N° 2 EXPERTISE COLLECTION

Better Knowledge for Better management

COMPLEMENTARITY BETWEEN FIELD DATA AND SATELLITE DATA

Towards a better understanding of field hydrology

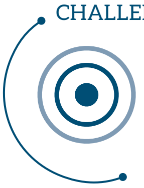
french water partnership

partenariat français pour l'eau

Contents

PICTOGRAMS OF THE EXPERTISE COLLECTION

CHALLENGES



KNOW-HOW

KNOW-HOW

Editor's note

In view of the threats to populations, water resources and ecosystems, it is now urgent that we put in place the concrete measures necessary for us to collectively meet the objectives set by the Paris Climate Agreement and the 2030 Agenda.

In 2016, the French Water Partnership (FWP), with its pool of experts, identified knowledge as one of the major themes for the management of water and aquatic environments, adapting to climate change, and climate modeling. It consequently set to work, launching its thematic "expertise" collection with its first issue in 2016. This initial issue sets out the expertise of French public and private stakeholders in this area, whether in terms of acquiring hydrological and meteorological data, setting up functional water information systems, or developing hydro-climatic models that will help us deal more effectively with the challenges ahead. It also observes that networks for acquiring water data are shrinking in many countries, and developing countries in particular.

Since then, the IPCC's special 1.5°C report has revealed that the information relating to freshwater is classified as being of "medium confidence". Knowledge on this topic has in fact progressed very little since the fifth report due to a lack of data, regionalized expertise, and field data. In response to these observations, the FWP and its members have proposed to continue their work on knowledge with a second issue. This issue aims to provide decision-makers in developing or emerging countries with the keys to strengthening knowledge on the hydrology and quality of aquatic environments by using satellite data to supplement field data.

In this issue you will therefore find an overview of the major challenges related to knowledge, and a presentation of a large number of initiatives and projects by French stakeholders around the three major themes of quantitative monitoring of water resources; water quality; ecological monitoring and biodiversity; agricultural uses of water. The initiatives and projects chosen reflect the broad range of expertise among French stakeholders and their capacity for collective innovation around the major challenges of our century.

Jean Launay,
President of the French Water Partnership

AUTHORS
PART 1
Christophe Brachet, Deputy Director General, International Office for Water
Blaise Dhont, Research Officer, International Office for Water
PART 2
Alice Andral, Spatial Hydrology Specialist – SWOT-aval Program, Centre National d'Etudes Spatiales (French National Centre for Space Studies), CNES
PART 3
Etienne Dressayre, Deputy Director, agriculture and irrigation, BRL Engineering

COORDINATION
Jennifer Fernando, Project Manager, French Water Partnership, FWP
Jean Luc Redaud, President of the Water and Climate Working Group, French Water Partnership, FWP

GRAPHIC CONCEPTION
Anne-Charlotte de Lavergne, www.ancharlotte.fr

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Foreword

Water is vital to the development of our societies *because it is indispensable for health, farming, energy and biodiversity, and water security is a vehicle for peace. Nevertheless, water resources are still* ***poorly understood, poorly managed, and poorly protected*** *from human activities. They are subject to* ***increasingly significant anthropogenic pressure*** *driven by a host of factors such as population growth, rapid urbanization, industrialization, pollution, agricultural intensification and changing ways of living, which are increasingly threatening water resources.*

The IPCC's publication of its three most recent reports has sounded the alarm once again about the risks related to global warming of 1.5°C, and in particular about the impacts of climate change on already fragile water resources. Global warming, even at +1.5°C by the end of the century compared to the preindustrial period, will ***play a part in changing the climate, and more specifically the water cycle.***

On continents, ***these different anthropogenic pressures, which affect water quality as much as quantity****, impact basin areas from source to sea by way of a variety of environments such as mountains, lakes and rivers, wetlands, and groundwater.*

The large water cycle

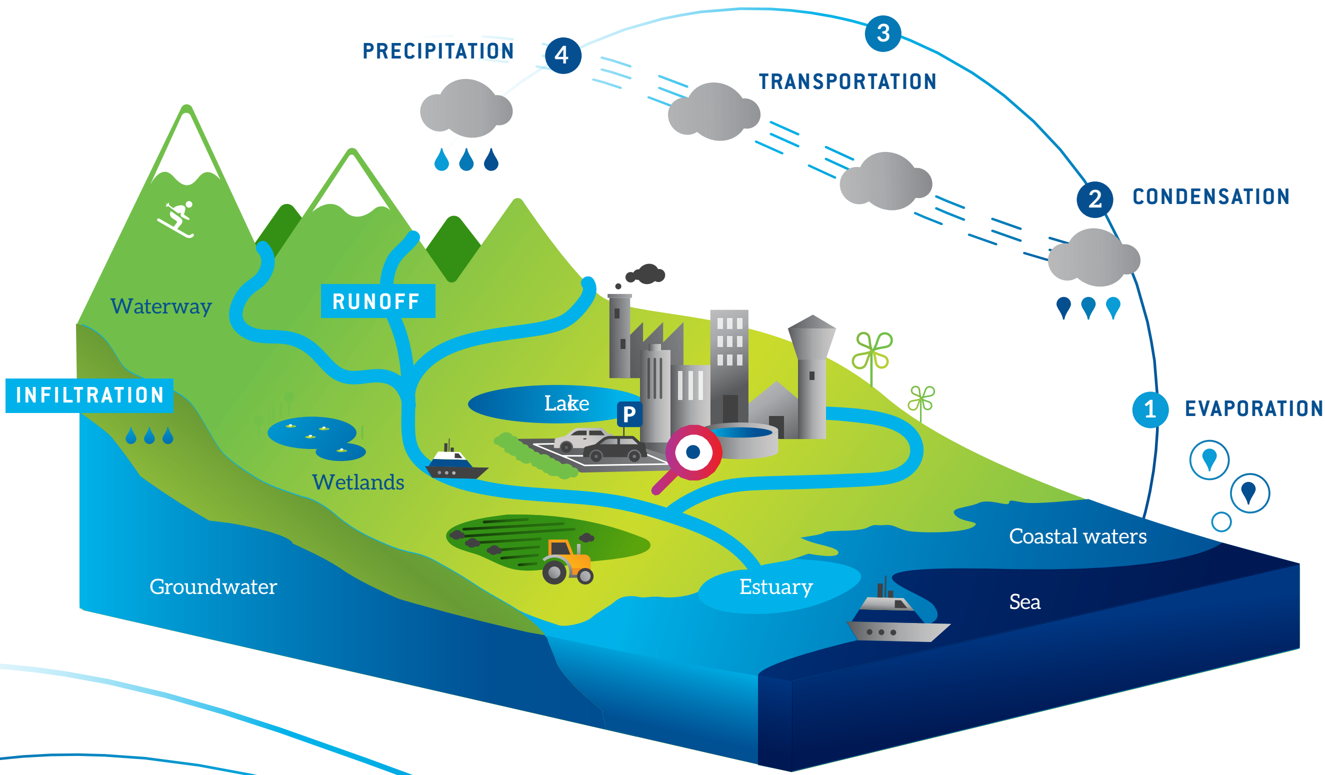


Figure 1 - Water cycle

*Furthermore, **biodiversity is today experiencing a major crisis**: according to the IPBES, close to one million animal and plant species are threatened, meaning that one in every eight species could disappear in the next few decades. The factors identified as directly influencing change are, in decreasing order: changes in use of land and sea; the direct exploitation of certain organisms; climate change; pollution and invasive alien species.*

*In the current context of global warming, world population growth and the erosion of biodiversity, **concrete measures must be implemented in order to progress towards integrated, sustainable management of water resources and aquatic environments.** These are also the objectives of the Paris Climate Agreement and the 2030 Agenda with its 17 Sustainable Development Goals, the sixth of which is dedicated to clean water and sanitation while the others, with 12 targets related to water, highlight its cross-cutting nature.*

*Thorough knowledge and understanding of water resources is crucial if we are to act effectively. This requires us to **strengthen knowledge about climate and the water cycle at the regional and local level,** particularly that relating to freshwater, confidence in which is classified as by the IPCC as "medium" due to a lack of data, regional expertise, and field data.*

***The acquisition of data on the hydrology and quality of aquatic environments (rivers, lakes, wetlands, etc.) therefore represents an essential activity in the context of decision making,** and more specifically for developing, implementing and monitoring action plans. Hydrological information is necessary since it allows for better planning for water resources and investment, better sectoral management of the latter, better land use planning, and support for operations around major events (emergency and crisis management).*

*In spite of the increased need for data, an assessment carried out by the FWP via its first issue nevertheless identifies[1] a **fall in the density of hydrometric measurement networks in the field, and indeed a lack of them worldwide and more specifically in developing countries.***

*The development of spatial technology since the 1960s means that **observations of the Earth from space allow us to track almost in real time the natural or anthropogenic phenomena in different parts of the planet and at different times.** They enable us to s**upplement, reconstruct and densify existing in-situ data sets, and to extract from them, using models and processing and analysis tools, physico-chemical environmental parameters** (turbidity, water levels, etc.) to support decision making. Moreover, the synoptic nature of spatial observations (spatial coverage, revisit frequency, etc.) means that coverage of bodies of water has been improved. Satellite data thus enables areas in which field data do not exist to be reached, and at a lower cost than placing instruments in the field. It is less precise, but its accuracy is improving, making it adequate in a growing number of applications.*

In what follows, concrete examples of the use of satellite data are presented with the aim of supporting decision makers around three major challenges relating to water resources and aquatic environments:

- *quantitative monitoring of water resources;*
- *water quality, ecological monitoring and biodiversity;*
- *agricultural uses of water.*

[1] http://www.partenariat-francais-eau.fr/en/wp-content/uploads/sites/2/2018/03/Water-climate-and-development-Better-knowledge-for-better-management-October-2016-.pdf

PART 1

Quantitative monitoring of water resources

DEFINITION

What are spatial altimetry and hydrology?

Hydrometry looks at measurements of the flow rate of continental waters, both surface and groundwater. Most often, this discipline relates to measurement of the flow rate of waterways, i.e., of the amount of water flowing through a given section of a river per unit of time. However, quantitative monitoring of water resources is not restricted to the flow of surface waters and includes other activities such as the measurement of soil moisture or snow cover.

Since directly measuring the flow is a complex operation, most hydrometric stations record the water level which is then converted into flow rate using a rating curve (flow-level relationship) specific to each measurement site.

For a long time, measurement of water levels consisted of visual readings (typically every day) on graduated scales. Over time, the process has become automated with the installation of sensors that enable more detailed monitoring of variations in level and are adapted to the various types of hydrological regime in the waterways.

More recently, with the development of spatial tools, new satellite-measurement techniques have appeared: this is spatial altimetry.

This method relies on satellites equipped with a radar device (altimeter) which regularly fly over a series of the same points on the earth's surface (low orbit). The elapsed time between the issuance of the VHF signal from the radar and the reception of the echo effectively enable the distance between the satellite and the bodies of water (oceans, lakes, major waterways) to be measured, and hence their water level. Spatial altimetry is thus proving to be a highly promising technology, to supplement "traditional" in-situ hydrometry, for monitoring water resources.

Satellite data from space programs for Earth observation (such as the European Copernicus program) are also used to measure variables other than water level. They also enable monitoring of changes in expanses of water, snow-covered areas, and soil moisture, with global coverage and constantly improving spatio-temporal resolution: this is spatial hydrology. It is not to be confused with spatially distributed hydrology, where the term spatial is seen as taking into account heterogeneities of the ground.

CHALLENGES

SPATIAL ALTIMETRY, A KEY TOOL FOR THE HYDROLOGIST OF THE FUTURE

Knowledge about water levels and flow rates in waterways is key to understanding their dynamic and also for their efficient, sustainable management. A river's hydrometric stations are therefore necessary for:

- knowledge and understanding of the hydrological regime and the related natural hazards (floods, droughts) by compiling long time series (more than 100 years for some);
- warning systems in flood situations for protecting people and property;
- sizing of hydraulic facilities;
- operational management of hydraulic facilities (hydroelectric production, flood control, low-water level support, etc.);
- regulatory control, particularly as regards obligations to restore flow (for example, low-water target flows downstream of works);
- monitoring of the good ecological status of waterways and wetlands is dependent on it.

Current interest in hydrometry is reinforced by the challenges posed by the growth in uses of water (domestic, irrigation, industrial, hydroelectric, recreational, etc.) and the associated pressure on resources, by climate change and the increased vulnerability of populations, and by the restoration and preservation of natural environments and their biodiversity.

There are currently some 3,500 hydrometric stations in mainland France, more than 80% of which are transmitting in real time, which corresponds to the European average. Yet in other parts of the world the number of hydrometric stations is limited and in decline (particularly due to their maintenance costs). For example, this is the case in sub-Saharan Africa, even though this region is particularly exposed to climate change and its impact on the water cycle. In such geographical areas, characterized by large rivers and hard-to-access areas such as the Congo River basin, the potential of spatial altimetry is particularly strong.

FOCUS

The working group on spatial hydrology: a French initiative

A working group on spatial hydrology was created in 2014 and then consolidated by a group agreement signed during COP22 in Marrakech in 2016. It is currently led by OIEau and brings together the following French institutions: CNES, IRD, French Development agency (AFD), IRSTEA, BRLI, CNR and CLS. The group's work looks at the use of satellite data for monitoring water resources, including by setting up virtual stations. In fact, any intersection of a continental body of water with the ground track of a satellite equipped with an altimeter represents, after correction of the measurement, a virtual hydrological station capable of being used to monitor water levels in the body of water over time. In-situ stations are used to calibrate the virtual stations, and the transition from water levels to flow rates is one of the major projects in progress within the group. With the Hydroweb service (http://hydroweb.theia-land.fr/?lang=en&), a database of variations in water levels in the world's lakes and rivers based on satellite altimetry has been gradually established since 2003. Several thousand virtual stations are monitored and available on the platform, in real time or in deferred mode. In addition, more than 150 lakes are monitored and variations in size and volume are measured for many of them. The Hydroweb service is intended to inform users, scientists or others, about the status variables related to the hydrology of continental areas based on a variety of satellite data. Most of these variables are in the list of Essential Climate Variables put together by the Global Climate Observing System. The service is hosted on the platform of the national organization THEIA, and operated by CLS with coordination from LEGOS, IRD and CNES.

1

Monitor droughts through assimilation of data from satellite observations

Jean-Christophe Calvet (CNRM)

The Centre National de Recherches Météorologiques (University of Toulouse, Météo-France, CNRS) has developed a data-assimilation system that can operate at the global level for any type of vegetation (prairies, crops, forests, savannas). This tool is known as LDAS-Monde (http://www.umr-cnrm.fr/spip.php?article1022&lang=en). It incorporates satellite observations of vegetation and soil moisture in a model of the soil-plant system, the Soil-Biosphere-Atmosphere Interaction model (ISBA). The ISBA provides continuous information over time and produces a number of variables that are mutually consistent (biomass of vegetation, deficit or excess water in the soil, evapotranspiration, carbon fluxes, surface temperature). Satellite observations are used to improve the quality of the simulated variables. The model is populated by meteorological data available at low spatial resolution at the global level (from 10 to 25 kilometers). At the regional level, meteorological data is available at a higher spatial resolution. For example, Météo-France's AROME-France digital weather-forecasting system produces this information at a resolution of 1.3 km over much of western Europe. LDAS-Monde uses data produced by the Copernicus Global Land service: the leaf area index and a soil moisture index. Since these products have been available for several years, it is possible to calculate anomalies in soil moisture and vegetation growth. When implemented at the global level, LDAS-Monde enables droughts to be detected; the system is then used at higher spatial resolution in the region(s) concerned.

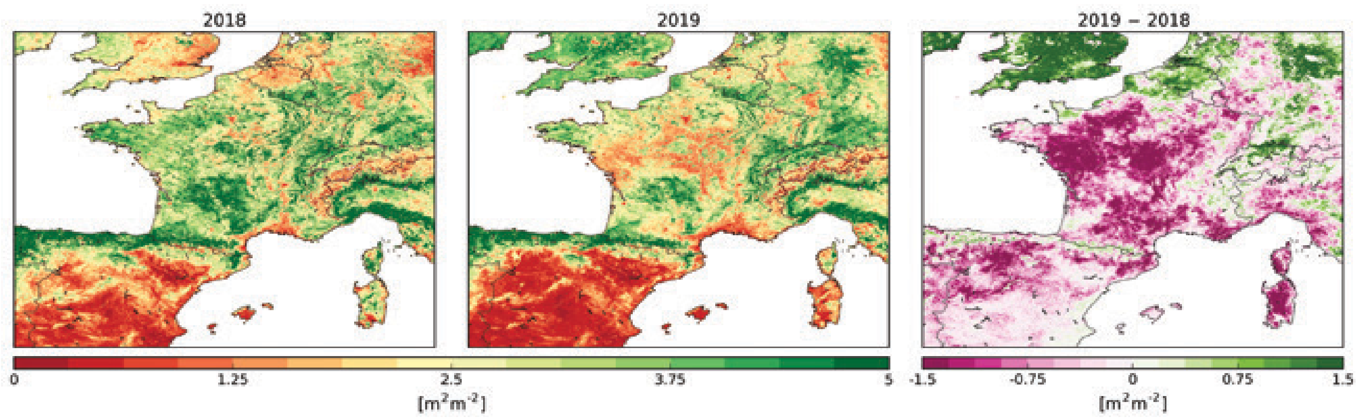


Figure 2 - Effect of the 2018 and 2019 heatwaves on vegetation. The leaf area index for vegetation for the month of July is displayed for 2018 and 2019. This is a value that was simulated by Météo-France's ISBA model using satellite data from the *Copernicus Global Land* service. The difference between these two maps illustrates the very marked droughts that affected southern England, Belgium, the Netherlands and Lower Saxony in 2018 (green), and almost all of France, northern Spain and Sardinia in 2019 (purple).

Combine spatial data with modeling to supplement in-situ hydrometeorological information when it is difficult to acquire (Amazon and Uganda)

Laurent Tocqueville (BRLI) , Yoann Aubert (BRLI), Thomas Legay (BRLI), Julien Verdonck (BRLI)

“HydroSIM Amazon” and “Smart Basin Uganda” aim to combine data from spatial altimetry and pluviometry with hydrological modeling tools, and link them to an optimized in-situ metrological network to correlate the simulation results with the “field truth". These two projects provide a “real-time” service for monitoring and forecasting water levels and flow rates in large basins. They therefore provide basin managers with the hydrometeorological information that is essential to the strategic management of their water resources. This Smart Basin service relies on historical and real-time data acquired by the different altimetric satellites (Jason 2 and 3, Sentinel-3A and -3B) and the Global Precipitation Measurement (GPM) meteorological constellation. Partially deployed in the Amazon, Nile and Congo basins, Smart Basin could be further enhanced in the near future by the arrival of the SWOT satellite. Delivered by the Water Information Management Ecosystem and Services (WIMES) platform of services developed by BRLI, Smart Basin thus offers a whole range of hydrometeorological functions for operating the network. It also offers a range of web services to ensure its seamless integration into the manager’s own information system. Smart Basin produces data on water level and flow rate via the GR hydrological models (rainfall-flow rate models developed by IRSTEA), and some water-quality parameters such as turbidity (via the Soil and Water Assessment Tool agro-ecological model - SWAT). These are essential data, particularly for dam-builders to anticipate the arrival of sedimentary inflow and potentially bypass the dam, to reduce sedimentation in the reservoir.

Strengthen monitoring of water resources with the SWOT spatial program

Philippe Maisongrande (CNES)

Monitoring of water resources at the global level is a major challenge for society, in which spatial techniques have a decisive role to play. Describing the water cycle on land surfaces with increasing precision means that the planet’s water resources can be managed with greater refinement, in terms of human activities such as drinking water and sanitation, irrigation, river navigation, urbanization, the production of hydroelectric energy, and so on. Within an international programmatic landscape of Earth observation, there are many missions providing information more or less directly on each component of the water cycle, including the future CNES/NASA SWOT (Surface Water Ocean Topography) mission due to be launched in 2021. SWOT’s main objective is to combine the needs of hydrologists and oceanographers in a single satellite, by collecting previously unseen data, at the global level, such as coastal fringes and estuarine systems. In continental areas, the SWOT mission will measure water levels in rivers, lakes and flooded areas using a new technical concept: wide-swath interferometric altimetry. This will provide images of water levels to centimeter accuracy, slope profiles of bodies of water and their width - for rivers wider than 100 meters and rivers, lakes and reservoirs of more than 250 x 250 meters - with a temporal resolution of one week.

4

Supplement in-situ hydrological information using spatial hydrology: EXAMPLE OF THE CONGO BASIN

Christophe Brachet (OIEau), Blaise Dhont (OIEau), Pierre-Olivier Malaterre (Irstea),

Stéphane Debard (IRD), Stephane Delichère (BRLI), Sébastien Chazot (BRLI), Damien Barral (BRLI)

The SWOT-aval preparatory program aims to facilitate the use of products derived from spatial technology in hydrology, particularly in anticipation of the SWOT data soon to be available, and to trigger the development of services and applications. The Congo Basin was chosen as the pilot basin in 2016, and an agreement was signed between seven French institutions (forming the "Working Group on Spatial Hydrology" and bringing together the CNES, IRD, Irstea, French Development agency (AFD), International Office for Water (IOWater), BRLI and CNR) at the COP22 in Marrakech, with the aim of initiating collaboration with the International Commission of the Congo-Oubangui-Sangha Basin (CICOS), the transboundary basin agency for the Congo River. With the support of the AFD, this work has led to the co-creation of a Hydrological Information System (HIS) with the CICOS. This information system is one of the first to combine in-situ data with data derived from spatial altimetry within a single environment. The HIS was designed to host downstream services in the most automated way possible, and the architecture chosen enables information to be exchanged and additional modules to be developed. The data derived from spatial altimetry are incorporated into the HIS in the form of virtual stations extracted from the Hydroweb platform, which give water levels at the intersection of altimetric tracks and bodies of water (the Congo Basin had 518 virtual stations in February 2019). The satellite data, supplemented by data from global databases and from a few in-situ stations, have enabled hydraulic models of these rivers and rating curves to be generated, allowing flow rates to be calculated from altimetric satellite data. Current challenges for the CICOS include raising awareness of the HIS among relevant stakeholders in the different countries, organizing exchanges of data with the national hydrological services, making the tool durable, and developing it, particularly with the development of downstream services.

Figure 3 - Virtual stations in the Congo Basin accessible from the Hydroweb service (http://hydroweb.theia-land.fr/?lang=en&, November 2019)

5

Applications for hydroelectricity and navigation in the Congo Basin

Sébastien Legrand (CNR)

The CNR (Compagnie Nationale du Rhône) is the concession operator of the Rhone river, with three missions: production of hydroelectricity, navigation and irrigation. The CNR extends the benefit of its expertise to other rivers, and as such it has developed services for the CICOS (International Commission of the Congo-Oubangui-Sangha Basin) relating to navigation and hydroelectricity, using spatial altimetry. As far as the hydroelectricity element is concerned, the CNR has calculated and then mapped an indicator which identifies the sections offering the best conditions in terms of flow rate and slope for developing hydroelectric power in the Congo and Ogooué basins. This indicator is based on spatial altimetry for calculating the slope, in-situ or reconstructed flow rate data, pluviometry data, and a Digital Terrain Model (DTM).

This method is useful currently in research into hydroelectric projects of several tens of MW. The SWOT satellite will help to improve this method in the future. The navigation component has enabled an operational service to be established to improve navigation on the Sangha, a tributary of the Congo. Since the Ouesso hydrometric scale on the Sangha is a navigability indicator that is monitored daily, CNR has developed a model for predicting water levels at this scale, using as input the previous days' water levels and precipitation data. The contribution of spatial altimetry data, acquired by the Jason-2 satellite and incorporated into the model, was also evaluated.

6

A new method of satellite measurement of snow depths in mountains

Simon Gascoin (CNRS, CESBIO)

Water from the melting of the snowpack is often used to produce hydroelectricity, and supplies irrigation channels in the cultivated areas downstream. For managers of dams in particular it is therefore important to know how much snow has accumulated at the end of the winter in mountain catchment areas. The ground measurement network is generally inadequate for estimating this amount due to the natural variability of snow depths. Recently, a new method for measuring the annual volume of snow available in mountain areas has been developed based on very-high-resolution satellite observations, such as Pléiades and WorldView. A snow-depth map is produced with resolution of 2 meters per pixel. Stereoscopic pairs of images are obtained for this in summer and at the end of winter. Each stereo pair enables a Digital Elevation Model (DEM) to be generated, which gives depth per 2 meter pixel. The snow depth is obtained from the difference between the two DEMs. The summer DEM can serve as a reference for several years to the extent that only one stereo pair needs to be obtained each year at the end of winter to establish the available stock of snow before the melt season. The method was validated in France with Pléiades images in a Pyrenean basin with the help of snow-depth measurements obtained by manual survey and by drone. The results indicate that the snow-depth map produced at 2 meters of resolution is accurate to within 50 centimeters in terms of snow depth. Studies are in progress to better characterize the uncertainty of this new product based on airborne Lidar (remote sensing by laser) campaigns. In the meantime, a number of teams have begun using this method, the only existing method to date, for determining snow depths in mountain areas from space.

Figure 4 - Field campaign in the Pyrenees to measure snow depths (manual survey and measurement by drone) with a view to validating the results of the method based on analysis of Pléiades satellite images.

2

PART

Water quality, ecological monitoring and biodiversity

DEFINITION

Which water-quality parameters can be tracked by satellite?

The water-quality parameters that can be evaluated by optical imagers are turbidity, surface temperature, chlorophyll (an indicator of phytoplankton biomass, trophic status and nutritional status), colored dissolved organic matter (used as an indicator of organic matter and aquatic carbon), and suspended matter and non-algal particles.

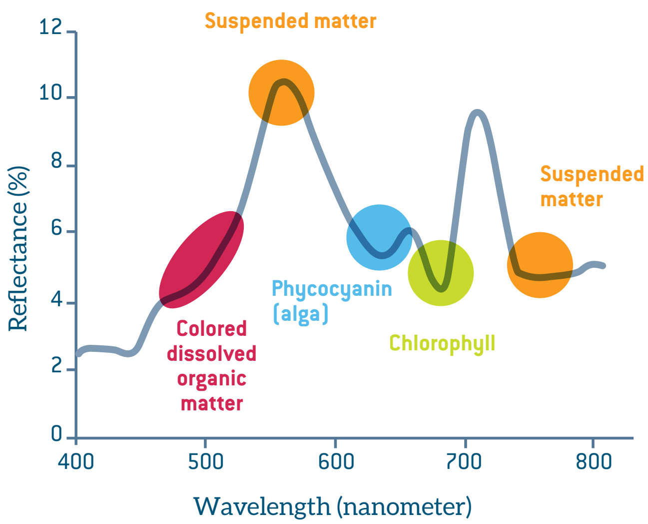


Figure 5 - Reflectance (relationship between reflected energy and total incident energy) according to the typical wavelength of continental water and the spectroscopic signatures of the water-quality parameters.

CHALLENGES

MONITOR WATER QUALITY AND ECOLOGICAL MONITORING TO BETTER UNDERSTAND AND ANTICIPATE CHANGES IN BIODIVERSITY AND CLIMATE

Human activities exert pressures on the environment which alter the climate, disrupt the hydrological cycle and affect catchment areas and biodiversity. In response to these challenges, regular monitoring of continental waters is required to anticipate changes and determine areas for improvement. The decline in the quality of continental and coastal waters has become and will continue to be a major problem in environmental, societal and economic terms. The monitoring of water quality therefore represents one of the most important elements of the environmental management of aquatic ecosystems. In Europe, it is defined by the Water Framework Directive which demands the good status of bodies of water.

By observing water color, satellites provide information on the concentrations of the constituents responsible for these colors. More generally, Earth observation now enables almost real-time monitoring with increasingly refined temporal and spatial resolutions (around 10-30 meters) of various water-quality parameters (see Definition) and other optical environmental characteristics (turbidity, water clarity), and to detect changes in land uses which affect wetlands and biodiversity. These observations and measurements supplement the in-situ network, providing global ecological monitoring.

This chapter presents concrete examples of the use of Earth observation for monitoring the quality of continental and coastal waters, ecological monitoring, and the challenges of preserving wetlands. The techniques and tools derived from spatial technology are now sufficiently mature for operational applications, whether to support crisis management or to preserve coastal ecosystems, wetlands and the quality of bathing water. There will also be a focus on monitoring of lake ecosystems, true sentinels of the climate: the Tonlé Sap lake in Cambodia where anthropogenic pressures are significant, and in France where monitoring of lake ecosystems is a genuine challenge for responding to the Water Framework Directive.

KNOW-HOW

7

Monitor the quality of river waters and bodies of water:

EXAMPLE OF THE MINING DISASTER IN BRAZIL

Jean-Michel Martinez, Guillaume Morin, Gérard Cochonneau, William Santini (GET, Université Paul Sabatier, IRD, CNRS)

In the past few years, the Institut de Recherche pour le Développement (IRD), with the Laboratoire Géosciences Environnement Toulouse (GET) and the support of the CNES, has been developing automated processing chains for monitoring water quality by satellite, which are then validated with confirmed partners. One such partnership was formed with the Brazil Water Agency, in order to monitor the country's largest catchment areas via satellite imagery, including the development of a dedicated internet portal (http://hidrosat.ana.gov.br). Initial development and validation work began in 2009 with the use of optical images from the NASA MODIS (Moderate-Resolution Imaging Spectroradiometer), which enable daily monitoring of large bodies of water. These processing chains enable water-reflectance data to be exploited in order to extract water-quality parameters using various forms of pre-processing that aim to correct the raw satellite images (corrections for atmosphere, the effects of slope, "mirror" effects of water, etc.). The images are used to detect eutrophication in artificial lakes or estimate sediment flows in rivers and can support crisis management in the event of environmental disasters. Such satellite data were used during the mining disaster in Brazil in January 2019 which caused more than 300 deaths and discharged several million tonnes of mine waste into the environment. At the height of the crisis, images from the Landsat and Sentinel -2 satellites enabled the progress of the waste along the river draining the region to be tracked for over 200 kilometers. These same images were subsequently used to measure the environment's recovery several months after the disaster. Work is currently focused on the new generation of open-access satellites such as those in the Sentinel series of the Copernicus program. Compared to images from the MODIS satellite, they allow smaller bodies of water (of a few tens of meters) to be monitored with unprecedented accuracy. These new images represent a major step forward, and mean that a monitoring system can be envisaged that monitors the quality of rivers and lakes on a wide scale on every continent. The initial products for monitoring water quality by satellite are available for several sites throughout the world on the THEIA website, the French portal for continental surfaces.

FOR FURTHER INFORMATION:
https://theia.cnes.fr

8

Access the spatio-temporal variability of hydro-sedimentary flows to improve understanding of the seasonal cycle of floods:

EXAMPLE OF THE TONLÉ SAP LAKE

Charles Verpoorter (LOG, Université de Lille, Université du Littoral Côte d'Opale, CNRS, UMR 8187), Frédéric Frappart (LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS), Sylvain Biancamaria (LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS), Thomas Combes (LOG, Université de Lille, Université du Littoral Côte d'Opale, CNRS, UMR 8187) and Jules Greusard (LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS ; ISPA, INRA, Bordeaux Sciences Agro)

Since the 1990s, Cambodia's Tonlé Sap basin has been experiencing a population increase with more than 16 million people living close to the lake. This hydrosystem is subject to many different pressures of anthropogenic origin (urbanization, deforestation, overfishing, soil pollution and the impact of upstream dams). Understanding the hydrological and sedimentary processes acting on them, and their bio-geo-chemical characteristics, is crucial step in the monitoring of these water resources, and more broadly for comprehensive understanding. The largest freshwater lake in Southeast Asia, the Tonlé Sap lake covers a minimum area of some 2,500 km². It has a subtropical monsoon climate with a pattern of heavy precipitation (around 1,400 mm/year). It is unusual in being directly linked to the high and low flows of the major river to which it is connected: the Mekong. In the wet season the lake is fed by the Mekong, while in the dry season the lake flows towards the river. The lake therefore acts as a "buffer" in the hydrology of the Mekong downstream of its confluence with the river Tonlé. Researchers from LOG and LEGOS, supported by the CNES, are studying the hydro-sedimentary variability of the Tonlé Sap lake via multi-sensor spatial remote sensing (Sentinel -2, MERIS, SeaWIFS). This work has enabled mapping of matter in suspension, chlorophyll-a, the lake's water levels, its area, and the variations in its volume, thus allowing the hydro-sedimentary variability to be traced in detail between 2002 and 2019 (Figure 6).

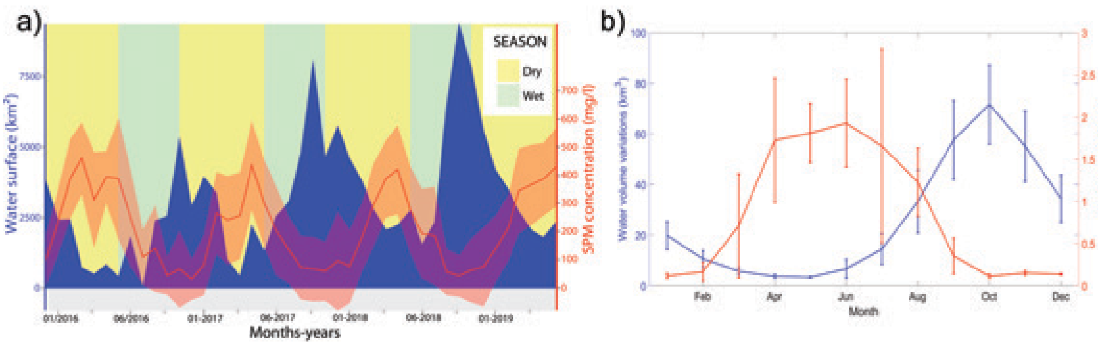


Figure 6 - Demonstration of the seasonal cycles of hydro-sedimentary flows (matter in suspension, chlorophyll-a, water surface area, volume), in response to the high/low flows of the Tonlé Sap river through analysis of: a) multi-spectral Sentinel-2 images and b) OC-CCI (Ocean Color Climate Change Initiative) and altimetric images.

The seasonal cycles of high/low flows (Figure 6) with their distinct intensities and patterns govern the variations in concentrations of suspended matter and chlorophyll. The link between these variations in volume and the "El Niño Southern Oscillation" and "Pacific Decadal Oscillation" climate indices has also been demonstrated, as has a memory effect of the lake's volume from the previous year on its variations. The continuity of this monitoring on "sentinel" sites such as Tonlé Sap are proving to be essential to a longer-term understanding of the impacts of hydro-sedimentary flows from a hydrological, ecological and also economic perspective, and to anticipating significant changes in these sensitive environments.

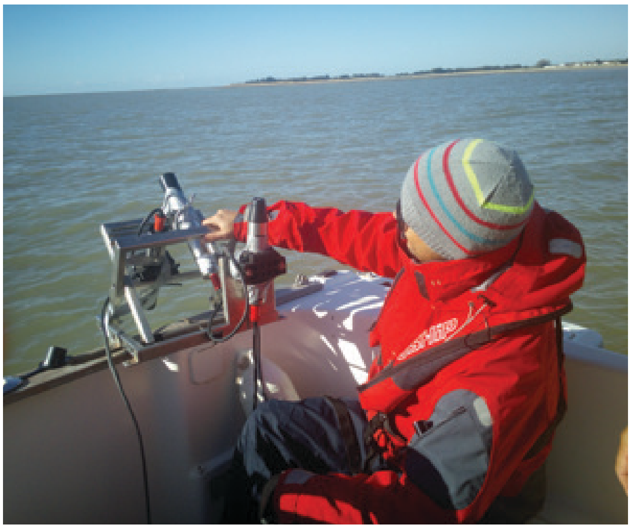
9

Characterize the natural turbidity of coastal waters by satellite:

EXAMPLE NEAR LA ROCHELLE

Virginie Lafon, Stéphane Kervella, Aurélie Dehouck, Olivier Regniers (i-Sea)

Studies have to be carried out in advance of maritime works to predict the potential effects of the resuspension of particles on the marine environment, and particularly on the most sensitive biological elements such as stationary species. These impact studies need to be supported by a detailed definition of the natural ranges of turbidities that characterize the site. In this context, the satellite tool complements the conventional systems by giving a true, dynamic view of the situation over the whole area of the works and the adjacent coastlines. Recorded several times a day, the satellite images allow an archive of maps to be compiled showing suspended-matter content or turbidity covering several hundreds of km^2. To obtain the best possible estimate of these two parameters, the physical laws for their calculation are calibrated directly in the field. In concrete terms, many years of archives of VIIRS (Visible Infrared Imaging Radiometer Suite), MODIS and Sentinel-3 images are processed to provide daily average turbidity. Statistical analysis of this database, in accordance with local hydrodynamic and meteorological forcings, allows turbidity climates to be determined and the average and extreme turbidity levels characteristic of the various bodies of water present to be extracted. These results are directly used to help establish the alert thresholds to be observed during the works. In addition to this stage of initial characterization, the Sentinel-2 and Landsat images, with higher ground resolution, are used to help manage the turbidity generated during the works and limit its impact. Once again, series of images are converted into turbidity to statistically determine the most appropriate areas for installing the probes that will be used during the works as devices for monitoring and alerts in real time. These innovative approaches received the Port du Futur 2019 award in the "Digital" category, awarded jointly to i-Sea and Atlantic Port La Rochelle, a pioneer in the appropriation of this new technology.



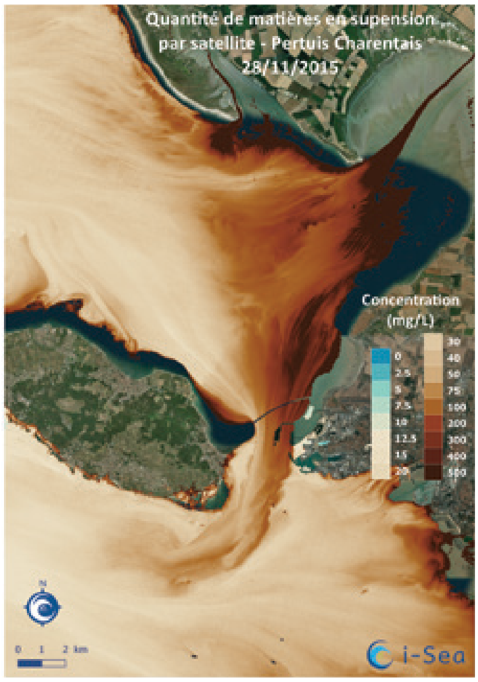


Figure 7 - Boat measurement campaign (above) and map of suspended matter (concentration in mg/L) generated by satellite on 28 November 2015 in Pertuis Charentais.

10

Monitor lake ecosystems and climate change:

EXAMPLE OF THE FRENCH LAKES

Thierry Tormos, Pierre-Alain Danis (AFB, ECLA (Ecosystèmes Lacustres) R&D division)

The functioning of lake ecosystems, the quality of their water as well as the goods and services that depend on it, are closely related to the temperature of the water. With the current changes in the climate, it is essential to take into account the thermal trajectories of bodies of water in order to (i) draw up strategies for mitigating anthropogenic impacts; and (ii) maintain the biodiversity of these ecosystems. The French Agency for Biodiversity (AFB), has a particular focus on the impacts of these changes on these ecosystems. It instigated the set-up of the RNT, a network for the continuous (hourly frequency) and long-term surveillance of the temperature of bodies of water. Since this type of monitoring is limited spatially, tools for monitoring by remote satellite sensing and for modeling are developed to supplement the RNT to better characterize the thermal and thermodynamic trajectories of bodies of water in their entirety several decades into the past and future. Estimation of surface temperature by remote sensing is carried out based on infra-red Landsat imagery. The method, which consists of correcting the energy emitted by the water surfaces (both continental and marine) for atmospheric effects, is constantly validated using historic in-situ data (scientific or from managers) or that obtained via the RNT. This validation is currently based on about one hundred lakes. The average error on estimates of surface temperature derived from Landsat imagery is ± 1.2°C. These data are produced routinely for all continental water surfaces (visible by Landsat imagery) in mainland France and the overseas departments and regions. They provide the temporal evolution and spatial distribution of surface temperatures of bodies of water and serve as calibration/validation data for models of the thermal trajectories of French bodies of water.

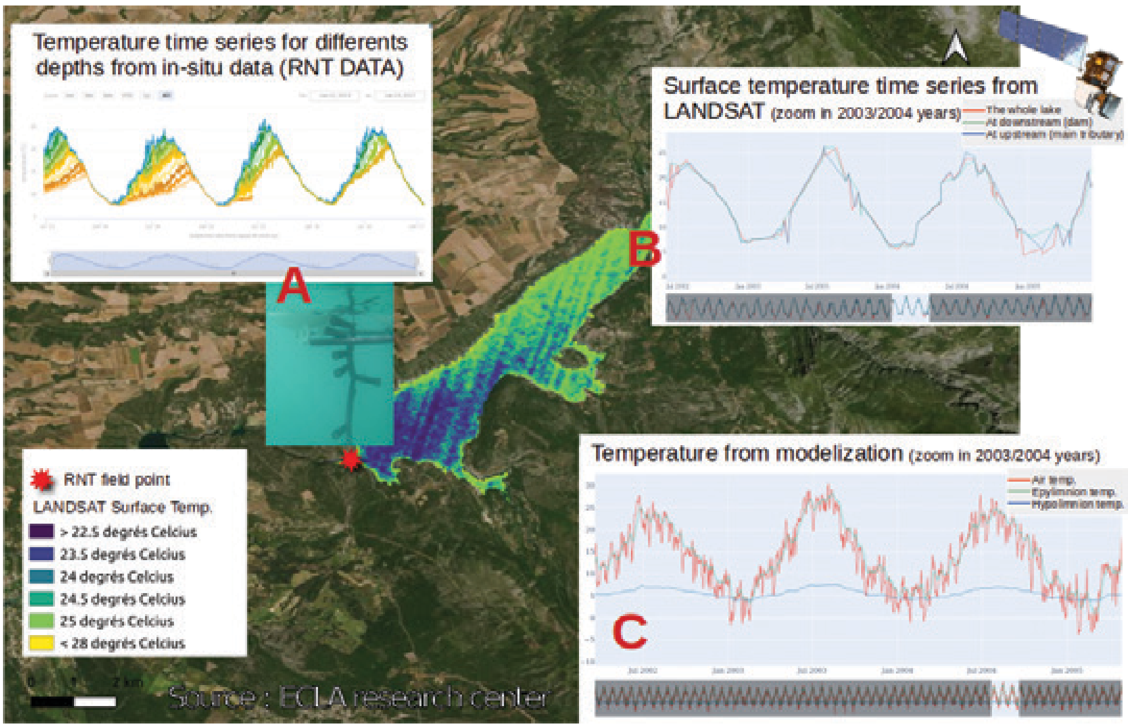


Figure 8 - Sainte-Croix lake: (A) time series of in-situ temperatures provided by the RNT at different depths, (B) time series of surface temperatures provided by Landsat satellite imagery, and (C) the results of modeling the lake's thermal strata (epilimnion above the thermocline and hypolimnion below).

11

Monitor the Mediterranean wetlands:

EXAMPLE OF THE MEDITERRANEAN REGION

Guelmami Anis (Institut de recherche pour la conservation des zones humides méditerranéenneswet-lands (Tour du Valat))

The Mediterranean wetlands are considered to be the region's most productive ecosystems, supporting some of the world's most remarkable biodiversity. Yet these are also the ecosystems subject to the greatest anthropogenic pressures, and the loss of their natural habitats is estimated at around 48% between 1970 and 2013 (MWO, 2018).

In 2012, the Mediterranean Wetlands Observatory (MWO) established a system for monitoring these habitats, based on the diachronic mapping of land uses from the data provided from Earth Observation (EO), for a sample of over 300 sites (Figure 9). The mapping tool used was developed as part of the GlobWetland-II (GW-II, 2010-2014) and Satellite-based Wetlands Observation Service (SWOS, 2015-2018) projects. First and foremost, this has enabled a spatialized database to be put in place, covering three individual years (1975, 1990 and 2005), using data from the Landsat time series images. This is currently being updated, to incorporate new maps developed from Sentinel-2 images, covering the year 2018.

The methodological approach includes two components: (1) remote sensing enabling processing of satellite images and mapping of land use (based on a hybrid nomenclature combining CORINE Land Cover and Ramsar) with a supervised object-based classification by segmentation (Figure 10) and; (2) the Geographic Information System (GIS) for automated calculation of spatialized indicators (e.g., total area of wetlands, urban and agricultural pressures, how these change over time, etc.).

The trends observed in the three periods analyzed (1975, 1990 and 2005) demonstrate that unfortunately many natural wetland habitats are continuing to disappear. This is primarily because of their conversion to urban or agricultural areas (+294% and 42% respectively) or because of the significant growth in dams and other water-storage sites in some countries (more than 64% of new artificial wetlands created between 1975 and 2005 came at the expense of natural wetland habitats).

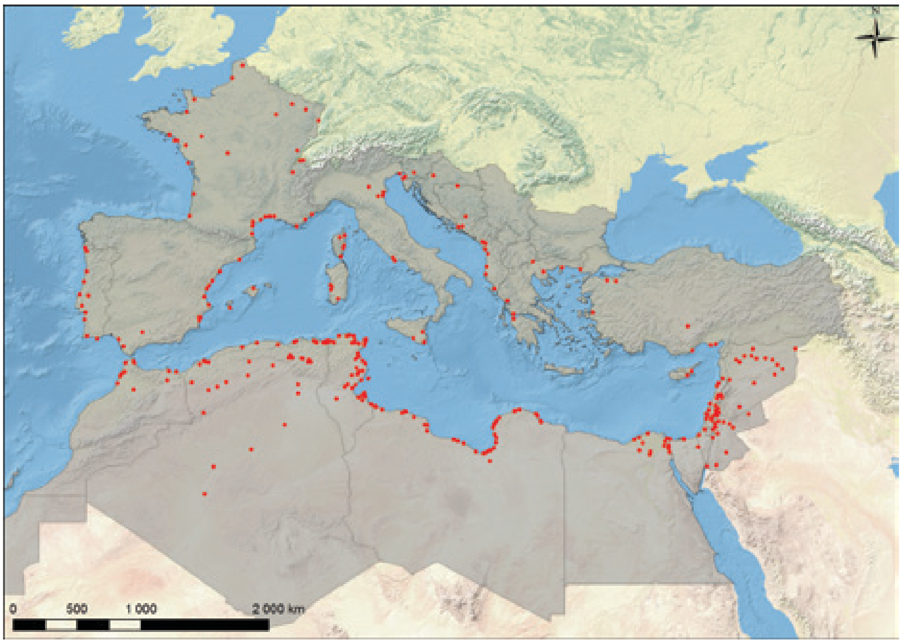


Figure 9 - In red, distribution of sites whose land use is monitored by the MWO.

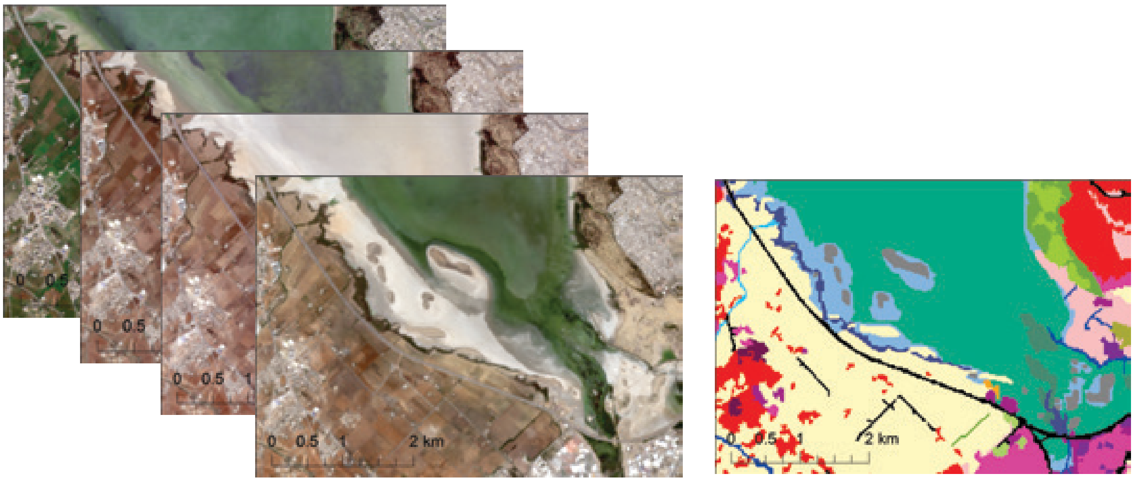


Figure 10 - Mapping of land use derived from Sentinel-2 temporal series covering the year 2018 (from left to right: acquisition of multi-date images, object-based segmentation and classification of land use).

12

Detect and predict the drifting of cyanobacteria blooms:

EXAMPLE OF AN OPERATIONAL APPLICATION IN THE BALTIC SEA

Virginie Lafon, Olivier Regniers, Nicolas Debonnaire (i-Sea)

Cyanobacteria, which are increasing rapidly worldwide, grow in fresh and marine waters in the form of highly abundant colonies that are often visible from space. The linking of toxins with many species of cyanobacteria often leads to bathing sites being closed when blooms occur, to avoid any health risk. The Baltic is particularly affected by frequent, intense blooms throughout the summer. As part of a study based on the Copernicus Marine Environment Monitoring Service (CMEMS), a consortium of European small and medium-sized enterprises (SMEs) built the *HAB Risk* service which provides daily observations as well as three-day predictions of drift of the blooms detected throughout the Baltic. The method of detection is based on analysis of Sentinel-3 data. Concentrations of phycocyanin, a pigment characteristic of cyanobacteria, are calculated using an algorithm calibrated in situ. This parameter is calibrated to estimate the abundance of cyanobacteria. Every day, in the hours following the acquisition of a Sentinel-3 image of the Baltic Sea, a data-processing server retrieves the image and calculates the concentration of phycocyanin wherever there are no clouds. At the same time, simulated flow fields are downloaded from the CMEMS server in order to predict the trajectory of the blooms for the subsequent three days and to produce an indicator of the risk of these blooms impacting bathing areas. All of these products are put online on the Web and a smartphone app only three hours after the image is made available. At the end of each day, users therefore obtain an assessment of the risk of bloom for the following day on a certain beach, either as users or to decide whether to open it for bathing.

FOR FURTHER INFORMATION:
WEBSITE :
https://sinice.pl/
APP :
https://play.google.com/store/apps/details?id=com.n7mobile.habrisk&hl=fr

The pilot has currently been configured and is being tested on the Polish coastline. HAB Risk also aims to provide assistance with decision-making in the management of aquaculture farming areas.

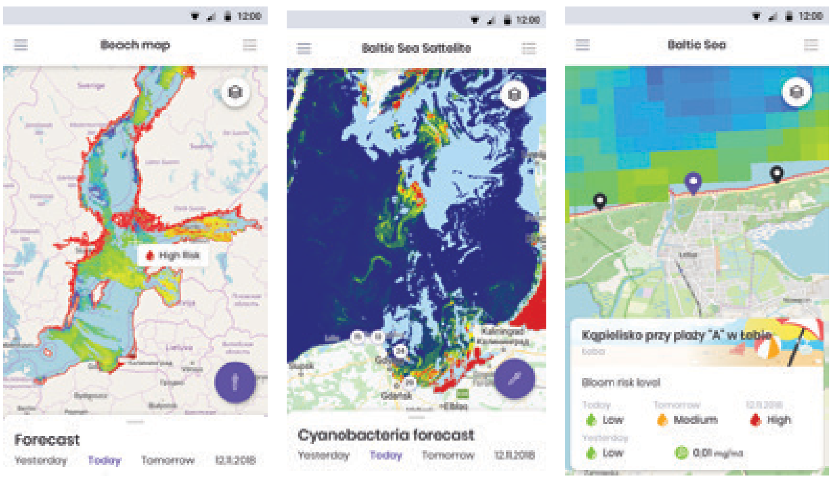


Figure 11 - Examples of the *HAB Risk* smartphone app demonstrating alert thresholds for the Baltic Sea and Polish beaches. .

3

PART

Agricultural uses of water

DEFINITION

What does agricultural uses of water mean?

By "agricultural uses of water", we mean human use related to agriculture (irrigation). The consumption of meteoric water by agriculture, and by the whole biosphere, is not taken into account here. Another water-related issue linked to agriculture is drainage and the associated wetlands. This aspect has been very little studied by remote sensing to date, and we have not included it in this document.

CHALLENGES

AGRICULTURE IS THE PRIMARY USER OF WATER

Agriculture occupies some 1.5 billion hectares of land, or around 11% of the planet's land surface. Prairies and permanent pastures, representing another 21%, can be added to this area. In total, one third of the planet's land surface is taken up by agricultural uses. Most of these areas are watered purely by precipitation, but in areas where this is insufficient, irrigation systems take water from resources to deliver the necessary water to crops. Despite this already significant use of space and resources, the need for agricultural production is increasing to meet the challenges of food security (at least 1.5 billion people currently suffer from hunger worldwide) and the energy challenges of replacing fossil fuels. Agriculture is therefore the largest consumer of water on the planet (70% of water used is for agricultural purposes). This share is even larger in countries with limited water resources. Irrigation is currently increasing, especially in developing countries where the irrigated areas measured 202 million hectares in 1997-99 and are expected to reach 242 million by 2030.
While the proportion of renewable water resources consumed by irrigation remains relatively modest at the global level, it differs widely by region (Figure 12) and by season. Moreover, in a number of climates, the period in which the agricultural requirement for water is highest corresponds with the period when water resources are at their lowest. These phenomena could be amplified by climate change, which reduces the available resource while increasing agricultural needs. There is therefore a high risk that water shortages and competition between its different uses will increase.

Renewable water and water withdrawal (km³)

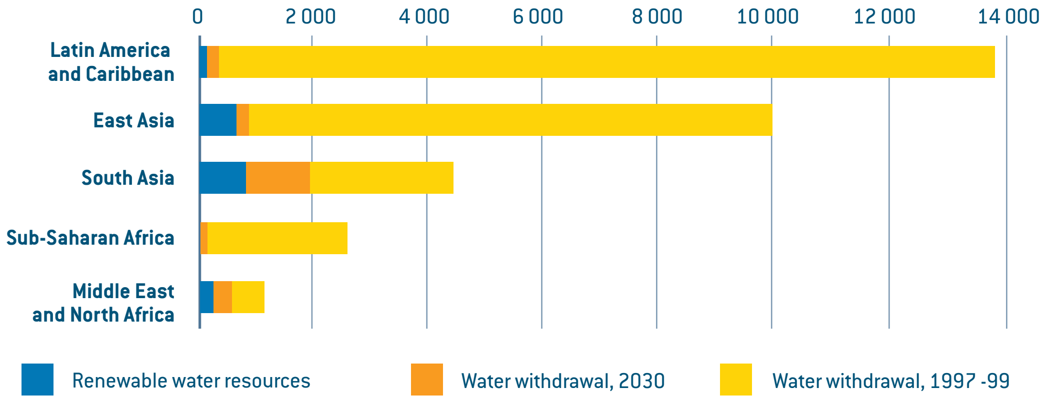


Figure 12 - Share of withdrawals from renewable water resources for different regions of the world (Source: FAO data and projections).

We can therefore see where agriculture fits in terms of consumption of the planet's water, and its predictable increase in the years to come. Competition with other uses and the challenges of the risks of shortages for food security make it necessary to provide governing bodies with tools for monitoring, managing, and ultimately predicting and optimizing the consumption of water for agriculture.

Recent developments in remote sensing provide vital information to supplement the field data and statistical data which enable:

- cultivated plants, their growth stage, their vegetative state, etc., to be identified;
- water requirements to be deduced from this information;
- provision to be better managed according to needs and to the availability of the resource.

These methods are applied at various levels, from the intra-parcel level in the context of precision agriculture, to parcel level to enable farm management that is closer to needs despite the absence of accurate field data, and up to broader levels by enabling water resources to be managed according to the needs of crops and their status at the level of a region or a catchment area.

13

Locate and quantify water-filled rice-growing areas:

EXAMPLE OF THE SENEGAL RIVER VALLEY

MOSIS PROJECT

Marie Lefrancq (CACG), Françoise Goulard (Adour-Garonne Water Agency)
Organizations associated with the project: SOGED-OMVS, CACG, E2L, Adour-Garonne Water Agency, CNES

The aim of the approach developed is to monitor rice-growing areas through remote sensing in the Senegal River catchment area in order to establish dialog between the various users of water to improve the management of the quantities of water used and the collection rate of the fees related to irrigation. The Sentinel-2 multi-temporal optical images provided and processed by the Théia organization are processed and exploited in order to assess the rice-growing areas in the Senegal River basin every five days with spatial resolution of 10 meters. The water-filled areas are detected using a water indicator (MNDWI) and subsequently confirmed by the presence of crops (NDVI). Two field campaigns have assessed the consistency of the results across the two rice-growing seasons (warm off-season and overwintering). This project was conducted in the spirit of the "Living Lab" approach in which usage is the core consideration. A shared platform for web-mapping was co-constructed with the local operator, the SOGED (Organisation for the Development of the Senegal River, OMVS), based on an innovative methodology known as "service design" in order to focus on the needs and contexts of future users. This platform enables the operator to act on the basis of spatialized information and indicators. In concrete terms, it enables cultivated areas to be viewed by time period, and linked to the users' database so that theoretical equivalents of the volumes of water used can be estimated, as well as collection of the potential fee. The platform is now operational. Its use has already indicated a great deal of added value in the field: improved identification of users and of land, and increased revenue from fees. The challenge for the future is to use this tool on other issues such as monitoring invasive plants and erosion.

FOR FURTHER INFORMATION:
https://mosis-cacg.e2l-coop.eu/

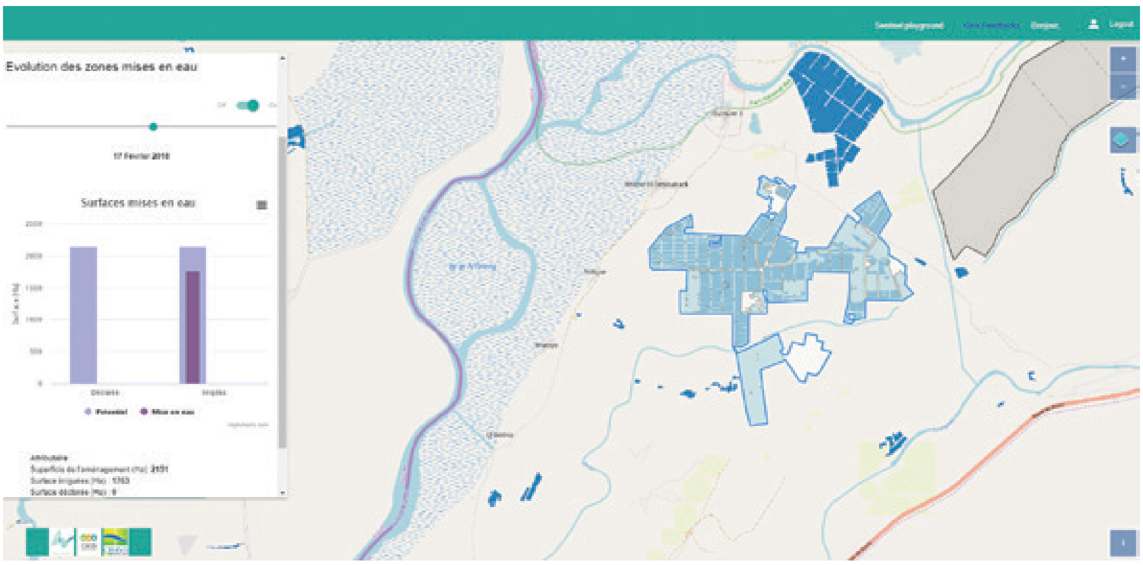


Figure 13 - Example of the WEBGIS interface of the MOSIS tool showing changes in water-filled areas.

14

Map irrigated crops

THEIA IRRIGATION SEC (SCIENTIFIC EXPERTISE CENTER) PROJECT

Valérie Demarez (CESBIO)
Organizations associated with the project: CESBIO, CES Theia

To help basin managers understand and anticipate the water needs of crops, so that the water resource can be more closely managed, a method of processing (classification) Sentinel (Sentinel -1 and -2) images has been developed for mapping irrigated crops during and at the end of the season. The tool used is the iota² operational processing chain developed at CESBIO and available with open access. Maps of irrigated crops at 10 meters of resolution have been produced for southwest France (Figure 14). The results show that at the end of July the distinction between summer and winter crops can be made with 85% accuracy. From the end of July the distinction can be made between irrigated and non-irrigated crops (75% accuracy), thus allowing decisions to be anticipated to estimate production or to manage water, at department level.

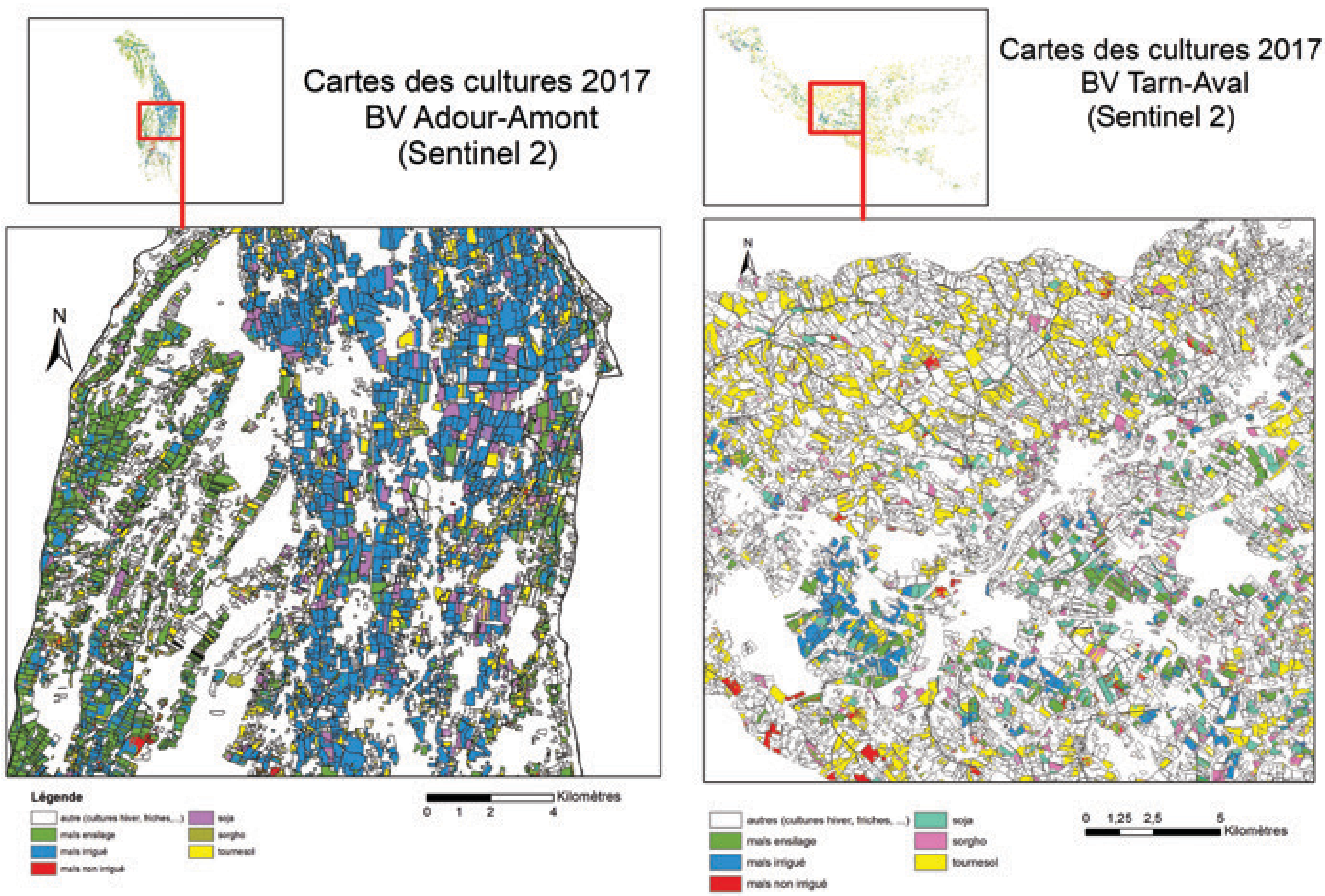


Figure 14 - Map of irrigated crops in the Adour-Amont catchment area (left) and Tarn-Aval catchment area (right) obtained from 20 Sentinel-2 images acquired between March and October 2017 (SIMULTEAU project,

Calculate water balance at agricultural-parcel level to characterize water stress and provide guidance on irrigation

15

SAT-IRR ("SATELLITE FOR IRRIGATION SCHEDULING") PROJECT

Guillaume Rieu (TerraNIS)
Organizations associated with the project: TerraNIS, CESBIO

The aim of the approach shown above is to provide farmers with guidance on irrigation according to the true requirements of their crops. To calculate the water balance at agricultural-parcel level, the tool developed is based on a web platform and enables users to: (i) enter the input data: parcel profile, type of crop, sowing date and soil type, (ii) view maps of the development of the vegetation throughout the crop season and water-stress indicators (e.g., water content in the root compartment). The application uses the multi-temporal optical images from Sentinel (L2A) with a frequency of 5 days and a resolution of 10 meters, and applies the FAO water balance method. It thus enables (i) water losses by evapotranspiration to be estimated from spatial data (estimate of biomass and bare ground fraction) and from meteorological data (reference evapotranspiration), (ii) the water input into the "parcel system" to be incorporated: rain and irrigation, (iii) the "soil" compartment of the "parcel system" to be modeled by estimating its useful reserve. The application is now operational and in production.

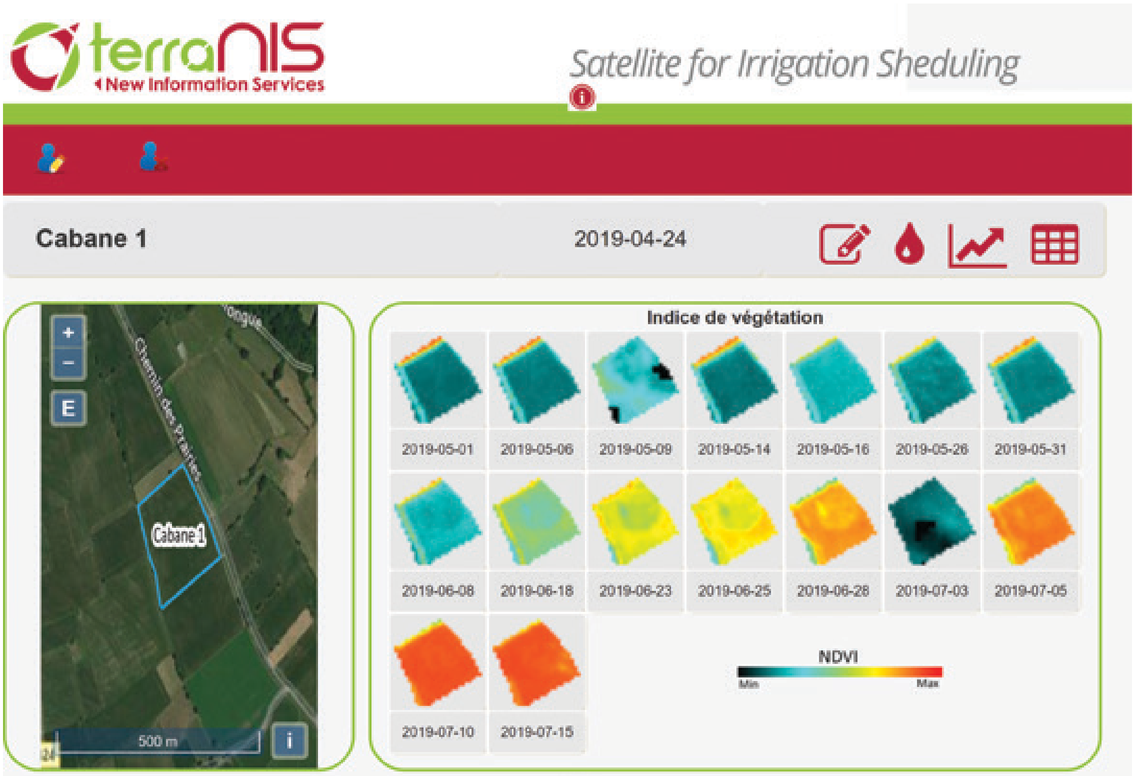


Figure 15 - Screen shot of the SAT-IRR web platform showing changes over time in the vegetation index in one parcel.

16

Estimate and map soil moisture at sub-parcel level

Nicolas Baghdadi (IRSTEA, UMR TETIS Maison de la télédétection)
Organizations associated with the project: Maison de la télédétection, Theia SEC

To help farmers adapt the quantity and frequency of irrigation to the soil's moisture conditions, radar data are used to estimate and map the surface moisture of bare ground (the first 5-10 centimeters). Estimating moisture in covered soil requires optical data to be coupled with the radar data, to take into account the characteristics of the vegetation. The data used come from the Copernicus Sentinel-1 radar and Sentinel-2 optical series of images. The radar signal inversion algorithm uses neural networks. It is applied to the agricultural parcels extracted from the land-use maps drawn up by Theia's land-use SEC. The final product is offered at the intra-parcel level (from 0.2 hectare). A major field campaign close to Montpellier (some 500 in-situ measurements) has resulted in soil-moisture estimates in these maps achieving accuracy of 6 vol.%. Other sites have been tested, including overseas (Lebanon, Morocco, Italy, etc.).

FOR FURTHER INFORMATION:
https://www.theia-land.fr/en/data-and-services-for-the-land/

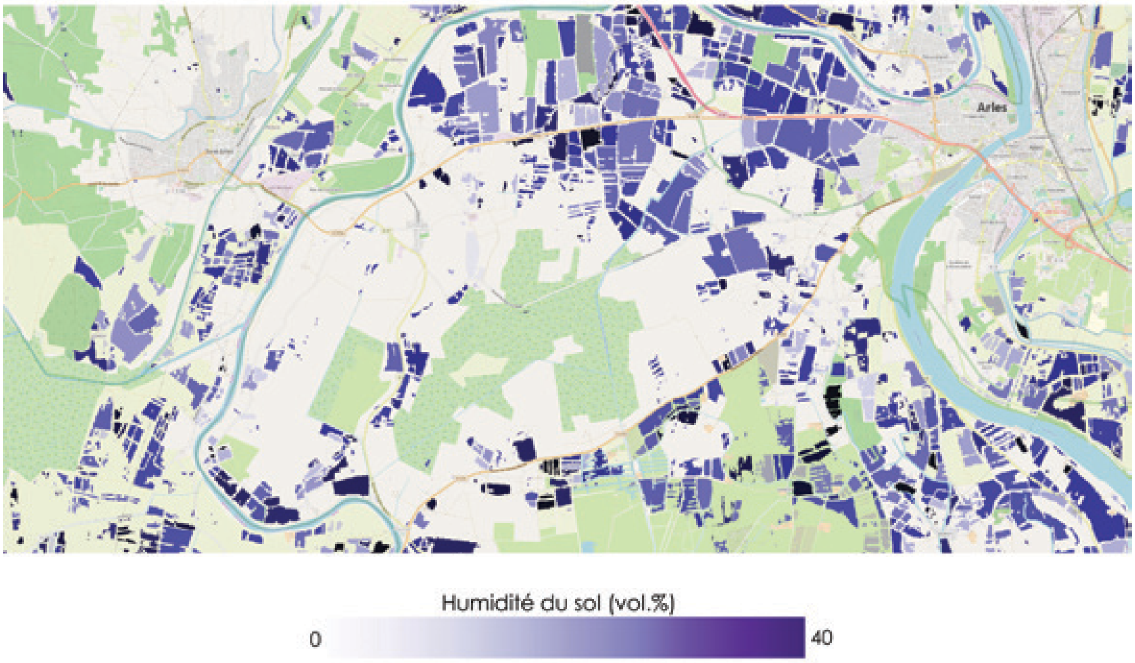


Figure 16 - Soil-moisture map (volume in %) for parcels (darker when wetter) in the Arles region, 19 September 2018.

17

Identify the biophysical parameters of crops for precision farming

VERDE PROJECT

Charlotte Gabriel-Robez (AIRBUS Defense and Space)

The objective of Verde is to give farmers more accurate knowledge of the status of their crops, and to adapt treatments and irrigation to requirements at intra-parcel level. Verde automatically provides maps characterizing vegetation, cropped by individual parcel, using a wide range of satellite and unmanned aerial vehicle (UAV) images. The application programming interface (API) enables turnkey analysis based on the extraction of biophysical information characterizing the status of the crops (brown cover, green cover, leaf area index, chlorophyll content, etc.). The API can be called from any precision-agriculture portal. Airbus's Verde service uses the Overland processor, an optical image processing suite developed by Airbus to generate vegetation maps such as the leaf area index and the leaf's chlorophyll content. The first algorithms were developed in the early 2000s, and have undergone constant improvement since then. Overland is capable of processing a wide range of multi-spectral images, covering spectral ranges from 0.4 to 2.5 microns, obtained from a variety of sources (satellite, airborne, UAV) and with spatial resolutions. Each crop's water requirements are then specified by extracting the crop coefficients from the fraction of green cover which is derived from satellite images and therefore provides a better fit to the crop cycle than the FAO56 method. The API is operational, providing time series of biophysical parameters derived from satellite images to give a better understanding of the status of crops throughout the growing season, and their water requirements in particular.

FOR FURTHER INFORMATION :
https://www.intelligence-airbusds.com/monitoring-services-for-agriculture/#verde

Figure 17 - Application on smartphone and tablet.

18

A spatialized crop model

SARRA-O PROJECT

Christian Baron (CIRAD, UMR TETIS Maison de la télédétection)

The aim is to provide decision-makers and farmers with climate services during the cropping season: early warnings about crop status and yield forecasts to help them optimize their sowing and/or irrigation strategies. It also allows the impact of variability and climate change on crops and agricultural practices to be analyzed.

SARRA-O is the spatialized, multi-scale version of the SARRA-H crop model, which aims to monitor crop conditions, forecast yields, and provide climate services, from the territorial scale to the regional one. It can use different sources of meteorological and precipitation data estimated from satellite images. Its output maps enable areas displaying strong anomalies to be detected and characterized in semi-real time, water reserves to be estimated, different sowing and/or irrigation strategies to be tested, and so on. Initially developed for the major cereal crops of tropical countries, it has been configured and verified for the various cultivars of millet, sorghum and maize. It has also been calibrated for rice, soy and cotton. It is used in: (i) a broad range of topics from parcel to regional level: monitoring crops, estimating and forecasting yields, early warning systems, impacts of and adaptation to climate change, etc., and (ii) a broad range of environments and applications: mainly in tropical African countries (early warning systems), in Brazil (agro-ecological zoning and securing loans), and also in more temperate to cold countries: in France, Germany, and the US. It enables farming strategies to be taken into account: i) choice of cultivars (photoperiodic or not), ii) crop density, iii) sowing dates and strategies, iv) irrigation quantities and strategies, and v) degree of intensification (technical and fertilization) ranging from very low to optimal.

FOR FURTHER INFORMATION:
https://sarra-h.teledetection.fr/SARRAH_Home_En.html

Cited in more than 60 publications, SARRA-O has been used since 2016 by AGRHYMET, Niger, in its early-warning system covering 17 countries in West Africa. Training has been carried out in eight West African countries.

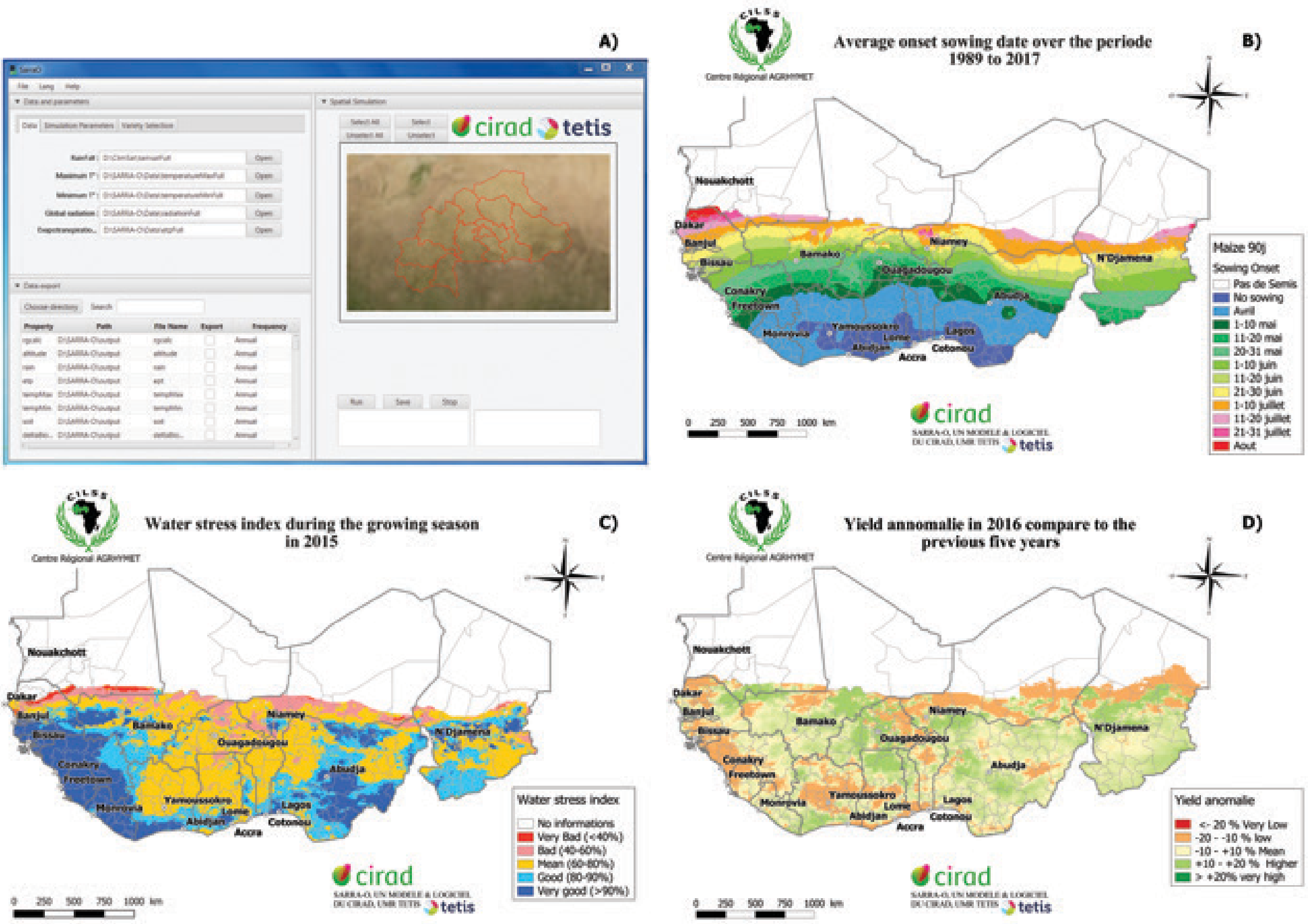


Figure 18 - The SARRA-O software, and various types of output: A) User interface, B) Estimate of average sowing dates, C) Index of the crop's water stress during the season, D) Anomaly of crop yields at harvest compared to the 5 previous years.

Glossary

AFB: Agence Française pour la biodiversité (French Biodiversity Agency)

AFD: Agence Française de Développement (French Development agency)

BRLI: BRL Ingénierie (BRL Engineering)

CES/SEC: Centres d'Expertise Scientifique / Scientific Expertise Centers

CESBIO: Centre d'Etudes Spatiales de la Biosphère (Centre for the Study of the Biosphere from Space)

CICOS: Commission Internationale du Bassin Congo-Oubangui (International Commission of the Congo-Oubangui-Sangha Basin)

Cirad: Centre de coopération international en recherche agronomique pour le développement (French Agricultural Research Center for International Cooperation)

CNES: Centre National d'Etudes Spatiales (French National Centre for Space Studies)

CNR: Compagnie Nationale du Rhône (National Company of the Rhone)

CLS: Collecte Localisation Satellites

CNRM: Centre National de Recherches Météorologiques (National Center for Meteorological Research)

COP: Conference of the Parties

FAO: Food and Agriculture Organization

IPCC: Intergovernmental Panel on Climate Change

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IRD: Institut de Recherche pour le Développement (French National Research Institut for Sustainable Development)

IRSTEA: Institut national de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture (National Institute for Environmental and Agricultural Science and Research)

ISBA: Interaction Sol-Biosphère-Atmosphère (Soil-Biosphere-Atmosphere Interaction model)

LEGOS: Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (Laboratory of Studies on Spatial Geophysics and Oceanography)

DEM: Digital Elevation Model

DTM: Digital Terrain Model

SDG: Sustainable Development Goals

OIEau/IOWater: Office International de l'Eau / International Office for Water

OMVS: Organisation pour la Mise en Valeur du Fleuve Sénégal (Organization for the Development of the Senegal River)

GIS: Geographical Information System

HIS: Hydrological Information System

SWOT: Surface Water and Ocean Topography

While water is essential to the development of our societies, it is today subject to increasingly significant anthropogenic pressure driven by a host of factors such as population growth, rapid urbanization, industrialization, pollution, and changing ways of living.

In this context, concrete measures must be implemented in order to progress towards integrated, sustainable management of water resources and aquatic environments. However, thorough knowledge and understanding of water resources is crucial if we are to act effectively. The acquisition of hydrological data is therefore crucial to decision-making.

F ollowing the initial edition of the "FWP Expertise" collection, on the challenges related to knowledge, and the expertise developed to respond to these challenges in France and worldwide, this latest edition focuses on the acquisition of spatial hydrological data and presents a number of initiatives and projects by French stakeholders in water, highlighting the ways in which satellite data can complement and help improve our knowledge of hydrological data from the field.

The **French Water Partnership (FWP)** is the go-to platform for public and private French actors in water who are active internationally. It has engaged in advocacy internationally for over 10 years to make water a priority in sustainable development policies, and encourages exchange between French expertise and that of other countries. With its various members (State and public institutions, authorities, NGOs, businesses, research and training institutes, and qualified experts) it delivers collective messages on water in international arenas such as the United Nations, climate and biodiversity conventions, high-level political forums and World Water Week in Stockholm. Find out more: **www.partenariat-francais-eau.fr/en/**

In cooperation with:

Produced with the support of:

51 rue Salvador Allende
92027 Nanterre / France

+33 (0) 1 41 20 19 49
+33 (0) 1 41 20 16 09

www.french-water-partnership.fr
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