be pivotal, as public water management authorities are often keener to work with such actors. In that regard, some international activities such as GeoERA promise to raise awareness, build networks and lay the path for private actors to serve the market.

In light of these considerations (for geographic extension and market penetration), we refrain from projecting the economic benefits of this case on a scale outside of Spain, as the "onboarding" of new clients cannot be represented with a "one-size-fits-all" extrapolation model.

- **Improved Technological Maturity**

Technological maturity should be understood here as (i) the capacity of the users to make optimal use of a given service (even when this service remains unchanged over time), (ii) the ability of the providers to improve their value proposition using the feedback (and data analytics) from their customers. In the case of InSAR-based monitoring of ground subsidence in Murcia it seems that the user is already in a very good position to make the most of what is provided. If we extend, however, beyond Murcia, it is safe to assume that users will require quite some effort to integrate the relevant reports and products into their operational workflows.

With regards to the value proposition provided by DARES and IGME there is no doubt that, whilst at the forefront of innovation, still has room to further improve. Establishing correlations with piezometric measurements, validating data with other means (e.g. GNSS total stations) and studying such complex systems as the aquifers and the decisions made around their management, will – in principle – result in better services (that is not to say that they don't already have excellent quality!). Moreover, advances in Artificial Intelligence, machine learning and Big Data handling may result in better processing algorithms for DARES and thus enhanced services.

6.4 Final Thoughts

The value of Sentinel-1 data in enabling accurate measurements of ground subsidence (with InSAR), supporting sustainable aquifer management and, consequently, generating significant benefits along the value chain has been clearly showcased. Whilst this case has primarily focussed on aquifer management in Murcia, its narrative and conclusions are valid not only for similar cases across Spain and beyond, but also for other ground deformation contexts. In that regard, this case forms part of a family of cases analysed under the *Sentinels Benefits Study*.

Individually, but also collectively, such cases underpin how public investment in a cutting-edge technological asset (i.e. the Copernicus Sentinels) returns significant benefits to governmental authorities, businesses, research institutes and the public at large. Moreover, the InSAR services generated using Sentinel-1 data, support processes (here sustainable groundwater management) that are directly tied to European (Water Framework Directive) and national (River Basin Management Plans) legislation which promotes the wellbeing of our environment and our society. This becomes more prevalent as the challenge of water management is exacerbated by climate change effects. In that regard, such cases act as a "lighthouse" illuminating how different actors can cooperate along the value chain and produce a wide array of benefits, economic, environmental, societal, regulatory, innovation- and science-related.

In light of all the above, we hope that the analysis presented herein will spark further uptake of the solutions discussed here – by authorities dealing with similar issues. In that sense, the fact – as indicated by DARES and IGME – that a "Regional InSAR Service" is being discussed among a wider circle of Murcia authorities is considered very encouraging. We also hope that researchers will be inspired to carry out complementary analyses, in relation, for instance, to (i) developing more rigorous extrapolation models, (ii) assessing how better knowledge of ground subsidence can be integrated in regulatory considerations, and (iii) tying the analysis done here with the policy/economic instruments (e.g. water buybacks, environmental taxes, etc.) required for sustainable aquifer management.

Annex 1: References and Sources

The list below covers only the main sources used extensively throughout the study. The reader can find more references in the form of footnotes or hyperlinks throughout the report.

1. G. Bru, G. Herrera, R. Tomás, J. Duro, R. De la Vega & J. Mulas (2013) Control of deformation of buildings affected by subsidence using persistent scatterer interferometry, Structure and Infrastructure Engineering, 9:2, 188-200, DOI: 10.1080/15732479.2010.519710
2. Javier Calatrava & David Martínez-Granados (2019), Water buybacks to recover depleted aquifers in south-east Spain, doi: 10.1080/07900627.2018.1504756
3. T. Rodríguez–Estrella (2014), The problems of overexploitation of aquifers in semi-arid areas: characteristics and proposals for mitigation,
4. Şen, Z. (2015). Groundwater Management. *Practical And Applied Hydrogeology*, 341-397. doi: 10.1016/b978-0-12-800075-5.00006-6
5. Directorate General for Water (2017), Summary of Spanish River Basin Management Plans – 2nd Cycle of Water Framework Directive
6. European Parliament (2016), Study on River Basins and Water Management in Spain
7. Ministerio de Medio Ambiente, y Medio Rural y Marino (2011), BOE-A-2011-16725
8. Murcia Today, Understanding Water and the Drought in Murcia and Segura Basin, November 2017: Link
9. Various webpages and documents from the:
    a. Segura River Basin Authority CHS (Link)
    b. Geological Survey of Spain IGME (Link)
    c. DARES (Link)

Annex 2: General Approach and Methodology

This case has been analysed as a part of the Sentinel Benefits Study (SeBS), which looks at the value being created by the use of Sentinel data. It follows a methodology[97], established during a previous study, looking at a value chain for the use of a single EO service.

For each case, a value chain is established with a service provider and a primary user. The value-chain is validated with these two key players. Through a combination of desk and field research, we develop our understanding of all the actors in the value chain, the role that they play and how they may benefit through the use of the satellite-derived products.

The value-chain is divided into a number of tiers where the supplier is Tier 1, and the primary user is Tier 2. The last Tier is always "Citizens and Society". The number may vary according to the complexity of the value-chain. The benefits are then analysed against each of these tiers.

Once written, the draft report is then shared with all the persons with whom we have spoken, and their comments are incorporated, or a further discussion is held to establish a common understanding. Note that we are not asking these experts to endorse our findings but to indicate any gross errors or sensitivities which may have been introduced. At the end of this process, the report is made public.

As work has proceeded and more cases analysed, some modifications have been made to the methodology described in reference 97. The first of these has been to expand from the two dimensions used earlier, namely economic and environmental benefits, to add those connected to societal, regulatory, innovation and entrepreneurship and scientific and technological. These six dimensions are described in the table A2-1 below.

Dimension	Definition
ECONOMIC	Impacts related to the production of goods or services, or impacts on monetary flow or volume, such as revenue, profit, capital and (indirectly, through turnover generation) employment.
ENVIRONMENTAL	Impacts related to the state and health of the environment, particularly as regards the ecosystem services on which human societies depend.
SOCIETAL	Impacts related to societal aspects such as increased trust in authorities, better public health or secured geostrategic position.
REGULATORY	Impacts linked to the development, enactment or enforcement of regulations, directives and other legal instruments by policymakers.
INNOVATION-ENTREPRENEURSHIP	Impacts linked to the development of new enterprise and/or the introduction of technological innovation into the market.
SCIENCE-TECHNOLOGY	Impacts linked to academic, scientific or technological research and development, the advancement of the state of knowledge in a particular domain.

Table A2-1: Definitions for the benefit dimensions

[97] SeBS Methodology; June 2017.

For each of these, a ranking has been introduced to give an immediate, visual impression of the scale of the benefits under each dimension. To aid in the quantification of these, a guide has been introduced which is shown in Table A2-2.

Rank	Benefit status	Criteria
0	**Null**	The case presents no perceivable benefits in this dimension, and no potential for such benefits to emerge is anticipated.
1	**Latent**	The value chain described in the case may, in general, present potential benefits in this dimension, but none have been identified or described in this particular instance.
2	**Manifest**: At least one benefit in this dimension has been identified through the value chain within the case. Its significance in the context of the case overall is judged to be:	**Low**
3		**Moderate**
4		**High**
5		**Exceptional**

Table A2-2: The ranking of the benefits.

In order to introduce further basis for comparison, a systematic approach has been developed for the analysis of the benefits. A series of indicators have been defined for each of the benefit dimensions against which each case can be considered.

The indicators used in the case are listed in section 5.3.6, and a full list of all indicators considered is provided in Table A2-3.

Dimension	Indicator	What it can mean.
Economic	Avoided costs (AV)	Alternative means to gather data
	Increased Revenues (IR)	Increased production/sales
	Reduced Inputs (RI)	Less time spent or material saved
	Improved Efficiency (IE)	Better use of resources
Environmental	Reduced pollution (RP)	Reduced amounts of pollutants in key resources e.g. water, air
	Reduced impact on natural resources (RR)	Reduced environmental impact e.g erosion, habitats/biodiversity.
Societal	Improved public health (IPH)	Less toxicological risk
	Common Understanding (CU)	Better control and communication of remedial efforts i.e through common maps.
	Increased trust and better transparency (ITT)	Improved preparedness / response
	Strategic Value (SV)	Common societal value to a country or region.
Regulatory	Improved policy / regulation design/drafting	Better information (scale, accuracy) leading to better regulation
	Improved efficiency in policy/regulation monitoring	Better information available to monitor adherence to regulations.
Innovation & Entrepreneurship	Innovative products	Sentinel data leads to creation of new products / services
	New Business models	New ways to generate income.
	New markets	Global nature of sentinel data enables international business development
	New businesses	Creation of new companies; start-ups
Science & technology	Academic output	
	Research exploitation	Applied science to operational services
	Research contribution	New product enabling scientific research

Table A2-3: Complete list of indicators considered within SeBS analyses.

Annex 3: Winners… and losers?

The creation and subsequent usage of Sentinel data down the value chain has a significant economic impact. Quite prominently, product and process innovation based on the availability and subsequent application of the data, lead to positive effects where new products and services emerge, and existing processes can be run more effectively and efficiently. Conversely of course, there are also 'negative' consequences as jobs are displaced and sometimes even destroyed, creating technological unemployment.

> As we have shown in our study 'Winter navigation in the Baltics' as the captains on the icebreakers in the Baltics could suddenly rely on Sentinel based ice charts providing a fully synoptic picture of the ice, the helicopter pilots they traditionally relied upon, became abundant.[98] Similarly, in our study 'Forest Management in Sweden' the Swedish Forest Agency could reduce the number of forest inspectors, as Sentinel data allowed for a reduction of in situ inspections.[99]

How technological progress and innovation are related to employment has been an area of fierce debate for centuries. From fairly recent studies appear that product innovation spark new economic activities, creating new sectors, more jobs, whereas process innovation[100] is more job destroying, although market mechanisms can sometimes largely compensate for the direct job losses, mitigating the ultimate impact on demand for labour. Such price and income compensations can derive from a decrease in wages, leading to an increase in demand for labour or the effects of new investments (enabled by accumulated savings) creating new jobs elsewhere. Obviously, the speed and impact of such effects are highly dependent on the flexibility of markets, the level of competition, demand elasticity, the extent of substitutability between capital and labour and, of course, possible institutional rigidity.[101]

> A German study on the co-evolution of R&D expenditures, patents, and employment in four manufacturing sectors concluded that patents and employment are positively and significantly correlated in two high-tech sectors (medical and optical equipment and electrics and electronics) but not in the other two more traditional sectors (chemicals and transport equipment).[102] Similarly, a study using a panel database covering 677 European manufacturing and service firms over 19 years (1990–2008) detected a positive and significant employment impact of R&D expenditures only in services and high-tech manufacturing but not in the more traditional manufacturing sectors.[103] Another study found a small but significant positive link between a firm's gross investment in

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98 Sawyer, G. and De Vries, M. "Winter navigation in the Baltics." Copernicus Sentinels' Products Economic Value: A Case Study (2015)

99 Sawyer, G. and De Vries, M. "Forest Management in Sweden." Copernicus Sentinels' Products Economic Value: A Case Study (2016)

100 As process innovation is defined as producing the same amount of output with less labour (and sometimes other) inputs, logically the direct impact of process innovation is job destruction when output is fixed.

101 Vivarelli, M. "Innovation and employment: Technological unemployment is not inevitable—some innovation creates jobs, and some job destruction can be avoided." IZA World of Labor 2015: 154

102 Buerger, M., T. Broekel, and A. Coad. "Regional dynamics of innovation: Investigating the coevolution of patents, research and development (R&D), and employment." Regional Studies 46:5 (2012): 565–582.

103 Bogliacino, F., M. Piva, and M. Vivarelli. "R&D and employment: An application of the LSDVC estimator using European data." Economics Letters 116:1 (2012): 56–59.

innovation and its employment based on longitudinal data set of 575 Italian manufacturing firms over 1992–1997.[104]

Clearly, this tells us that the ultimate 'net' impact of innovation – both at product and process level - brought about by the availability of new technology, such as Sentinel data, will be closely related to the market and institutional settings in which they become effective. However, on the whole the conclusion seems justified that the 'negative' effects, in the form of possible loss of employment, is largely outweighed by the positive economic effects throughout the value chain.

Accordingly, in this study – and likewise for the past and future ones - we will concentrate on the positive effects brought about by the availability of the Sentinel data throughout the value chain. That there are also (temporary) 'negative' impacts is a given, but the net effect at macro level will always be positive.

[104] Vivarelli, M. "Innovation, employment, and skills in advanced and developing countries: A survey of the economic literature." Journal of Economic Issues 48:1 (2014): 123–154 as well as "Technology, employment, and skills: An interpretative framework." Eurasian Business Review 3:1 (2013): 66–89.

Annex 4: About the Authors

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