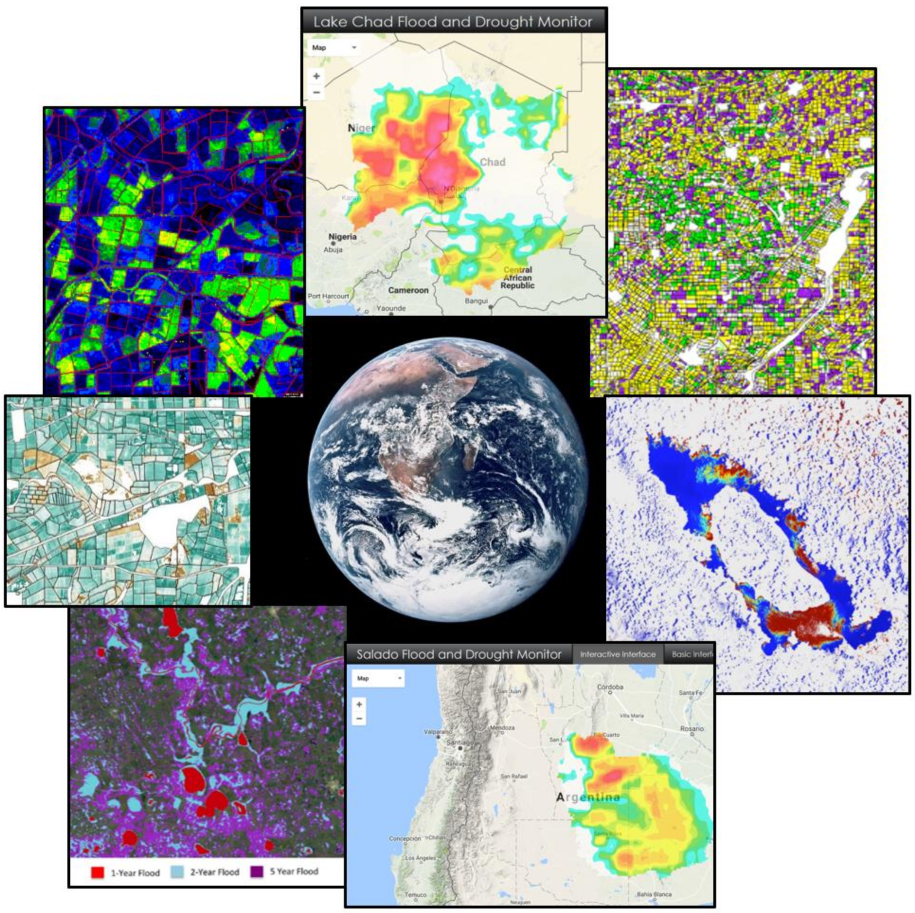
Public Disclosure Authorized

WATER
PARTNERSHIP
PROGRAM

Mainstreaming the Use of Remote Sensing Data and Applications in Operational Contexts



Global Initiative on Remote Sensing for Water Resources Management
Phase 2

WORLD BANK GROUP

Contributions and Acknowledgements

This report is the result of a collaborative effort led by Aleix Serrat-Capdevila (Senior Water Resources Management Specialist, GWAGP, and TTL of the Remote Sensing Initiative) with Stefanie Herrmann (Remote Sensing Specialist, The University of Arizona) and integrating contributions from Mutlu Ozdogan (University of Wisconsin, Madison), Jordi Cristobal Rossello (University of Alaska, Fairbanks), Fernando Miralles-Wilhelm (University of Maryland), Ivan Lalovic, Justin Sheffield (University of Southampton, UK), Eric Wood (Princeton University), Beth Tellman, Jonathan Sullivan, Jared Tomlin and Bessie Schwarz (Cloud to Street), Charles Morton (Desert Research Institute), Nick Bearson (U. of Wisconsin, Madison) and Michael David Thibert (Water Expert Team). This work was financed by the World Bank Water Partnership Program.

The Bank project team members with whom the Remote Sensing Initiative has worked are Diego Rodriguez (Sr. Water Resources Management Sp., GWA04, for Mexico), Victor Vazquez (Sr. Water Supply and Sanitation Sp., GWA04, for Argentina) and Maria Catalina Rodriguez (Water and Sanitation Specialist, GWA04, for Argentina), Marcus Wishart (Sr. Water Resources Management Sp., GWADR, for Indonesia) and Amy Chua Fang Lim (Consultant, for Indonesia), Marie Laure Lajaunie (Lead Water Resources Management Sp., GWA07, for Lake Chad), Abedalrazq F. Khalil (Senior Water Resources Specialist, GWA02, for India), Marcus Wijnen (Sr. Water Resources Management Specialist, GWA01) and Luis Alberto Andres (Lead Economist, GWAGP, for water point monitoring). This work would have not been possible without their involvement and interest. William Young (Lead Water Resource Management Sp., GWA09), Satya Priya (Sr. Water Resources Management Sp., GWA06) and Liping Jiang (Sr. Irrigation Engineer, GWA02) also provided valuable insights.

We wish to thank peer reviewers Winston Yu (Senior Water Resources Specialist, GWA03), Susanne M. Scheierling (Sr. Irrigation Water Economist, GWAGP), and Marie-Laure Lajaunie (Lead Water Resources Management Specialist, GWA07), and (in a previous review) Marcus Wijnen, Nagaraja Rao Harshadeep and Victor Vazquez for their valuable feedback inside and outside the formal review process, as well as for the overall guidance of Maria Angelica Sotomayor Araujo (Practice Manager, GWAGP).

This work has also benefitted from direct collaboration, ideas and insights from Martha Anderson (US Dept. of Agriculture), Christopher Neale (U. of Nebraska, Lincoln), Forrest Melton (NASA Ames, California State Univ.), Christine Lee (Jet Propulsion Lab NASA), Faisal Hossain (University of Washington), Abdou Ali (AGRHYMET), Will Logan (Institute of Water Resources, IWR-USACE), Nicholas Tufillaro (Oregon State University), Koen Verbist, Abou Amani and Anil Mishra (UNESCO-IHP). We also want to acknowledge the team that started the Remote Sensing Initiative at the World Bank and edited the book *Earth Observation for Water Resources Management*, outcome of Phase I, on which Phase II was built: Luis Garcia, Diego Rodriguez, and Marcus Wijnen, who have been a source of guidance and support for the work that led to this report.

We also wish to express our appreciation for the *Comisión Nacional del Agua (CONAGUA)* headquarters, and the *Organismo de Cuenca de la Península de Baja California*, in Mexico; the Lake Chad Basin Commission; the *Agencia del Agua* and the *Demarcación Provincial de Obras Hidráulicas*, in the Rio Salado Province, Argentina; for their direct involvement and feedback.

Table of Contents

Abbreviations

ADA	*Agencia del Agua* (Water Agency, Buenos Aires Province, Argentina)
AFDM	African Flood and Drought Monitor
ALEXI	Atmospheric Land Exchange Inverse (ET estimation algorithm)
CONAGUA	Comisión Nacional del Agua (National Water Commission, México)
DLI	Disbursement Linked Indicator
DPOH	Demarcación Provincial de Obras Hidráulicas (Provincial Demarcation of Hydraulic Works, Buenos Aires Province, Argentina)
ESA	European Space Agency
ET	Evapotranspiration
EVI	Enhanced Vegetation Index
GFS	Global Forecasting System
GIS	Geographical Information System
GWADI	Global Network on Water and Development Information for Arid Lands (UNESCO Program)
DisALEXI	Spatially distributed version of ALEXI (ET estimation algorithm)
GEE	Google Earth Engine
GP	Global Practice
GRACE	Gravity Recovery and Climate Experiment (satellite mission)
GRDC	Global Runoff Data Center (Koblenz, Germany)
GW	Groundwater
HAB	Harmful Algal Bloom
ICIWaRM	International Center for Integrated Water Resources Management
IWR - USACE	Institute of Water Resources – US Army Corps of Engineers
LAC	Latin America and the Caribbean
LAFDM	Latin American Flood and Drought Monitor
LANDSAT	Land Remote Sensing Satellite System
LCBC	Lake Chad Basin Commission
MERIS	Medium Resolution Imaging Spectrometer (satellite sensor)
METRIC	Mapping Evapotranspiration at high Resolution with Internalized Calibration (ET estimation algorithm)
MODIS	Moderate Resolution Imaging Spectroradiometer (satellite sensor)
MSWEP	Multi-Source Weighted Ensemble Precipitation (rainfall product)
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
OCPBC	*Organismo de Cuenca de la Península de Baja California* (Basin entity of CONAGUA for the *Península of Baja California*, *México*)
RS	Remote Sensing
SEBAL	Surface Energy Balance Algorithm for Land (ET estimation algorithm)
SMAP	Soil Moisture Active-Passive (satellite mission)
SPI	Standardized Precipitation Index
SPOT	*Satellite Pour l'Observation de la Terre* (satellite)
SRTM	Shuttle Radar Topography Mission
SSEBop	Simplified Surface Energy Balance (ET estimation algorithm)
StarFM	Spatial and Temporal Adaptive Reflectance Fusion Model

TTL	Task Team Leader
TMPA	TRMM (Tropical Rainfall Measuring Mission) Multi-satellite Precipitation Analysis (rainfall product)
UNESCO-IHP	United Nations Educational, Scientific and Cultural Organization – International Hydrological Program
USDA	United States Department of Agriculture
VHR	Very High Resolution
VIC	Variable Infiltration Capacity (land surface hydrological model)
VIIRS	Visible Infrared Imaging Radiometer Suite (satellite sensor)
WET	Water Expert Team (World Bank internal technical assistance program)
WPP	Water Partnership Program

Executive Summary

About this Report: Context and Goals

This report presents the activities and outcomes to date of the Global Initiative on Remote Sensing for Water Resources Management Phase 2. The Initiative was conceived to help mainstream the use of beneficial remote sensing applications in operational projects of the Bank, as well as to facilitate the adoption of remote sensing applications in World Bank client countries. By bridging the gap between the supply of remote sensing data and the needs from the Bank's operational projects, Earth Observations can better inform client country agencies by improving monitoring and predictive capabilities and supporting better water-related operations.

This report is addressed to technical staff in national water agencies, project leads from development and financing institutions, and water practitioners in general. The goal of the report is to present insights from a range of innovative remote sensing applications developed within the Remote Sensing Initiative, to help address specific water resources management challenges. The results presented here include constraints identified in the adoption of remote sensing, the approaches adopted to make applications functional in different contexts, the project applications themselves, insights on their sustainability, and ways forward. These applications can be replicated, up-scaled, and adapted in many other contexts to address similar challenges. We hope the information contained in this report will help country agencies and project teams in integrating the use of remote sensing in their water resources management practices, as well as in project design, implementation, monitoring and evaluation.

The Remote Sensing Initiative

Water is a fundamental ingredient to economic and social development, and it contributes to reducing multiple dimensions of poverty. In order to build resilience and progress towards water security, planning and management decisions need to be based on good quality information and understanding. Observational capabilities from ground monitoring networks and remote sensing provide the foundation for such understanding.

The Global Initiative on Remote Sensing for Water Resources Management was launched in October 2013. Its first phase (2013-2016) was dedicated to researching, documenting, and disseminating the potential and limitations of remote sensing applications in water resources management. The goal of Phase 2 (Oct 2016-Sept 2017) is to concretely demonstrate the different operational uses of remote sensing technology, by implementing relevant and innovative applications within ongoing Bank projects. To this end, Phase 2 of the initiative has supported Bank project teams and the broader Water Practice through a three-pronged approach: (1) remote sensing applications in operational Bank projects in selected countries to serve as the basis for the development of recommended approaches and procedures that can be replicated in other countries facing similar challenges; (2) in synergy with the Water Expert Team and with the goal of achieving a broader impact in the Bank's project portfolio: targeted, short term engagement of world-class experts aimed at advising and providing remote sensing orientation on specific problems related to Bank investment operations; and (3) knowledge dissemination, as well as advocacy and capacity-building activities, in partnership with leading global and regional remote sensing and capacity-building organizations.

The pilots or case studies, were selected to represent a range of different water resources management applications and geographical contexts, are meant to help mainstream remote sensing technologies to benefit operational Bank projects by showing the integration of innovative remote sensing applications in operational contexts. The case studies were designed to respond to client needs expressed and bottlenecks previously identified, namely the limited implementation capacity in client countries, concerns about operation and cost, the need for clear methodologies and recommended approaches, uncertainty representation, and ease of use.

Obstacles

One important task of the Remote Sensing Initiative is to help overcome obstacles to the more widespread adoption of remote sensing technology in operational Bank projects. The following main obstacles were identified in discussions with applied practitioners and project TTLs with remote sensing experience:

- Lack of capacity and human resources in developing country contexts
- Pre-processing required to make data ready for analysis and interpretation
- Uncertainties in remote sensing-based estimates and their applications
- Varying remote sensing data accuracies in different decision contexts
- Lack of clearly defined methodologies and guidelines
- Skepticism from end users and from authorities regarding the benefit of remote sensing
- Lack of familiarity of remote sensing scientists with the realities on the ground

Remote Sensing Applications

The following applications were carried out to help bridge the gap between available remote sensing technology and operational water resources management challenges, while addressing the obstacles identified above:

Bank Context	Remote Sensing Application
Strengthening Water Security and Resilience in Mexico	**ET and Crop monitoring at field level:** Given the strong limitations of the client to monitor irrigation water use and agricultural practices across irrigation districts in Mexico, remote sensing of ET provides an essential spatial and temporal perspective: analysis of ET and crop dynamics over irrigation district 014 Rio Colorado and development of capabilities for future periodic monitoring of ET over the district. **Operationalizing ET estimation** by implementing algorithms in the cloud (Google Earth Engine) and running them periodically.
National Groundwater Management Improvement Program	**Inferring groundwater use through ET monitoring:** After assessing feasibility of using ET to monitor groundwater pumping reductions, obstacles that make this application challenging were identified. The initiative then worked to overcome the main obstacle by developing capabilities for field-scale (30m) periodic monitoring of ET over large areas aiming to support the design, implementation and evaluation of a remote sensing ET-based system to monitor groundwater use changes.
Salado Integrated River Basin Management Support Project	**Flood monitoring and analysis:** In the flood-prone and poorly monitored Salado River Basin, a retrospective probability flood mapping and vulnerability analysis was produced, based on historical occurrence of floods as well as populations affected. Design and development of the freely accessible and now operational Salado Flood Dashboard.
Lake Chad Climate Change Adaptation and Development Project & Salado Integrated River Basin Management Support Project	**Hydrometeorological monitoring, understanding and prediction – Lake Chad and Rio Salado (Argentina) Flood and Drought Monitors** Lake Chad: In the fragile and conflict context of the Lake Chad Basin, real-time remote sensing can complement very scarce ground observations. Building on the continental-scale African Flood and Drought Monitor a tailored version was developed: the Lake Chad Flood and Drought Monitor, in order to improve monitoring and forecasting capabilities, as well as to increase system understanding.

	Rio Salado (Argentina): In this poorly gauged basin, development of hydromet monitoring capabilities in near real-time and hydrologic prediction from a few days ahead to several months ahead. The continental-scale Latin America Flood and Drought Monitor has been fine-tuned and adapted to produce the Rio Salado Flood and Drought Monitor. With the aim of having a higher resolution, more accurate and more management-relevant hydromet monitors, improved precipitation data (combining ground gauges and satellite data) and other types of high-resolution data were implemented into the monitors. A dialogue is taking place with the clients, UNESCO, and other invested partners for the development and upscaling of these tools.
Water Quality Assessment in Lake Toba, Indonesia & Strengthening Water Security and Resilience in Mexico & Regional Wastewater and Water Quality Initiative & Nutrient Modeling at Basin Scale, Uruguay	**Water Quality Monitoring** Coordinating efforts from three requests to the Water Expert Team, methods and best practices are being shared in synergy among the three case studies: Lake Toba (Indonesia): an approach is designed to use remote sensing tools to estimate eutrophication in the lake as well as characterize its drivers in the lake (expansion of aquaculture) and in the catchment (land use changes). Mexico & LAC Integrated wastewater regional planning**:** using remote sensing, ground data, and basin-wide water quality modeling develop and apply analytical methods to support a strategic move from ad hoc and isolated wastewater solutions to integrated basin-wide planning. Santa Lucia Watershed (Uruguay)**:** exploring options for an integrated view using the potential of remote sensing of water quality in open water surfaces (rivers) as a complement to ground measurements and modeling.
Water Point Monitoring	**Very High-Resolution Imagery, pattern recognition and machine learning to detect human activity at water points:** pilot study to assess the feasibility of monitoring the use or non-use of water supply points as a proxy for their state of functionality. The state of the art technology was investigated in three areas: (1) availability, accessibility, and current and future resolutions of very-high-resolution satellite imagery, (2) pattern recognition and machine learning techniques for the remote sensing-based detection of people and livestock at water points, (3) alternative or complementary ground sensing methods to indicate water point functionality.

Main Outcomes

The main contributions to date of the RS Initiative to different RS application fields for World Bank projects, client countries and beyond, can be summarized as follows:

Operationalizing field-scale evapotranspiration ET monitoring capabilities over large areas with the use of Google Earth Engine: With Bank leadership and support and through synergies with key partners, one of the main ET algorithms (DisALEXI) to estimate field-scale evapotranspiration has been implemented in Google Earth Engine and is in the process of validation. The algorithm will initially run to cover project areas in Mexico and India, with future aims at running many other regions of interest. Coordination is ongoing with a broad range of partners to implement all of the main field-scale ET algorithms (METRIC, SEBAL, DisALEXI, SSEBop, etc) into Google Earth Engine through the OpenET Framework Project and work with end-users to operationalize this multi-product ET platform. The Irrigation District 014 Rio Colorado in Mexico will be the first international case study. This effort aims to enable regular and periodic ET monitoring across all of the Bank's operating regions and projects.

Retrospective historical flood archive in ungauged basins: The Rio Salado case study demonstrated a low-cost method for creating spatially explicit historical flood archives in ungauged basins, building on flood detection algorithms used on MODIS, LANDSAT, and SENTINEL data, implemented in Google Earth Engine, and accessible to agency staff through a user-friendly Flood Monitoring and Analysis Dashboard. These historical flood archives will reveal spatial and temporal patterns of flood exposure over the past several decades, and can be used to extract spatial statistics on flood frequency and duration per pixel. In combination with ancillary data (such as population density and socio-economic data), they form a basis for flood probability and vulnerability assessments. Future efforts focus on incorporating real-time flood extent monitoring, leveraging an increase in real-time imagery availability. The time and labor demands of this application on the client are very low, and the opportunities for easy replication across projects and regions are very high

Hydromet monitoring and prediction: The development of operational and near real-time Lake Chad Flood and Drought Monitor and the Salado Flood and Drought Monitor, provides hydromet monitoring, weather forecasts (10-15 days ahead), seasonal forecasts (6 to 9 months ahead) and the resulting hydrologic predictions. The models within the application integrate high resolution remote sensing and other spatial data with ground data, and are accessible through a user friendly online platform. Client agencies in Argentina and the Lake Chad Basin Commission, with lacking or scarce real-time hydromet data, have now these functioning monitors requiring no operating resources from them.

Linkage with international hydrologic knowledge networks: Within each application, efforts have been made to connect with broader international knowledge networks of partners and parallel efforts. Many partners have gathered around the implementation of field-scale ET estimates in Google Earth Engine, vested and willing to contribute to these efforts. Close coordination is also taking place with UNESCO-IHP efforts in LAC and Africa, with similar case studies in other countries to improve hydromet monitoring capabilities using remote sensing. These synergies are key for adoption and long term sustainability of applications, joint capacity building efforts, and knowledge spillovers.

Adaptation of remote sensing tools to settings with low capacity: Owing to the rapid advancements in cloud computing, storage and data repositories, the remote sensing applications and tools created in this initiative have been developed with a focus on settings with low financial, human, technical and internet capacity. Stakeholder feedback has helped develop functional applications that best address user needs.

RS reaching the project portfolio through operational technical assistance: Requests for technical assistance to the Water Expert Team that could benefit from remote sensing expertise were identified as a vehicle for the RS initiative to further influence the project portfolio. Teams worked together to explore solutions to best address the challenges within projects in the operational portfolio, or relating to overarching issues with high potential across regions and projects.

Going Forward

Six strategic investments are proposed as high-impact applications that should be part of the Water GP project portfolio toolkit, providing monitoring and analytical power to address current threats to water security. These proposed investments would take advantage of recent technological advances such as the wealth of data, large data archives in the cloud, cloud computing power, and widespread but sometimes limited internet connectivity.

- Periodic and regular Evapotranspiration (ET) and crop monitoring at the field scale (resolution ~30m) over large areas: a cloud based platform with all the main ET algorithms and vegetation indexes will enable to regularly monitor irrigation dynamics as well as crop types and growth.

- Flood Extent Monitoring and Analysis (retrospective and real-time): using flood detection algorithms in satellite archives within the cloud is an efficient and very cost-effective way to produce flood analysis using all available imagery. This is an easy tool to quickly gain a good understanding of floods in regions without data, as well as to monitor the effects of new infrastructure or other measures on flood dynamics.
- Hydrometeorological Monitoring and Prediction (Including Floods and Droughts): An easily accessible monitor integrating historical datasets, real-time satellite rainfall, evapotranspiration and soil moisture estimates, meteorological forecasts (7-14 days ahead), seasonal forecasts (6 to 9 months ahead) and ground data, is a baseline tool for regions to monitor the state of their basins in near real-time, water balance accounting purposes and to inform management and planning.
- Monitoring of Riparian Ecosystems and the Environment: Vegetation indices and the estimation of riparian ET are a good way to monitor changes in the area and the health of such ecosystems. This application will enable the monitoring of impacts on riparian environments from projects and other interventions.
- Water Quality Monitoring Systems: Remote sensing can provide a much needed spatio-temporal view of water quality dynamics and relate it to other processes such as land use change and meteorology (rainfall, temperature, etc). In regions with observable water surfaces such as lakes, reservoirs or large rivers, capabilities to complement ground measurements of water quality with remote sensing will provide key information to inform the prioritization of measures and investments to improve and protect water quality.
- Transboundary Reservoir Systems Monitoring: In large transboundary basins with upstream and downstream states, with challenges of information-sharing, transboundary flood risks, water flow allocation issues, and the operation of reservoirs in each country, remote sensing can level the field by providing a transboundary view of the state of the basin, its flows, and the observed operation of reservoirs.

1 – Introduction

Water, Development and Remote Sensing

Water is a fundamental ingredient to economic and social development, and it contributes to reducing multiple dimensions of poverty. Water is essential to food and energy security, industrial growth, and the protection of ecosystems. Water resources are under unprecedented pressure as growing populations and emergent economies have increased demand and at the same time degraded supplies. As a result, water insecurity has become one of the greatest risks facing the world today.

In order to build resilience and progress towards water security, planning and management decisions need to be based on good information and good understanding. Ultimately, decisions in each setting will have to strike a balance between competing human demands, available resources, the environment, and short-term needs versus long term vision. To enable sound planning and management decisions, a detailed understanding of hydrologic processes in space and time is needed, and observational capabilities from ground monitoring networks and remote sensing are the foundation for good understanding and knowledge.

This report is addressed to an audience including technical staff from water agencies and institutions from country agencies, world bank project leads, and water practitioners in general. The goal of the report is to present insights from a range of innovative remote sensing applications developed within the Remote Sensing Initiative described below, to help address specific water resources management challenges within ongoing World Bank projects and assistance efforts with country agencies. The results presented here include constraints identified in the adoption of remote sensing, the approaches adopted to make applications functional in different contexts, the project applications themselves and insights on their sustainability, and ways forward. These applications can be replicated, up-scaled, and adapted in many other contexts to address similar challenges. We hope the information contained in this report will help country agencies and project teams in integrating the use of remote sensing in their water resources management practices, as well as in project design, implementation, monitoring and evaluation.

The structure of this report is as follows: Chapter 2 provides an overview of the Remote Sensing Initiative, its two phases and their goals. Chapter 3 provides an overview of the identified obstacles to the use of remote sensing applications, recommendations on how to overcome them and how these considerations guided the implementation of the Phase 2 applications within operational projects and efforts. Chapter 4 contains a summary and characterization of the different types of remote sensing applications being implemented within Bank projects (Table 1) and their overall approach, highlighting their contributions. Chapter 5 provides a discussion on the sustainability of applications in client contexts and ways forward. Chapter 6 highlights how the efforts of the Remote Sensing Initiative are pushing the boundaries of problem-driven research to date and are closing the gap to mainstream RS applications within operational projects. Chapter 7 proposes a list of strategic investments going forward including a range of remote sensing applications that would highly benefit the Bank's portfolio and its clients. Annexes 1 to 6 contain the detailed descriptions of the applications and the operational projects within which they are implemented, including technical approaches, geographic, political and social contexts of each case study. Two of the applications (Annexes 5 and 6) are products of synergies between the RS Initiative and the Water Expert Team program, which coordinate and connect efforts of the same nature, share across projects, and ultimately impact a wider range of operational projects with the innovative application of remote sensing technology. Annex 7 details the Capacity Building and Dissemination activities undertaken during Phase 2 of the RS Initiative.

Table 1: *Overview of Remote Sensing Initiative Phase 2 projects aimed at mainstreaming remote sensing applications.*

Bank Context	Remote sensing application	Partners	
Strengthening Water Security and Resilience in Mexico (P162473) **TTL: Diego Rodriguez**	**ET and Crop monitoring at field level:** Given the strong limitations of the client to monitor irrigation water use and agricultural practices across irrigation districts in Mexico, remote sensing of ET provides an essential spatial and temporal perspective: analysis of ET and crop dynamics over irrigation district 014 Rio Colorado and development of capabilities for future periodic monitoring of ET over the district. **Operationalizing ET estimation** by implementing algorithms in the cloud (Google Earth Engine) and running them periodically.	Jordi Cristóbal Rosselló (University of Alaska-Fairbanks); Mutlu Ozdogan (University of Wisconsin-Madison), *USDA (Martha Anderson), Google.*	Annex 1
National Groundwater Management Improvement Program (P158119, India) **TTL: Abedalrazq F. Khalil, Satya Priya**	**Inferring groundwater use through ET monitoring:** After assessing feasibility of using ET to monitor groundwater pumping reductions, obstacles that make this application challenging were identified. The initiative then worked to overcome the main obstacle by developing capabilities for field-scale (30m) periodic monitoring of ET over large areas and support the design, implementation and evaluation of a remote sensing ET-based system to monitor groundwater use changes.	Mutlu Ozdogan, University of Wisconsin-Madison, USDA (Martha Anderson)	Annex 2
Salado Integrated River Basin Management Support Project (P161798, Argentina) **TTL: Victor Vazquez, Maria Catalina Rodriguez**	**Flood monitoring and analysis:** In the flood-prone and poorly monitored Salado River Basin: Retrospective probability flood mapping and vulnerability analysis, based on historical occurrence of floods as well as populations affected. Design and development of a remote sensing-based flood monitoring application and flood vulnerability assessment, with aims at becoming operational in the near future.	Beth Tellman, Jonathan Sullivan, Bessie Schwarz, Jared Tomlin (Cloud to Street);	Annex 3
Lake Chad Climate Change Adaptation and Development Project (P144568) **TTL: Marie-Laure Lajaunie** **Salado Integrated River Basin Management Support Project (P161798, Argentina)**	**Hydrometeorological monitoring, understanding and prediction – Lake Chad and Rio Salado (Argentina) Flood and Drought Monitors** Lake Chad: In the fragile and conflict context of the Lake Chad Basin, real-time remote sensing can complement very scarce ground observations. Building on the continental-scale African Flood and Drought Monitor a tailored version was developed: the Lake Chad Flood and Drought Monitor, in order to improve monitoring and forecasting capabilities, as well as to increase system understanding. Rio Salado (Argentina): In this poorly gauged basin, development of hydromet monitoring capabilities in near real-time and hydrologic prediction from a few days	Eric Wood (Princeton University), Justin Sheffield (University of Southampton, UK); Also: UNESCO International Hydrological Program; Institute of Water Resources (USACE-ICIWARM)	Annex 4

TTL: Victor Vazquez, Maria Catalina Rodriguez	ahead to several months ahead. The continental-scale Latin America Flood and Drought Monitor has been fine-tuned and adapted to produce the Rio Salado Flood and Drought Monitor. With the aim of having a higher resolution, more accurate and more management-relevant hydromet monitors, improved precipitation data (combining ground gauges and satellite data) and other types of high-resolution data were implemented into the monitors. A dialogue is taking place with the clients, UNESCO, and other invested partners for the development and upscaling of these tools.		
Water Quality Assessment in Lake Toba, Indonesia **TTL: Marcus Wishart** **Strengthening Water Security and Resilience in Mexico (P162473) & Regional Wastewater and Water Quality Initiative** **TTL: Diego Rodriguez** **Nutrient Modeling at Basin Scale, Uruguay** **TTL: Remi Trier**	**Water Quality Monitoring** Coordinating efforts from three requests to the Water Expert Team, methods and best practices are being shared in synergy among the three case studies: Lake Toba (Indonesia): an approach is designed to use remote sensing tools to estimate eutrophication in the lake as well as characterize its drivers in the lake (expansion of aquaculture) and in the catchment (land use changes). Mexico & LAC Integrated wastewater regional planning**:** using remote sensing, ground data, and basin-wide water quality modeling develop and apply analytical methods to support a strategic move from ad hoc and isolated wastewater solutions to integrated basin-wide planning. Santa Lucia Watershed (Uruguay)**:** exploring options for an integrated view using the potential of remote sensing of water quality in open water surfaces (rivers) as a complement to ground measurements and modeling.	Fernando Miralles Wilhelm (University of Maryland), Ivan Lalovic (expert consultant); Brian Killough (CEOS) ; NASA. (Synergy of requests to the Water Expert Team)	Annex 5
Water Point Monitoring **TTL: Luis Alberto Andres**	**Very High-Resolution Imagery, pattern recognition and machine learning to detect human activity at water points:** pilot study to assess the feasibility of monitoring the use or non-use of water supply points as a proxy for their state of functionality. The state of the art technology was investigated in three areas: (1) availability, accessibility, and current and future resolutions of very-high-resolution satellite imagery, (2) pattern recognition and machine learning techniques for the remote sensing-based detection of people and livestock at water points, (3) alternative or complementary ground sensing methods to indicate water point functionality.	DigitalGlobe; SweetSense; Charity: Water; (IBM Research Africa) NASA – SERVIR (Synergy with request to Water Expert Team)	Annex 6

2 – The Remote Sensing Initiative

Financed by the WPP of the Water GP, a **Global Initiative on Remote Sensing for Water Resources Management** was launched in October 2013, with a two-phased approach. **Phase 1** (2013-2016) had the aim of developing and disseminating a clear picture of the potential role of remote sensing/earth observation in helping decision makers address particular water challenges, focusing on the accuracy, reliability, and validity of available earth observation products. It resulted in a publication "Earth Observation for Water Resources Management"[1], aimed at specialists and development practitioners around the world who are seeking answers to challenging technical questions about the usability of remote sensing for water resources management.

As only 18% of 800 World Bank projects with water themes had made use of remote sensing between years 2002 and 2012, the rest relied exclusively on ground observations, often scarce and incomplete. Complementing ground observations, remote sensing can play an important role in providing information to have a more complete picture needed to better confront key water challenges. The key remote sensing-derived hydrological variables assessed in the Phase 1 desk study include: (1) precipitation, (2) evapotranspiration, (3) soil moisture, (4) vegetation, (5) groundwater, (6) surface water, (7) snow cover, (8) water quality. A decision framework was elaborated to help determine (1) whether remote sensing/earth observation products would make a beneficial addition to a particular monitoring, evaluation or planning task, and (2) which would be the most suitable earth observation products and approaches to provide the desired information given the spatial and temporal resolutions required for the task. To this end, the decision framework lays out sets of questions on the nature of the water resource management problem, the capacity of sustaining remote sensing-based monitoring programs, the status of existing data an observation networks, and the adequacy of field observations.

Phase 1 concluded that there is still a large gap between existing remote sensing technologies and operational applications in support of the planning, design, and management of water resources. Although there is great potential for space-based remote sensing to enhance the capability to monitor the Earth's vital water resources, remote sensing data products are currently underutilized in water resources management. Practitioners, especially in developing countries, would benefit from efforts to bridge the gap between scientific-academic and operational uses of remote sensing technology.

The goal of the Remote Sensing Initiative – **Phase 2**, the activities of which are presented here, has been to help operationalize and mainstream the beneficial use of remote sensing applications in client countries and within World Bank projects to inform water resources planning and management. Phase 2 aims to concretely demonstrate the different operational uses of remote sensing technology, by implementing innovative applications within ongoing Bank

[1] The book *Earth Observations for Water resources Management, Current Use and Future opportunities for the Water Sector* is freely available and can be downloaded from the World Bank Open Knowledge Repository at https://www.openknowledge.worldbank.org/handle/10986/22952

efforts, accounting for client country contexts and local capacity constraints. To this end, Phase 2 has supported Bank project teams and the broader Water Practice through a three-pronged approach: (1) remote sensing applications in operational Bank projects in selected countries, serving as demonstrations for approaches and procedures that can be replicated in other countries facing similar challenges; (2) in synergy with the Water Expert Team and with the goal of achieving a broader impact in the Bank's project portfolio: targeted, short term engagement of experts aimed at providing remote sensing orientation on specific problems related to Bank operations; and (3) knowledge dissemination, as well as advocacy and capacity-building activities, in partnership with leading global and regional remote sensing and capacity-building organizations.

The pilots or case studies, which were selected to represent a range of different water resources management applications and geographical contexts, are meant to help mainstream remote sensing technologies to benefit operational Bank projects by showing the integration of innovative remote sensing applications in operational contexts. The case studies were designed to respond to expressed client needs and address previously identified bottlenecks such as limited implementation capacity in client countries, concerns about operation and cost, understanding uncertainties, the need for clear methodologies and outputs, and ease of use.

Knowledge for Implementation: the Importance of Global Initiatives

From the Bank's unique position at the intersection between client country needs, development solutions, and the supply side of research and global information (i.e. research institutions, technical agencies and science-policy networks), emerges its role of *Knowledge Producer*, *Implementer* and *Disseminator*. This is especially true in fast-evolving fields such as in remote sensing, where observational capabilities and information technologies are increasing exponentially.

In that sense, the Bank is in a privileged position to help connect contextual management and planning needs with the global innovation and development sphere, acting as an important knowledge generator in operationalizing new science and technology within management and planning contexts. The Bank is the one institution that has a direct insight (and access) to all the dimensions of a planning or management challenge and its potential solutions: institutional context, the human and technical capacity available to client agencies, resources, available science and technology, best operational setup, lessons learned from similar experiences, parallel efforts, and the potential sustainability of an operational system. While other actors may be knowledgeable about one or more of these dimensions, only the Bank from its position has the integrative view of the challenges and the solution space. For this reason, it is perhaps the best suited actor to operate in a bi-directional way to both *Operationalize Science and Technology Applications* within client settings, and to draw *Knowledge for Implementation* insights for successful replication and diffusion.

In addition, the knowledge produced at the conjunction of client needs and the development and supply of applications can also inform the agencies developing the science applications. While

the World Bank helps bring the latest applications and information into project settings and client countries, it also informs efforts to develop applications and products on the supply-side, so that they can gain in relevance and usefulness.
Relevant to all of the above, the Remote Sensing Initiative has:

1. Produced and published an integrative state of the art synthesis of available sensors, applications and opportunities.
2. Taken stock and identified some of the bottlenecks in making remote sensing applications operational and sustainable.
3. Implemented a range of key applications demonstrating what is possible with the current state of the art.
4. In many cases, such applications have established a baseline against which to compare and monitor the outcomes of large contracts (i.e. Rio Salado, Argentina).
5. Pushed key efforts with very high impact potential, such as making ET estimation operational (periodic, low cost, over large areas), bridging and catalyzing communications between the client and the suppliers of data and developers of applications.
6. Identified the components that need to come together for a certain application to be functional, the bottlenecks, and technological advances needed to make the application feasible.
7. Brought external knowledge, innovation and technology to the Bank through existing and newly developed networks of knowledge.
8. Informed and aligned external partner initiatives to better serve the needs of clients and better target end-user and management challenges.
9. Disseminated new knowledge and information to a broad range of clients, as well as to supply-side practitioners and other development partners.

It again emerged from the Initiative's case studies and involvement with other Bank projects that there is a strong but latent demand for this type of knowledge, both from the Bank's project teams as well as from the client agencies. While the case studies presented here were demand-based to address a particular challenge, the range of potential contributions and new possibilities maintained or increased demand for remote sensing within the projects. In the Argentina Rio Salado case, the initiative directly influenced the terms of reference for the large contracts to be procured within the project, and new demands emerged from other projects who heard about the Initiative.

Global Initiatives such as this one are a good mechanism to synthesize the current state of the art and skim new science and applications that are ready to support operations, in order to help bring new knowledge and ideas to World Bank projects and to the clients. Access to this cutting-edge knowledge positions the Water Practice and the Bank as leading global experts on knowledge for implementation, reflecting on its operations and services. It keeps the Bank competitive as a Knowledge Implementer, Producer and Diffuser. Importantly, knowledge and understanding from these global initiatives will guide the spending of public goods, provide baselines for procurement contract results, and overall help guide and prioritize investments, maximizing their rate of return. A portfolio that comes with expert *Knowledge Production for Implementation* is a competitive one, and it raises the Bank as a global leader in the development business.

3 – Mainstreaming of Remote Sensing Applications: Obstacles and Ways Forward

Phase 2 of the Remote Sensing Initiative, aimed at reducing the gap between research applications and operational use of remote sensing tools, builds on the identification of obstacles that create such a gap and impede the systematic use of remote sensing in developing contexts. The identification of these obstacles and difficulties was done during Phase 1 and early Phase 2 activities, taking stock from a range of applied practitioners and project TTLs with remote sensing experience (see the Water Week 2017 activities in the following chapter on *Knowledge Exchange and Capacity Building,* as well as other discussions in the setting of the case studies of the following chapter). Along with the identification of obstacles also came ideas on how to overcome them and help make remote sensing applications more accessible in developing country contexts.

The following main obstacles to the broader adoption of remote sensing in the water sector emerged from a range of discussions to date, along with recommendations to mitigate them, and a brief explanation of how these have been implemented in efforts to date:

(1) *Lack of capacity and human resources:* In most client country agencies, the single scarcest resource is often technical capacity (i.e. well trained technicians) to access, process, interpret and use remote sensing information. This lack of capacity touches on many other issues relating to data, monitoring, modeling and technology in general, and not only remote sensing. In some client countries, significant RS capacities are present but not well utilized, with academic institutions doing isolated research disconnected from water agencies that could use their applications to provide technical solutions to their planning and management challenges. Even within the Bank, literacy on the use of remote sensing applications can be increased.

Recommendation: Put more emphasis on the human resource side and find mechanisms to align parallel and appropriate training with the implementation of Bank projects, including longer term intensive training for key people functioning as early adopters in their countries. Encourage the connections with local and regional expertise, science-policy networks and *knowledge-to-action networks* where available. Develop a value chain of knowledge.

Implementation: In several bank projects, teams have sought to involve local centers of expertise such as universities and remote sensing agencies, usually disconnected from certain management spheres, and attempted to carve out funding from the project for their involvement. This is not an easy task as pitches may have to be made at different levels of government, but it is highly recommended to ensure long term sustainability. Discussing with AGRHYMET colleagues, they described ow they used to have formal programs (3 and 5 years) in operational hydrology funded by international donors, with the commitment of AGRHYMET to hire every graduate. Since that program stopped, it seems their technical capacity has decreased significantly. As part of the Remote Sensing Initiative case studies, training sessions were organized for client agencies and World Bank staff in the respective countries, often with the participation of local universities. The Bank team delivered workshop presentations at the World Bank offices in Mexico City, as well as at the CONAGUA regional offices in the Rio Colorado irrigation district (Mexicali), on monitoring evapotranspiration by means of remote sensing, with concrete examples from the Rio Colorado irrigation district. In the Rio Salado basin, the team held workshops for staff of the *Agencia del Agua* (ADA), the *Dirección Provincial de Obras Hidráulicas* (DPOH) and other local government personnel on the use of the flood monitoring dashboard, as well as the Rio Salado flood and drought monitor developed specifically for the basin. Research centers including the *Instituto de Hidrología de Llanuras* (IHLLA) were also present and participated actively in the discussions.

(2) *Complex processing*: Remote sensing data often require more, and more complex, processing than field data to make them ready for analysis and interpretation. The need to process the raw data, bias correct, assimilate or reconcile with ground data in order to use them in operational applications is an obstacle for their mainstream adoption. This obstacle gets compounded by the previously mentioned lack of capacity in client countries.

Recommendation: facilitate access to analysis-ready data that does not require extensive processing. This can involve the development of tailored applications that ingest RS data and produce useful outputs that require minimal processing and are analysis-ready. New information technologies and cloud computing advancements can facilitate this task.

Implementation: The RS Initiative has focused on developing applications that will minimize the need for involved data processing in favor of tailored and user-friendly interface. The Rio Salado and the Lake Chad Flood and Drought Monitors are good examples of this, where the user can visualize near real time data, short term forecasts, seasonal forecasts and in the future, climate change projections, and can download the variables of interest for the area and period of interest. The efforts to operationalize evapotranspiration (ET) algorithms within the Google Earth Engine environment, which will enable regular and periodic evapotranspiration estimation at the field level over areas of interest, will greatly overcome the currently costly applications at the project level. Such estimates processed in Google Earth Engine (or other cloud environment) are ready for use and interpretation by users themselves and do not require the complex data processing and analysis skills traditionally needed for creating these products from raw remote sensing data.

(3) *Uncertainties in the remote sensing estimates and their applications:* While the uncertainties contained in remote sensing data can be estimated and acknowledged, it is not common practice to report and represent them in the output data. While the use of any data involves uncertainty (i.e., assuming rain-gauge measurements are representative of a large area or watershed), the fact that remote sensing estimates are indirect leads to the perception of potentially higher uncertainties, which may or may not

be true. On the other hand, the minimum uncertainty requirements for specific applications and needs from client country agencies are often not well defined.

Recommendation: Quantify and communicate uncertainties associated with remote sensing estimates, and present outputs and results with an associated uncertainty or confidence interval. The use of different data products and models can also help provide a good idea of the uncertainty contained in estimates and predictions. Stakeholders can then make decisions based on the estimated uncertainties and the contexts of the specific applications.

Implementation: Discussions of uncertainty and errors have been present in all of the activities with the project teams and client agencies. The Salado and Lake Chad Flood and Drought Monitors will include confidence intervals for the streamflow predictions once they are calibrated with field observational data. In regards to the operationalization of ET algorithms in Google Earth Engine, an open access multiple product platform for different ET products will be created, along with a range of validation procedures including remote sensing ET estimates computed off-line as well as against estimates from ET flux towers on the ground. In addition, for areas without ground estimates, a multi-product platform will enable the comparison of different ET products and allow the user to better understand bias and uncertainties among ET products, sites and seasons.

(4) *Varying RS data accuracies and different decision contexts*: The accuracy of estimates can vary depending on the used data product and its algorithm but especially depending on the geography, climate, topography and land cover. Depending on the type of application, its uncertainties will also vary depending on how the errors are propagated in the transformation of input data within the application.

Recommendation: Need for capacity development through local understanding and site-specific evaluation of remote sensing data, and validation of applications within each context, addressing the needs and specificities of the specific decision context.

Implementation: Each application described in this report had its own set of efforts regarding its accuracy, calibration and validation efforts and an effort was made to clearly convey issues of accuracy and precision.

(5) *Lack of clear methodology*: As remote sensing for water resources management is an innovative and evolving field, many applications do not have an established recommended approach or methodology (i.e. rainfall-runoff modeling). As a result, different implementation of the same application type can produce different results.

Recommendation: Develop recommended approaches or guidelines for the development of each type of application. For example, regarding rainfall-runoff modeling: *bias correct satellite rainfall data, recalibrate hydrologic model with bias corrected inputs, and bias correct streamflows to reduce model structural errors and better match observations*.

Implementation: While these efforts have started for some applications such as rainfall-runoff modeling, they will be completed within a case by case basis during future efforts.

(6) *Skepticism from end users:* Some end users remain unconvinced of the benefit of remote sensing data, since they (a) are concerned about potential high errors in remote sensing data, (b) need to do in-situ measurements anyway, (c) find the remote sensing indices hard to interpret and not relevant to them.

Recommendation: Better communicate the benefits of remote sensing to end users and make them aware of the presence of errors in in-situ data as well. Demonstrate that the optimal monitoring is the joint and complementary use of remote sensing and in-situ data. Offer a better "packaging" of the remote sensing information to end users that is more explicit of the meaning of the data in the application context and of uncertainties.

Implementation: The workshops with country agency staff were designed to demonstrate the benefits of integrating remote sensing data in order to better understand and consequently be able to better manage hydrological/environmental systems, while also emphasizing the need for complementary in-situ data in order to optimize monitoring and assessment. Participants gained understanding of both benefits and limitations of remote sensing, and an increased appreciation for the value of monitoring tools combining in situ observations and remote sensing estimates.

(7) *Skepticism from authorities:* Authorities have been skeptical of using remote sensing for various reasons including (a) fear of transparency, e.g., excessive water consumption potentially being revealed by remote sensing, (b) national irrigation design standards based on the concept of irrigation efficiency rather than evapotranspiration, and (c) age structure in institutions, with key positions often held by seniors, who tend to be warier of change and innovation.

Recommendation: Present remote sensing data not as a replacement for conventional data but as complementary, as an additional opportunity. Engage with science-policy networks and make the economic case to show that the use of remote sensing data make sense financially. Make the financial case for the use of remote sensing data. Help put a "chain of command" in place for the adoption of remote sensing and its integration with operational planning and management, build the value chain of knowledge.

Implementation: see previous point (6). In addition, it has been emphasized with the client in all applications that remote sensing is a complementary tool which can be added to their traditional monitoring programs.

(8) *The supply-side (scientists) is unfamiliar with realities on the ground:* Remote sensing technology and applications are largely advanced from the vantage point of research in developed countries, not always bearing in mind the developing country stakeholder and his needs, challenges and cultural contexts on the ground.

Recommendation: Understand the country context of the client and the constraints in which he needs to operate, in order to develop adapted applications. Hold stakeholder meetings and let the specificity of the problems define the solutions.

Invest more into developing and delivering solutions that are intuitive and address the problems on the ground.

<u>Implementation:</u> Extensive meetings and discussions with the client country agency staff and bank teams took place to characterize the issues to be addressed with remote sensing applications. During the development of applications and until the their first version, the client agencies were informed and their feedback and insights were iteratively requested. In addition, the missions and associated field visits allowed for interactions and understanding among everyone involved, with a focus on the end-users and their perceptions and needs.

(9) *Difficulty in ensuring long-term operational sustainability (and scalability and updating) after an application has been developed*: In addition to the above limitations on human and technical capacity at the country level, applications may be developed and implemented in collaboration with external expertise but mechanisms are often lacking to retain that involvement over time for maintenance, scaling up and updating/upgrading purposes.

<u>Recommendation</u>: Look at the broader regional and international institutional landscape and try to build elements of sustainability around existing partners and capabilities, capitalizing on parallel efforts and building redundancies that may contribute to ensuring sustainability. Ultimately, the only way of ensuring this is to develop a strong local knowledge base, and a pool of trained staff to draw from.

<u>Implementation</u>: Significant efforts were made to establish collaborative synergies in each one of the applications. In the case of the Salado and Lake Chad Monitors, the work builds on significant previous investments to develop the Latin America and Africa Flood and Drought Monitors at the continental scale, an effort supported by UNESCO-IHP, IWR-USACE, and Princeton and Southampton Universities, with inputs and feedback from workshops at AGRHYMET, ICPAC and with the participation of river basin organizations and local agency staff. Coordination with these partners puts this effort within a broader context. In the same way, the ongoing efforts to operationalize ET estimation in a cloud environment such as GEE are also a team effort with a range of partners, including NASA, USDA, the main ET algorithm developers, private foundations, and Google.

Phase 2 activities have been designed and implemented with these obstacles in mind, in order to successfully bridge the gap into operational applications in projects.

4 – Operational Remote Sensing Applications

The Remote Sensing Initiative has supported several different operational projects and efforts as summarized above in Table 1. Within the context of these projects, the Initiative has covered a range of remote sensing application types, with ongoing implementation within several bank projects. While the implementation of the applications within each project context is described in detail in the Annexes, this chapter provides an overview of the different application types, the results obtained, relevance, and the approaches adopted to bring remote sensing closer to Bank operations and the client.

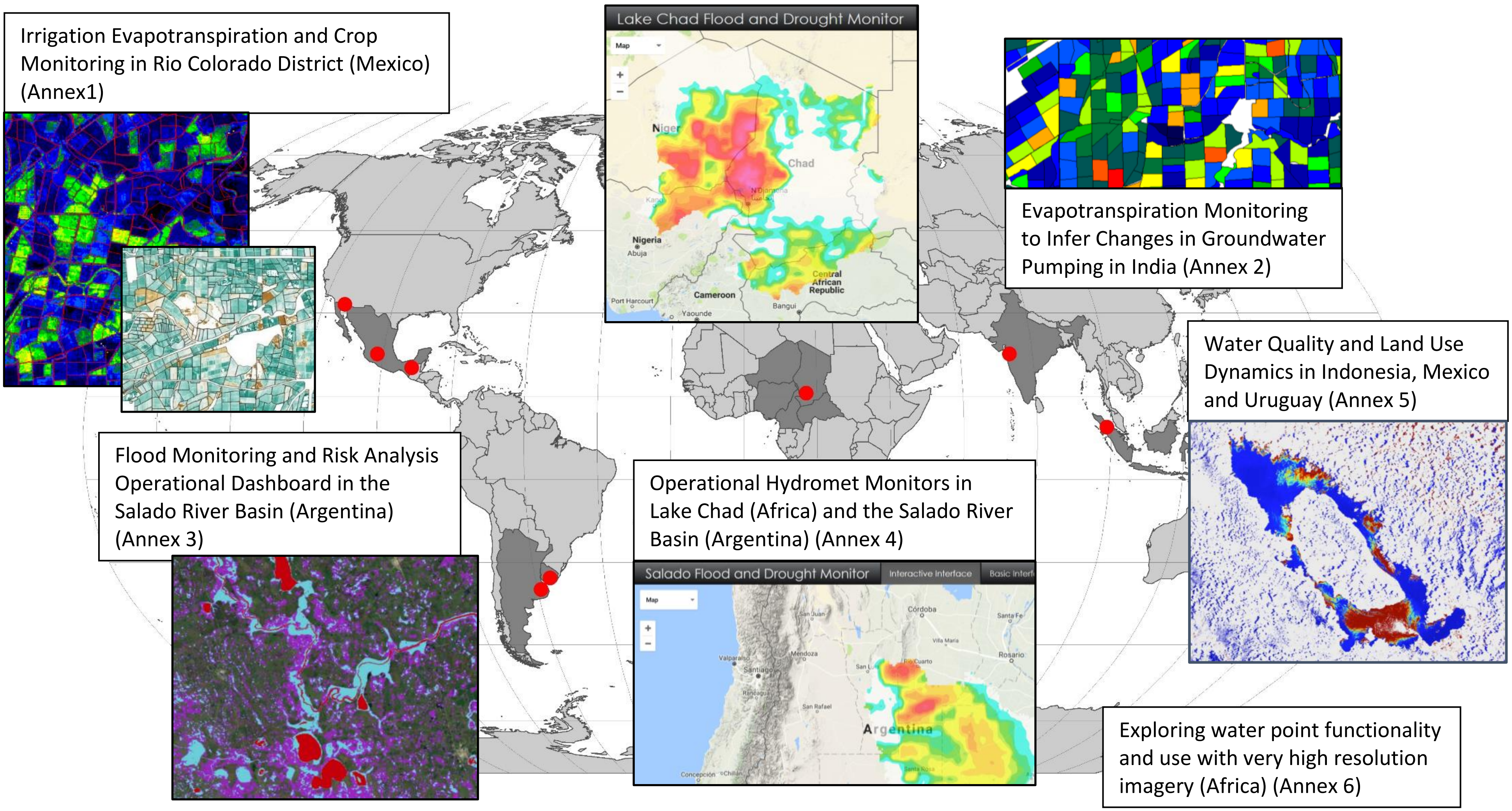


Figure 1: Case Studies of the Remote Sensing Initiative – Phase 2

4.1 – Operational Irrigation Evapotranspiration and Crop Monitoring – Mexico and India

Irrigation districts can be monitored using remote sensing through the observation of two main variables: evapotranspiration from the fields and vegetation indexes of the crops. Evapotranspiration (ET) is an important variable for irrigation water management as it represents all of the water evaporated from the soils or used by the plants, which directly depends on the irrigation water applied or rainfall. Time series of Vegetation Indices of the agricultural fields in the district allow us to follow the cropping patterns and the evolution of the crops through the year, as well as to distinguish different types of crops. Such remote sensing information can then be complemented with ground measurements to gain a full understanding of the crop and water dynamics and processes within an irrigation district.

The *Distrito de Riego 014 – Rio Colorado* is located along the lower reaches of the Colorado River, between the US-Mexican border and the Sea of Cortez, covering parts of the states of Baja California and of Sonora. With an irrigated area of 207,965 ha, the Distrito de Riego 014 is one of the largest irrigation districts in Mexico. Irrigation critically depends on the Colorado River, delivering surface water directly as well as providing a major source of shallow groundwater recharge. Groundwater and surface water are coupled tightly, so that additions or subtractions to one are felt by the other. The use of Colorado River water turns this otherwise arid region into one of the most fertile and productive areas of Mexico, with over 50 different crops grown. However, with growing water demand from the city of Tijuana and local urban centers and the ongoing drought in the Colorado basin since 2000, pressure on water management has been on the rise.

Groundwater Use Monitoring using ET data

As groundwater lies below the land surface, there are currently no remote sensing techniques for direct observation of groundwater level. The main indirect techniques are through satellite gravity field mapping (gravimetry), or mapping land subsidence using radar interferometry. Currently there is only one set of gravity measurements, the GRACE mission[2], which is already operating several years beyond its intended five-year lifetime, with the quality of its observations slowly degrading. GRACE's very coarse spatial resolution (300km) means that it can only be used for large basin-scale applications. As an alternative for more local-scale dynamics, evapotranspiration and cropping patterns can be used to infer groundwater extraction, if the areas irrigated with groundwater are known and some knowledge exists on local irrigation methods.

The India case study focused on assessing the feasibility of using periodically available operational low-resolution (5km) evapotranspiration (ET) estimates and other variables for the calculation of Disbursement Linked Indicators (DLIs) in a payment for results-based program aimed at reducing groundwater extraction and arresting the decline in the groundwater table. The study below

[2] Chen, J., Famigliett, J. S., Scanlon, B. R., & Rodell, M. (2016). Groundwater storage changes: present status from GRACE observations. *Surveys in Geophysics*, *37*(2), 397-417.

found that there are several obstacles to achieving the above using periodically available 5km resolution ET estimates. The main obstacle to accomplishing the above goal was the lack of capacity to produce operational field-scale (30m) ET estimates over large areas in a periodic and cost-effective manner. It is the field estimates at 30m that enable a better attribution of reduced pumping rates and consumptive use across farmers, districts and municipalities, enabling its potential use for DLI indicators.

Given this gap in the state of the art, **the Remote Sensing Initiative has pushed forward efforts to develop capabilities for operational field-scale estimation of ET over large areas**. One of the current cutting-edge algorithms for ET estimation (DisALEXI) has been translated to cloud language and implemented within Google Earth Engine, so that it can be run periodically over large areas taking advantage of all the GEE public data catalog and the cloud's computing power. We have coordinated with other experts and partners to contribute to a broader effort of porting all available field-scale ET algorithms into Google Earth Engine (these efforts are described at the end of this sub-chapter). Efforts are now at the validation step of the newly implemented algorithm within GEE. These capabilities will soon be able to assist the India groundwater management improvement program (and all other irrigation projects across the bank's portfolio) with regular and periodic estimation of field-scale ET for a multi-scale incentive scheme. Given these advances, the India team will continue to explore additional work to operationalize the use of remotely sensed ET in monitoring groundwater use during program implementation.

This chapter will focus on the application in the *Rio Colorado* Irrigation District in Mexico. The detailed reports on ET and crop monitoring for the Irrigation District 014 *Rio Colorado*, Mexico, and for the India case study can be found in Annex 1 and Annex 2, respectively.

Information-to-decisions Context:
The Mexican *Comisión Nacional del Agua* (CONAGUA) is responsible for monitoring, managing and protecting Mexico's water resources and ensure their sustainable use. However, over the last years, CONAGUA has seen its monitoring budget severely reduced, including a reduction on the number of personnel. In this context of having to achieve more with very little, CONAGUA through its *Organismo de Cuenca de la Peninsula de Baja California* has a keen interest in remote sensing applications to monitor what is happening in this large irrigation district. The Director General expressed very clearly the need of remote sensing to address the following questions:

a. Monitor Irrigated Cropped Area: Need to verify that farmers cultivate an area for which they hold water rights. It has been found that field expansions go unreported.
b. Monitor Crop Types: Need to verify that farmers plant what they declared each year in August/September in their "*permiso unico de siembra*" (i.e. sowing permit) which determines the amount of water needed and the water rights to be used in each field, effectively tying the agricultural land with a water use amount. It has been found that farmers may report a certain crop but later plant a crop with higher water use requirements.
c. Monitor ET to close the Irrigation water balance: both CONAGUA and the farmers themselves expressed interest in monitoring ET to better understand irrigation dynamics, efficiencies at various levels (conveyance, partitioning, field leveling, soils), and

consumptive water use. As the fields are very large and within-field variability is captured by the 30m resolution ET product, the farmers also saw that ET monitoring could help identify areas of the fields where irrigation water was not reaching well, to inform periodic laser leveling (done every 3 to 5 years approximately)

From a broader perspective, CONAGUA is interested in exploiting this application to detect problem areas in the district to focus on, and to determine whether farmers use their water allocations or whether their water usage exceeds or stays below their allocated water share. Knowledge of water usage by farmers would inform the design of hydro-agricultural policies aimed at improving water use efficiency and especially at increasing productivity.

Methods and Results:

ET is a flux measure and cannot be observed directly from satellite, but is derived indirectly through either empirical relationship between remotely sensed vegetation indices and thermal infrared data, or the physical principles of the surface energy balance (SEB) equation. The latter approach is considered to produce more accurate estimates and thus used in most ET estimation algorithms (SEBAL, METRIC, DisALEXI, SSEBopetc) including the one used in this study (DisALEXI). Estimation of ET at field level requires going beyond applying surface energy balance models to remote sensing data, and spatially disaggregating ET fluxes down to finer scales (30m) using Landsat imagery available every 8 days (if using 2 Landsat satellites). In order to produce daily 30m ET maps, an algorithm is used to fuse the periodic 30m resolution Landsat ET maps of every 8 days with the daily 1-km MODIS imagery to create a continuous daily 30-m ET product[3]. This fusion algorithm used here is called the Spatial and Temporal Adaptive Reflectance Fusion Model (StarFM, see Figure 3).

[3] Semmens, K. A., Anderson, M. C., Kustas, W. P., Gao, F., Alfieri, J. G., McKee, L., ... & Xia, T. (2016). Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. *Remote Sensing of Environment*, *185*, 155-170.

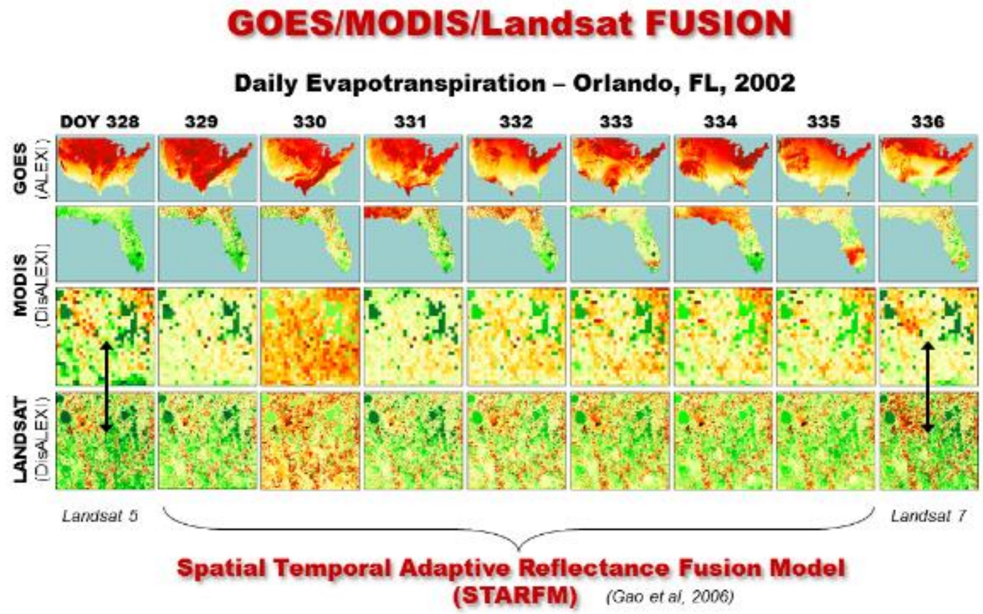


Figure 3. *Example of StarFM methodology applied in an Orlando (USA) selected area for 2002. Image courtesy of Dr. Martha Anderson (USDA-ARS Hydrolab). In this case both Landsat-5 and Landsat-7 data were used to retrieve daily ET.*

This method presents several advantages over other thermal-bases ET methodologies (e.g., SEBAL or METRIC) making it optimal to retrieve daily ET for large areas. The first advantage is the ability of this method to remove clouds when present in MODIS or Landsat imagery thanks to use of two training pairs from bracketing dates, generating a cloud free ET dataset. Another advantage is the use of ET retrieved from MODIS imagery when no Landsat image is present, allowing continuous time series of ET without having to use reference ET as SEBAL or METRIC do.

Figure 4 shows intermediate products of the DisALEXI and StarFM approach (including ALEXI ET product at 4km, MODIS NDVI at 1km, Landsat 8 Land Surface Temperature at 30m, and Landsat 8 NDVI at 30m), and Figure 5 is an example of the final daily ET maps at 30m resolution obtained. If integrated in a database, one can query a specific cell within a field and extract its time-series of ET throughout the year, as displayed in Figure 6.

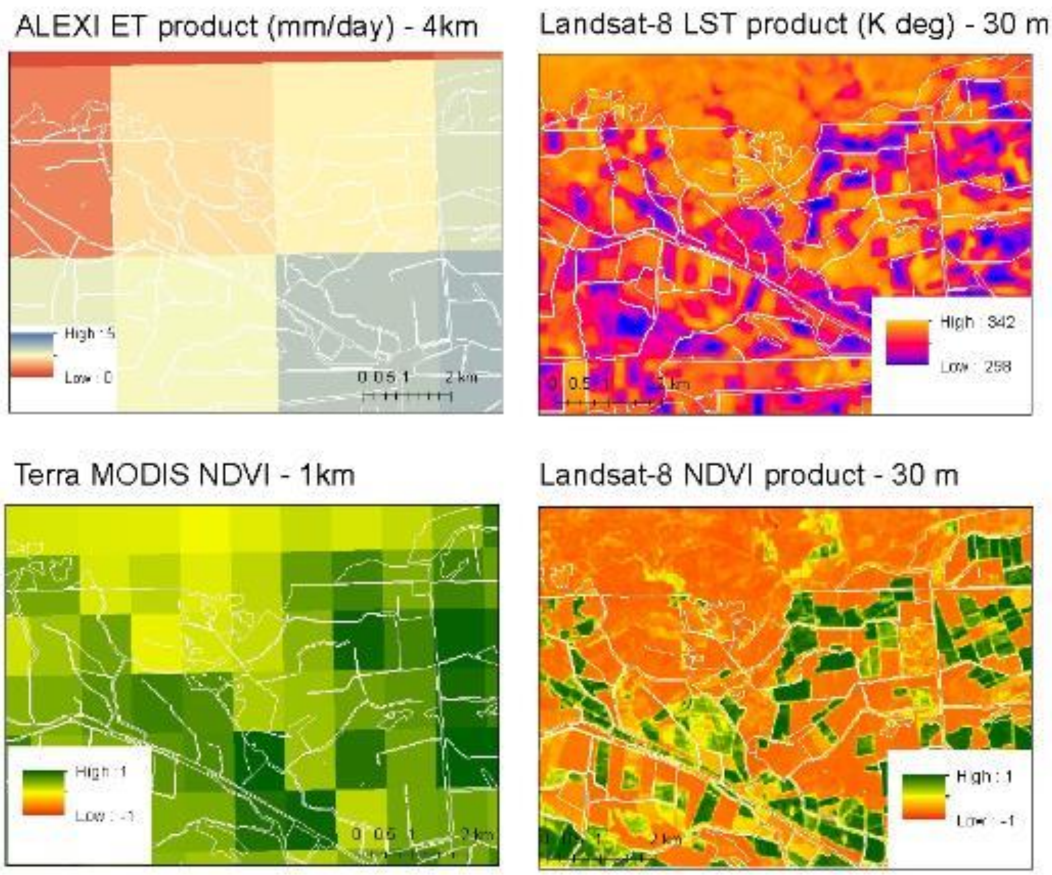


Figure 4. *ALEXI daily ET (mm day^{-1}), Terra MODIS NDVI, Landsat-8 Land surface temperature (K) and Landsat-8 NDVI for 08/07/2015. These are intermediate products used for the computation of continuous daily ET at 30m.*

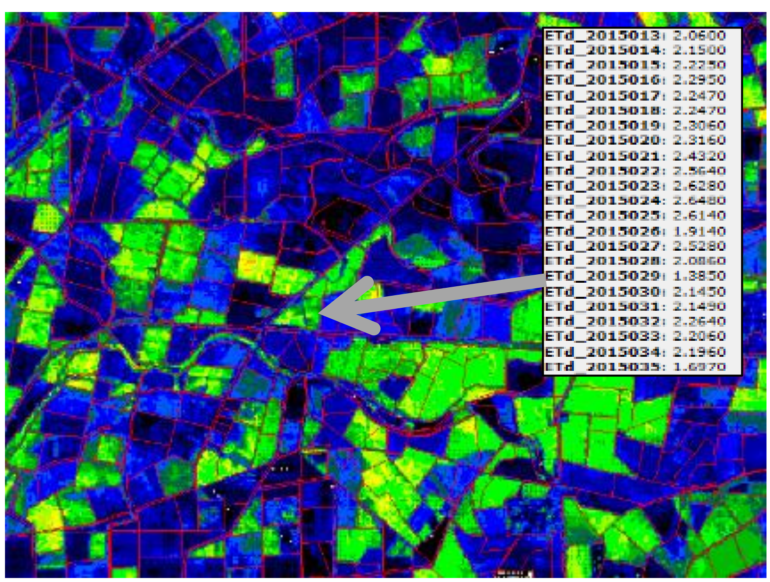


Figure 5. *An example image of daily ET (mm day^{-1}), with a dialogue window from a GIS platform displaying the daily ET values for a selected pixel, if the data produced by DisALEXI and STARFM is integrated within a GIS platform.*

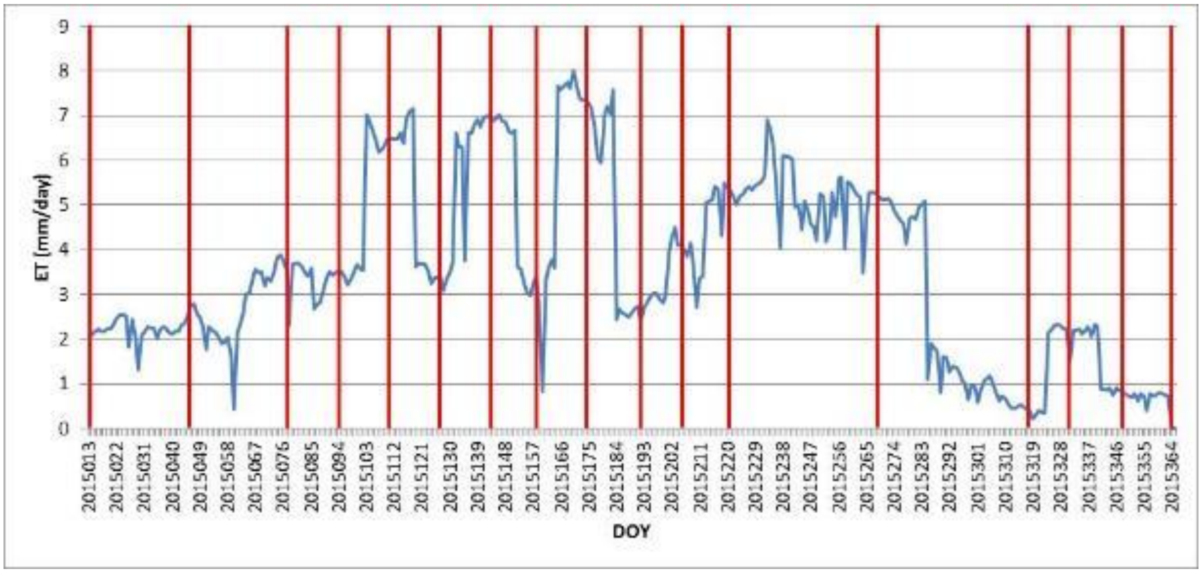


__Figure 6.__ Time series of daily ET (mm day^{-1}) computed using DisALEXI and StarFM for the above pixel. DOY is day of year. Red bars are days in which Landsat-8 imagery is available and cloud-free.

Crop Monitoring: the use of vegetation indices (VI) in the temporal mode is the best approach for separating cultivated areas from non-cultivated counterparts and monitoring the growing season. In this study we use the Enhanced Vegetation Index (EVI). The widely used Normalized Difference Vegetation Index (NDVI) is also a good choice, although the EVI index provides more sensitivity to vegetation activity, especially in high biomass situations. To build a time series of vegetation index images acquired on regular intervals, each image acquired is cloud screened, converted to an EVI image and stacked together (sorted by time). When combined, Landsat 7 ETM+ and Landsat 8 OLI observations provide an 8-day revisit period resulting in roughly 45 images per calendar year.

Having an accurate crop map showing the locations of individual crop fields and crop types over large areas is important as it conditions water requirements and thus irrigation decisions. Crops have well established cropping calendars that follow water and energy availability. At any point during the growing season, crops are at different stages of maturity, and these stages are manifested as differential levels of spectral reflectance in remotely sensed signals, thereby building a crop-specific temporal record. Hence, by monitoring spectral indices that are sensitive to vegetation cover over time it is possible to distinguish different crops from each other by monitoring each crop's growth stage such as sowing, emergence, flowering, senescence, and harvest. So in this analysis, the question of crop type mapping with remote sensing boils down to: 1) identifying growth cycles (i.e. phenology) of crop types that are considered important in the district with the help of experts in the region; and 2) relating temporal greenness information observed with remote sensing to these critical growth stages and label crop types (Figure 7).

In the case of district 14, we have simplified the crop types into four (4) major categories: spring crops (includes winter cereals such as wheat) which have the peak greenness in the spring period; summer crops (including cotton, vegetables and other crops) which have peak vegetative growth in the summer; alfalfa (which is a multi-seasonal crop and is distinguished in the field by periodic cutting events; and permanent crops (which are multi-year perennials with woody biomass and include date palms, citrus plantations and vineyards). The typical EVI profiles for each crop are shown in Figure 7 (left).

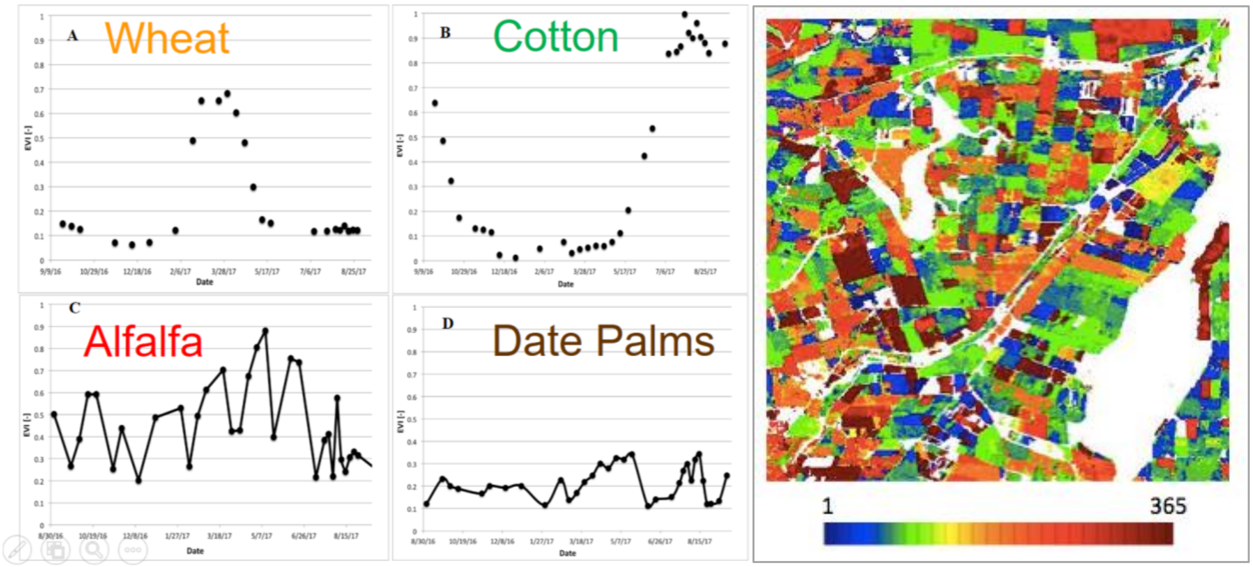


***Figure 7**. Left: Sample field scale temporal EVI signatures for selected crops in the district in the 2016/2017 growing season. A) wheat, B) cotton, C) alfalfa, and D) date palm plantation. Right: map of day of maximum EVI [1-365], which can be matched with crop type ETI evolution curves on the left.*

As different crops will have different peak vegetation (greenness) stages, it will be possible in many cases to map crop types by simply extracting the date of maximum EVI per year from the EVI time series for each pixel/field (Figure 7, right) and identifying crops of interest by their known date of peak greenness. Then, matching the known crop cycles to observed EVI temporal record for each pixel or field to make a map of "date of maximum" EVI observation, and matching these to known day of maximum VI values for the crop types of interest produces a crop type map with four major categories as shown in Figure 9.

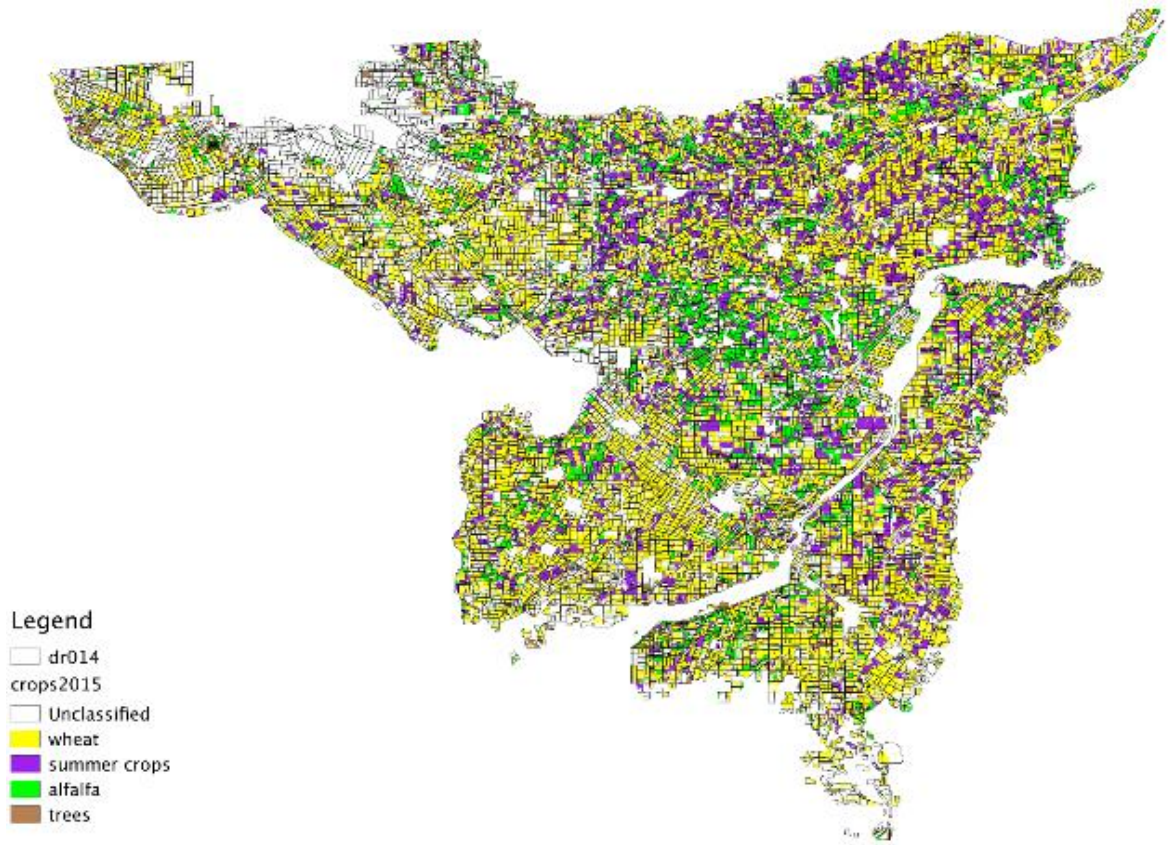
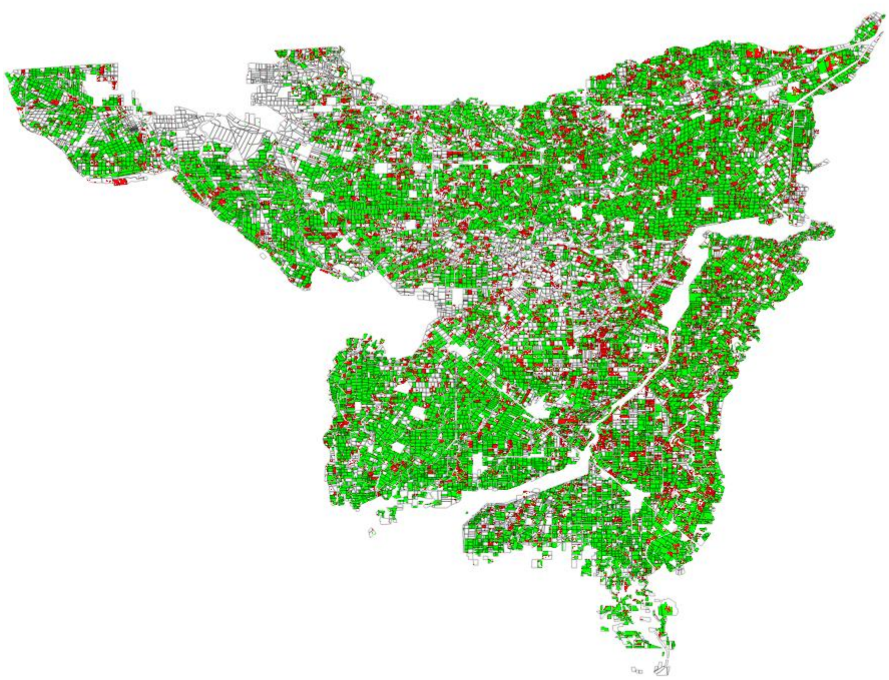


Figure 9. *Crop type map of District 14 in year 2015 overlaid with field/parcel boundaries. The map only shows four major crop type categories (wheat, summer crops, alfalfa, and tree plantations) used in this analysis.*



The temporal information of the vegetation indexes can also be used to determine if a single type of crop or double crops (winter cereals + summer crops) are cultivated, such as shown in Figure 10.

Figure 10. *Fields with single crops (green) and with double crops (red).*

Understanding Dynamics by Integrating Data: The integration of daily ET data, crop types, and vegetation index data within a database or GIS system with other types of information (soil texture, meteorological data) will enable cross analysis of cropping and water use in the district. Figure 11 shows an example of integration within a GIS database, displaying ET values averaged for each field, and an example of daily ET and EVI for a specific field plotted for 2015. A double cropping pattern can be observed, likely corresponding to wheat (or winter cereal) and cotton, as well as a clear lag between the first peak of vegetation and the peak of irrigation. While this information provides a unique spatial and temporal perspective, complementary ground information can then help understand the reasons for observed dynamics and see if water and crop management processes could be improved.

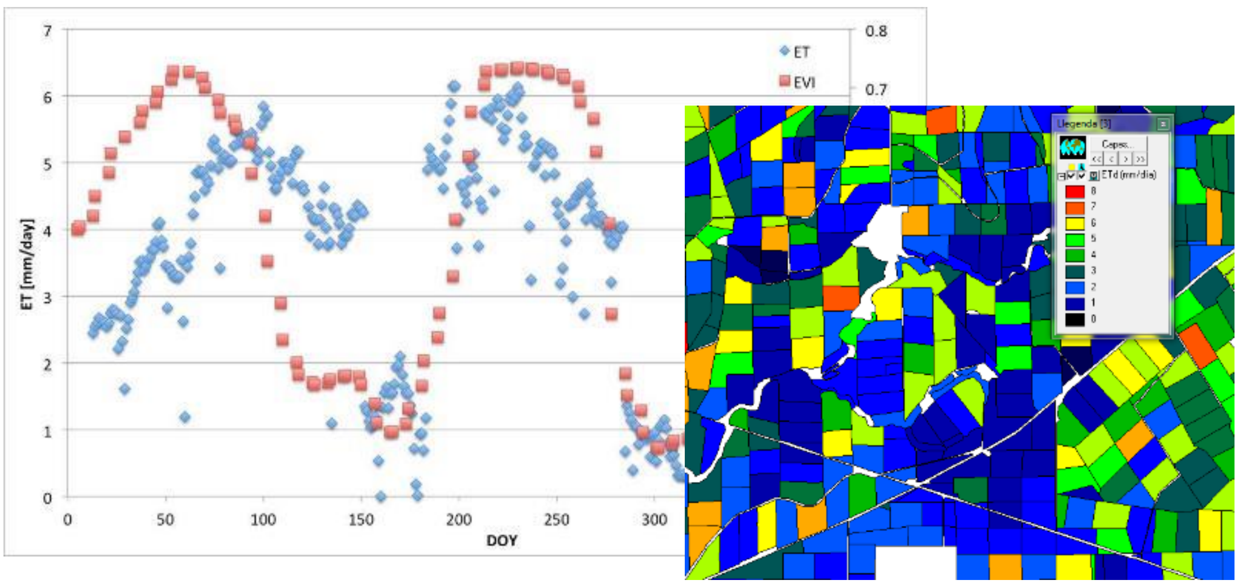


Figure 11. *Daily ET (mm day^{-1}) and EVI (Enhanced vegetation index) dynamics for a selected parcel of*

Operationalizing ET estimation: periodic and over large areas

While ET estimation has been done in the past in an inconsistent manner depending on project needs and availability of funding, typically in retrospect and for limited periods of time, capacity to produce operational field-scale (30m) ET estimates over large areas in a periodic and cost-effective manner has been lacking. It is the regular estimation of field-scale ET estimates at 30m, produced periodically as the growing season unfolds, that will provide an invaluable operational monitoring tool to irrigation districts and farmers.

Given this gap in the state of the art, the Remote Sensing Initiative has pushed forward efforts to develop capabilities for operational field-scale estimation of ET over large areas. The DisALEXI algorithm, one of the current cutting-edge models of ET estimation, has been translated to cloud language and implemented within Google Earth Engine (GEE), so that it can be run periodically over large areas taking advantage of the GEE public data catalog and the cloud's computing power (see Figure 12). Efforts are now focused on troubleshooting the implementation of the algorithm in the cloud environment and applying necessary adjustments, in order to proceed to the validation step of the newly implemented algorithm within GEE. Validation will be performed in two ways: (1) using the ET estimation over the Irrigation District 014 Rio Colorado presented in this chapter, computed outside the cloud; and (2) using other ET datasets over other areas of the Western US, including from the same algorithm offline as well as from some flux towers.

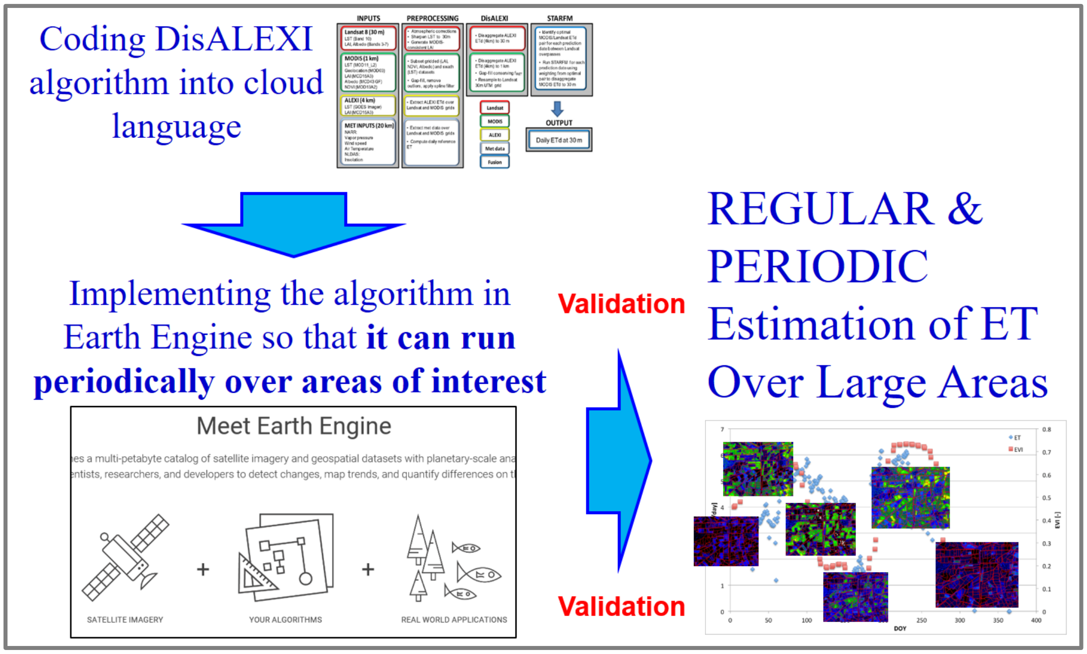


Figure 12. *Schematic illustration of the implementation of DisALEXI algorithm into Google Earth Engine to operationally produce field-scale ET estimation over large areas.*

The operational 30m resolution ET estimation capabilities are expected to be functional soon and will be able to assist and inform Irrigation Projects across the globe with regular and periodic estimation of ET at the field scale over large areas.

To put our efforts in a wider context, we have coordinated with other experts and partners at NASA, US Department of Agriculture, Univ. of Wisconsin-Madison, Desert Research Institute, Environmental Defense Fund, Google, and others, to contribute the DisALEXI cloud algorithm to the *OpenET Framework Project*, which will implement all of the main field-scale ET algorithms (METRIC, SEBAL, DisALEXI, SSEBop, etc) to run in a cloud environment, and available in an open-source multi-model platform of ET estimation, thus allowing periodic ET estimation at field level through not only one, but several different methods. Through a number of conference calls and email exchanges with donors and the above partners, the Remote Sensing Initiative has supported a consortium of partners in securing funding from private foundations.

Initially the geographic focus of the OPEN ET Framework Project was on the Western US, but the Remote Sensing Initiative team expressed the need to open it to international case studies in the near future. Given the Initiative's efforts in the Rio Colorado Irrigation District, and its geographical proximity to the Western US, it is an appropriate first international case study. The Initiative therefore invited two members of the above consortium of partners to join the Bank mission to Mexicali and the Irrigation District that took place the third week of September 2017. As a result, the I.D. 014 in Mexico will become the first international case study of the OpenET Framework in the future.

Aside from the contributions to these broader efforts, which are still underway, the Remote Sensing Initiative already produced the first cloud-computed ET estimates over the Irrigation District (in process of validation) using our implementation of DisALEXI within the Google Earth Engine environment (Figure 13). As validation and beta-testing of operational estimation of ET continue, the next steps with CONAGUA and the Irrigation District, which are excited to continue these efforts, are as follows: CONAGUA and the Irrigation District will select a *Modulo* (the I.D. is subdivided into 22 Modulos) or a study area of a few fields, for which they will provide ground data. These data will include (a) the formal sowing permits of each field within the Modulo or study area, issued each year once the farmer declares what he will plant (tying the field to a water requirement, linking agriculture with water use); (b) official figures of water deliveries to the fields, registered and available at each Modulo administration (irrigated area and water volume that was charged); (c) available meteorological data, including atmospheric ET demand, and soil data. Combining the ground data available and the remote sensing data presented above, a joint analysis will be developed to help close the water balance at the field scale, understand cropping and water use dynamics, and integrate the operational production of ET and crop monitoring data within the District and CONAGUA's operations.

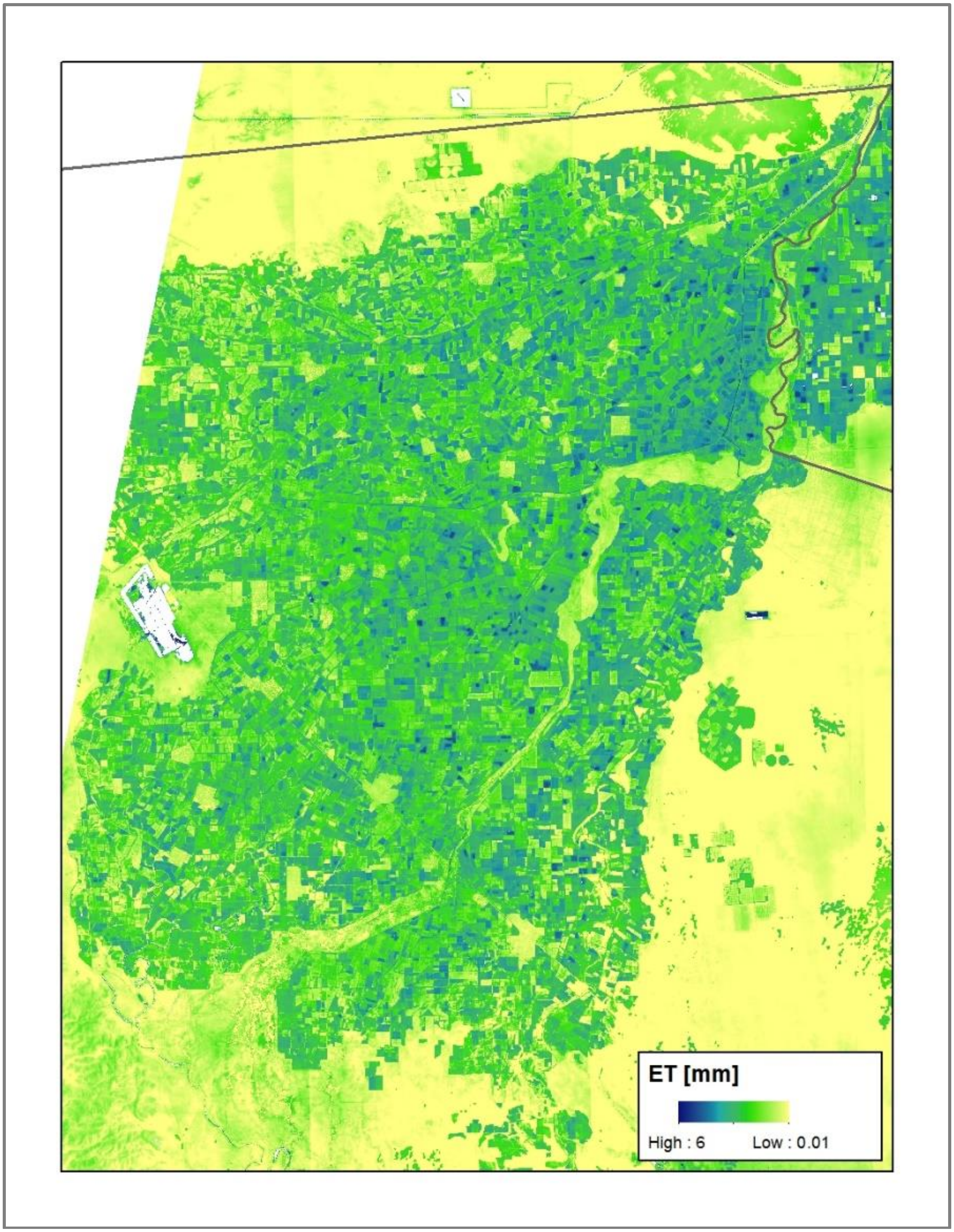


Figure 13. *Illustration of the first image of ET estimation produced by the implementation of DisALEXI in Google Earth Engine, in course of validation.*

Adopted approach for a successful implementation: The goals of the ET and crop monitoring efforts within Mexico were many, including: demonstrating that remote sensing of ET can be a reliable estimation of consumptive water use, showing the advantage of combining ET with other types of observations, retrospective analysis over irrigation districts, and devising ways to systematize a periodic or continuous-in-time estimation of ET for the client and the beneficiary project.

1. Pushing the Boundary of Operationalization: while the estimation of field-level ET has been common in the past, it is an intensive data processing application, requiring of complex algorithms, high-level know-how, a range of RS images and data, and computational power. Thus it has often been applied as discrete one-at-a-time studies and has been difficult to produce for large areas or operationally in the past. However, advances in IT are allowing us to push the envelope and start breaking that frontier.
2. Google Earth Engine Implementation: working in collaboration with USDA and the Desert Research Institute and the developers and producers of one of the most advanced ET products, (ALEXI, and its higher resolution algorithm DisALEXI) the team has been making progress on the implementation of the DisALEXI high resolution algorithm within Google Earth Engine to be able to periodically produce field-scale (30m) ET estimates over large areas, in the cloud. This requires several steps: the systematic uploading of the 5km resolution ALEXI product in GEE, leveraging other data and imagery already in GEE such as LANDSAT and other, and the coding of the high resolution ET algorithms in python and java-script (the languages of GEE) to be able to systematically produce high-resolution field ET estimates.
3. A High-Impact Effort: The above application will enable the periodic computation of field-level ET estimates over large areas in the cloud, in an operational manner. The RS initiative has spearheaded and pushed forward these efforts by aligning the above contribution with key partners that see the potential for high impact starting in the very short term. This work is contributing to a broader effort with our partners to have all the main ET estimation algorithms in the cloud and running operationally with a user interface to allow easy access from end users. This application will allow client country agencies to access field-scale ET estimates periodically without the need to invest significant human and financial resources for isolated ad-hoc studies.
4. Partner interests and synergies: External partners to this efforts are vested in these efforts and will continue to support them financially, as they will be a common good for the practitioner and user communities.

The detailed report on ET and crop monitoring for the Irrigation District 014 *Rio Colorado*, Mexico, can be found in Annex 1.

4.2 - Operational Hydrometeorological Monitoring – Rio Salado (Argentina) and Lake Chad

Hydrometeorological monitoring refers to the regular measurement and assessment of key variables relevant to the fields of hydrology and meteorology. Satellite remote sensing is a promising source of hydromet data, as it allows monitoring of the hydrological cycle at the land surface as well as of the state of natural vegetation and agriculture in near-real time[4], complementing available ground data. This remote sensing data can then be used to force a land-surface hydrologic model in near real-time, enabling the prediction of output variables such as runoff and streamflow in rivers. In addition, one can use weather forecasts of the next few days (i.e. 7 to 14 days for NOAA's Global Forecasting System, GFS) and seasonal forecasts of the next 9 months, to extend the precipitation inputs and the hydrological model simulations into the future, producing a forecast. The Africa Flood and Drought Monitor (AFDM)[5] and the Latin American Flood and Drought Monitor (LAFDM) are examples of operational hydromet monitoring and prediction systems using historical data, near real-time remote sensing data, precipitation forecasts (short term and seasonal) and a land-surface model, producing useful data at different time horizons relevant for a range of planning and management tasks.

Within the Remote Sensing Initiative and building on the experience of the above AFDM and LAFDM, we have developed two higher-resolution monitoring and prediction platforms: The Lake Chad Flood and Drought Monitor and the Salado Flood and Drought Monitor. The detailed report of the Lake Chad and Salado Flood and Drought Monitors can be found in Annex 4.

The Lake Chad Basin is an endorheic basin of about 2,300,000 km^2 expanding over Niger, Nigeria, Cameroon, Chad, and Central African Republic. Mean annual precipitation ranges from less than 50 mm in the arid north of the basin to over 1,000 mm in its subtropical south, with evapotranspiration potentials are of 2,200 mm. The lake itself is shallow – only 10.5 meters at its deepest – which makes it size very susceptible to seasonal and interannual fluctuations in streamflows. Over the course of the past decades, the lake area has varied significantly from over 22,000 km^2 in 1960 to about 1,700 km^2 in 1985, and has since that time increased again to an average of approximately 8,000 km^2 during the 2000-2015 period. The variability in the Lake's size is due to rainfall fluctuations, particularly in the basin of the Chari-Logone River, which accounts for about 85 percent of water inflows to the Lake. The size of the Lake has important implications for livelihoods (fishing, livestock and agriculture). The Basin is poorly instrumented and the Boko Haram conflict and lack of funding makes it impossible to do ground monitoring.

The Salado River Basin has a total area of 170,000 km2 and covers half of the Province of Buenos Aires. With over 1.4 million inhabitants, this highly productive basin generates 25-30 percent of

[4] Sheffield, J., Wood, E. F., Chaney, N., Guan, K., Sadri, S., Yuan, X.,… & Ogallo, L. (2014). A drought monitoring and forecasting system for sub-Sahara African water resources and food security. *Bulletin of the American Meteorological Society*, *95*(6), 861-882.

[5] Sheffield, J., Wood, E. F., Chaney, N., Guan, K., Sadri, S., Yuan, X., ... & Ogallo, L. (2014). A drought monitoring and forecasting system for sub-Sahara African water resources and food security. *Bulletin of the American Meteorological Society*, *95*(6), 861-882.

Argentina's grain and meat production, contributing significantly to the country's exports and global food security. The Salado River is 640 km long and has an average flow of 80 m3/s. It is a lowland river and its basin is characterized by a flat relief, poor natural drainage, and land use is dominated by extensive agriculture and livestock, with significant wetlands including a RAMSAR site. Being so flat, hydrological processes are mainly vertical and the water balance is controlled by precipitation and evapotranspiration. Flooding generally occurs by infiltration, saturation and ponding of water, resulting in long-lasting and widespread flooding. A significant increase in flood frequency and intensity has been observed in the Salado Basin since the 1980s. In 2015, the highest observed rainfall ever in the basin flooded over 800,000 ha and killed 6,000 cattle. This large basin is also poorly gauged.

Information to Decisions Context:

The Lake Chad Basin Commission (LCBC) is the Basin Organization which has the mandate to implement the Water Charter, a binding framework for promoting sustainable development in the Basin through the integrated, equitable and coordinated management of natural resources, in particular the basin's water resources. The development of the regional Lake Chad Flood and Drought Monitor aims to support the LCBC in fulfilling the following Water Charter related tasks:

a. Monitoring and analysis of the hydrologic system and its components (rainfall, ET, streamflows, soil moisture, vegetation).
b. Monitoring the hydro-ecological status of the basin in real time and in the context of short term and seasonal forecasts.
c. Manage all relevant information among member states through a water resources information management system (Hydro-meteorological information, model results, abstraction caps by sub-basins, water uses, practices impacting quantity and quality, new interventions and projects).
d. Support evidence-based decision-making for a good management of water resources in the Lake Chad Basin.

In the Rio Salado Basin, the two provincial agencies tasked with water management are the *Agencia del Agua* (ADA) and *Demarcación Provincial de Obras Hidráulicas* (DPOH). The development of the Salado Flood and Drought Monitor aims at supporting information needs for the Integrated Salado Basin Plan and for flood prediction, through basin-wide near real-time monitoring of hydromet variables and the points above.

Methods and Results:

The Lake Chad and Salado Monitors build on the AFDM and LAFDM system, developed over many years. The system estimates water availability (primarily flood potential and drought conditions) through a combination of hydrological modeling, satellite remote sensing, short term and seasonal climate forecasts. It draws from the long legacy of operational and experimental systems developed for the U.S. by the Terrestrial Hydrology Group at Princeton University (Luo et al., 2007)[6] that was developed within the North American Land Data Assimilation System Phase 2 (NLDAS-2; Xia et al., 2012[7]) and the NCEP Climate Test Bed program.

The system consists of three parts (Figure 14): First, a historic, multi-decadal reconstruction of the terrestrial water cycle is obtained by forcing hydrological models (currently the Variable Infiltration Capacity (VIC) land surface hydrological model) with a merged reanalysis/observation data set. This forms the climatology against which current conditions are compared. Second, the real-time monitoring system (2009-present) is driven by a precipitation data set and atmospheric analysis data that tracks flood and drought conditions in real-time. The simulated outputs are augmented by satellite remote sensing of soil moisture and vegetation indices. Third, a 7 day forecasting component provides hydrological forecasting of floods and water availability, and a seasonal forecast component provides hydrological predictions and derived drought products out to 6-months, based on bias-corrected and downscaled climate model forecasts that are used to drive the hydrologic and impact model.

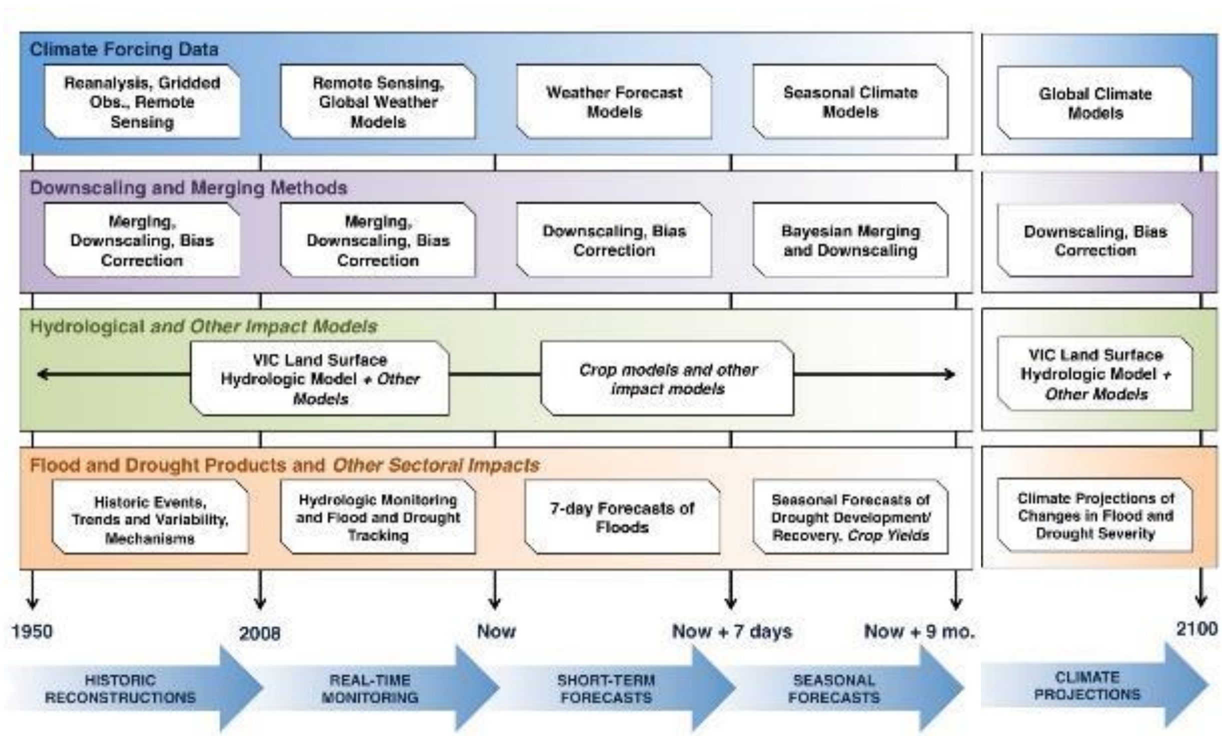


Figure 14*. Flow chart of the Drought Monitor and Forecast Systems. A system comprises three parts: 1) Historic reconstructions of the terrestrial hydrological cycle that is derived from simulations of the VIC land surface model forced by a hybrid reanalysis-observational meteorological dataset. The datasets are used for a variety of*

---

[6] Luo, L., E. F. Wood, and M. Pan, 2007: Bayesian merging of multiple climate model forecasts for seasonal hydrological predictions, *J. Geophys. Res.*, 112, D10102, doi:10.1029/2006JD007655

[7] Xia, Y., K. Mitchell, M. Ek, J. Sheffield, B. Cosgrove, E. Wood, L. Luo, C. Alonge, H. Wei, J. Meng, B. Livneh, D. Lettenmaier, V. Koren, Q. Duan, K. Mo, Y. Fan, D. Mocko, 2012: Continental-Scale Water and Energy Flux Analysis and Validation for the North-American Land Data Assimilation System Project Phase 2 (NLDAS-2), Part 1: Intercomparison and Application of Model Products. *J. Geophys, Res.*, Vol. 117, No. D3, D03110, http://dx.doi.org/10.1029/2011JD016051

applications including analysis of historic drought events, estimation of trends and variability, and investigation of drought mechanisms. 2) Real-time monitoring component that updates the model run to 2-3 days from real-time forced by bias-corrected and downscaled merged in-situ, satellite and reanalysis fields of precipitation (MSWEP: Beck et al., 2017[8]; Beck and Wood, 2017[9]), and GFS analysis fields of temperature and windspeed. There is also potential to force other impact models such as crop models. 3) Seasonal hydrological forecast component that uses bias-corrected and downscaled CFSv2 climate forecasts of precipitation and temperature to drive the model and provide ensemble predictions of drought conditions, for precipitation, soil moisture and streamflow. Existing components are shown in normal font, and potential future components in italic font. (from Sheffield et al., 2014[10].)

The monitor is set up as an internet application with an easy to use user interface and dashboard (see Figure 15), and data provided under the major sections are shown in Figure 16.

Figure 15. *User interface for the flood and drought monitors. Image shows precipitation over Latin America for September 26,2017.*

The strengths of the system are as follows:

1. The system is tailored for users, and designed for ease of use. The web-based interface allows extremely easy access for users. The systems are offered in multiple languages including Spanish and French, which we believe enhances their usefulness for local users in Argentina and the Sahel region of Africa. No other system includes the range of languages (English, French, Portuguese, Chinese and Arabic) offered in the systems
2. The LAFDM and the AFDM systems are the only internet-based data and analytics platform available that provides water information from in-situ, satellite, and modelling systems across all

---

[8] Beck, H. E., van Dijk, A. I. J.M., Levizzani, V., Schellekens, J.,Miralles, D. G.,Martens, B., and de Roo, A. 2017. MSWEP: 3-hourly 0.25_ global gridded precipitation (1979–2015) by merging gauge, satellite, and reanalysis data, Hydrology and Earth System Sciences, 21, 589–615.

[9] Beck, Hylke E. and Eric F Wood 2017 MSWEP V2 global precipitation (3-hourly 0.1): methodology and quantitative appraisal, *submitted.*

[10] Sheffield, Justin, Eric F Wood, N Chaney, K Guan, S Sadri, X Yuan, L Olong, A Amani, A Ali, S Demuth and L Ogallo. 2014. A drought Monitoring and forecasting system for sub-Saharan African water resources and food security. *Bull. Am. Meteor. Soc.* 95(6):861-882. June.

time scales in a consistent manner. As shown in Figure 14 and 16, the data is provided from historical data sets, to near real-time monitoring, 7-day forecasting and seasonal forecasting, all at a 0.25° (~25 km) spatial resolution. This holistic perspective allows users to fully understand current conditions within a framework that includes historical as well as future (forecasted) conditions.

3. Users have the opportunity to download available data in different formats, with the user specifying the location for point data and the region for spatial data. This would allow the user to interface their application models to the system.
4. It is seamless to download both remote sensing data (e.g. satellite TMPA precipitation and SMAP soil moisture) and model analysis fields from the systems. For users, downloading NASA satellite data is extremely difficult due to their different file formats, product file specifications (e.g. in tiles and some in swaths), and archived in locations.

Further details of the continental-scale flood and drought monitors can be found in Sheffield et al. (2014)[5].

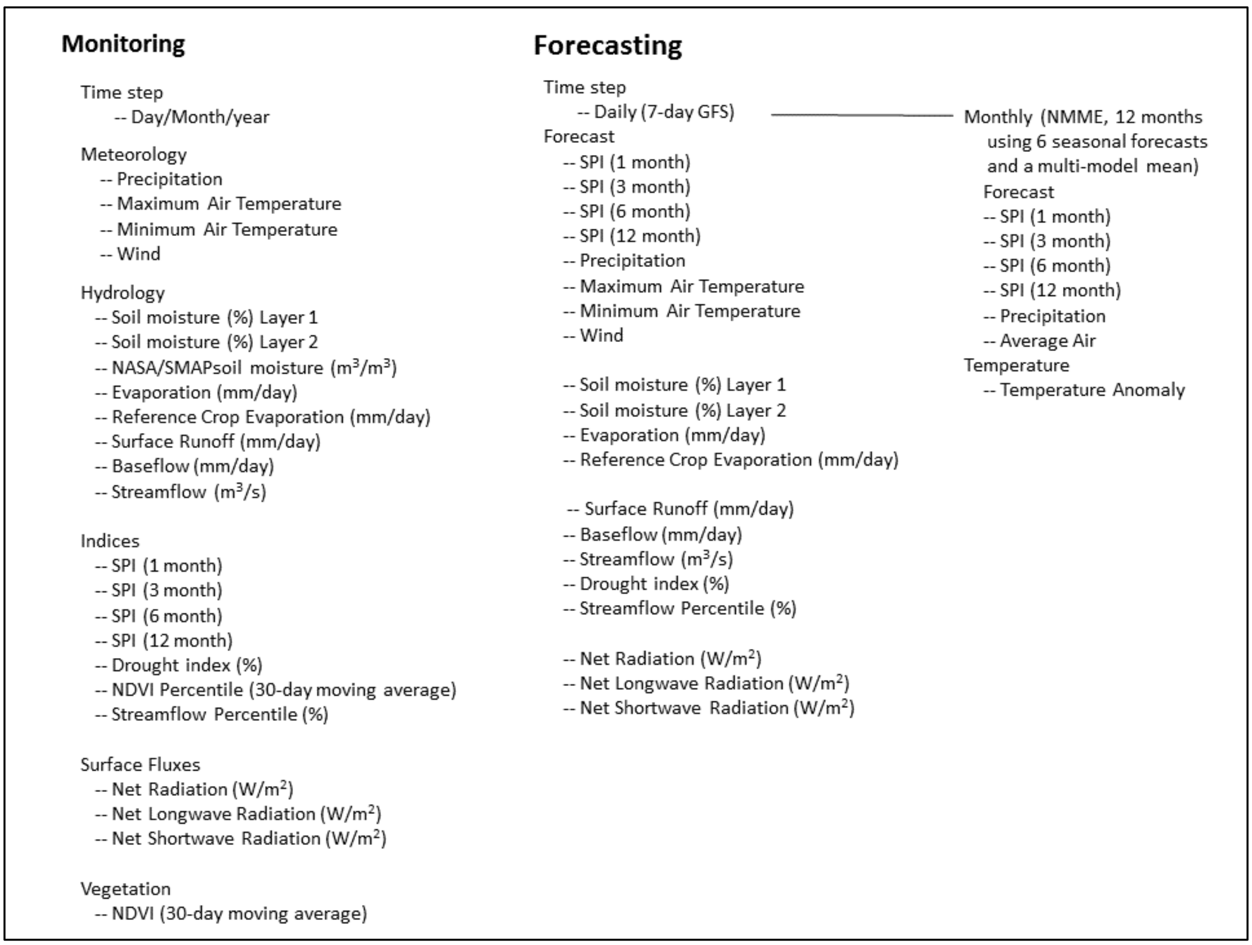


Figure 16. *Available data in the flood and drought monitors.*

The Lake Chad Flood and Drought Monitor and the Salado Flood and Drought Monitor use the same framework as the continental systems, so the structure and advantages of the continental systems are available to the regional systems. Due to time and effort constraints in the project, not all features are currently implemented, but they will be during future efforts.

The effort for the systems included (i) increasing the spatial resolution of the regional monitors; (ii) using historical and upgraded data to fine tune the hydrological modelling system; and (iii) Improving the calibration of the hydrological model by using data provided by World Bank client partners in the Province of Buenos Aires (for Rio Salado) and the Lake Chad Basin Commission (for Lake Chad). As local data for calibration was not available, data from the Global Runoff Data Centre (GRDC) and other sources available to the study were used.

The following improvements to the regional systems were achieved:

1. The spatial resolution was increased to 5km for the Rio Salado Monitor and to 10 km for the Lake Chad Monitor. This was accomplished by upgrading three aspects: the forcing precipitation data, the soil properties and the vegetation land cover.
2. A new precipitation data set was incorporated into the regional monitors that merges improved historical data, a large suite of satellite precipitation products, and weather model analysis information. This is discussed further in a section below.
3. Improved soil and land cover was incorporated into the hydrological model. The soil data comes from 'SoilGrids' dataset and the improved land cover from the GlobeLand30 dataset. These are further discussed below.

Figure 17 shows the internet user interface (dashboard) for the two regional systems showing precipitation on the specified dates. Note that the Lake Chad system includes a separate section for monitoring the lake itself.

To increasing the hydrologic resolution of the regional monitors, efforts were focused on improving the precipitation forcing. Thus, version 2 of the *Multi-Source Weighted-Ensemble Precipitation (MSWEP) data set* (Beck and Wood, 2017b[11]) that significantly enhances version 1 (Beck et al., 2017a[12]) was developed. The MSWEP dataset is a precipitation product (1979–present) recently completed for use in the new regional systems, with the potential to be used globally. The new (and unique) features include: a product that (i) optimally merges an unprecedentedly broad range of gauge, satellite, and reanalysis precipitation products; (ii) has a high spatial (0.1°) and temporal (3 hourly) resolution; (iii) provides a fully global coverage; (iv) corrects for distributional precipitation biases by probability matching; (v) corrects for long-term terrestrial precipitation biases using discharge observations from 13,762 stations around the globe; (vi) incorporates daily (rather than monthly) gauge observations from 66,993 gauges around the globe; and (vii) accounts for regional differences in the 24-hour accumulation period of gauges. A near real time extension has also been developed and is available to real-time versions of the regional systems. We are confident that MSWEP provides the best precipitation data set for the monitors. When local gauge data are available, they can be easily merged into

[11] Beck, Hylke E. and Eric F Wood 2017 MSWEP V2 global precipitation (3-hourly 0.1): methodology and quantitative appraisal, *submitted.*

[12] Beck, H. E., van Dijk, A. I. J.M., Levizzani, V., Schellekens, J.,Miralles, D. G.,Martens, B., and de Roo, A. 2017. MSWEP: 3-hourly 0.25_ global gridded precipitation (1979–2015) by merging gauge, satellite, and reanalysis data, Hydrology and Earth System Sciences, 21, 589–615.

MSWEP, shifting the weights towards the in-situ data from their increased availability. The implemented version of the regional monitors use MSWEP version 2.

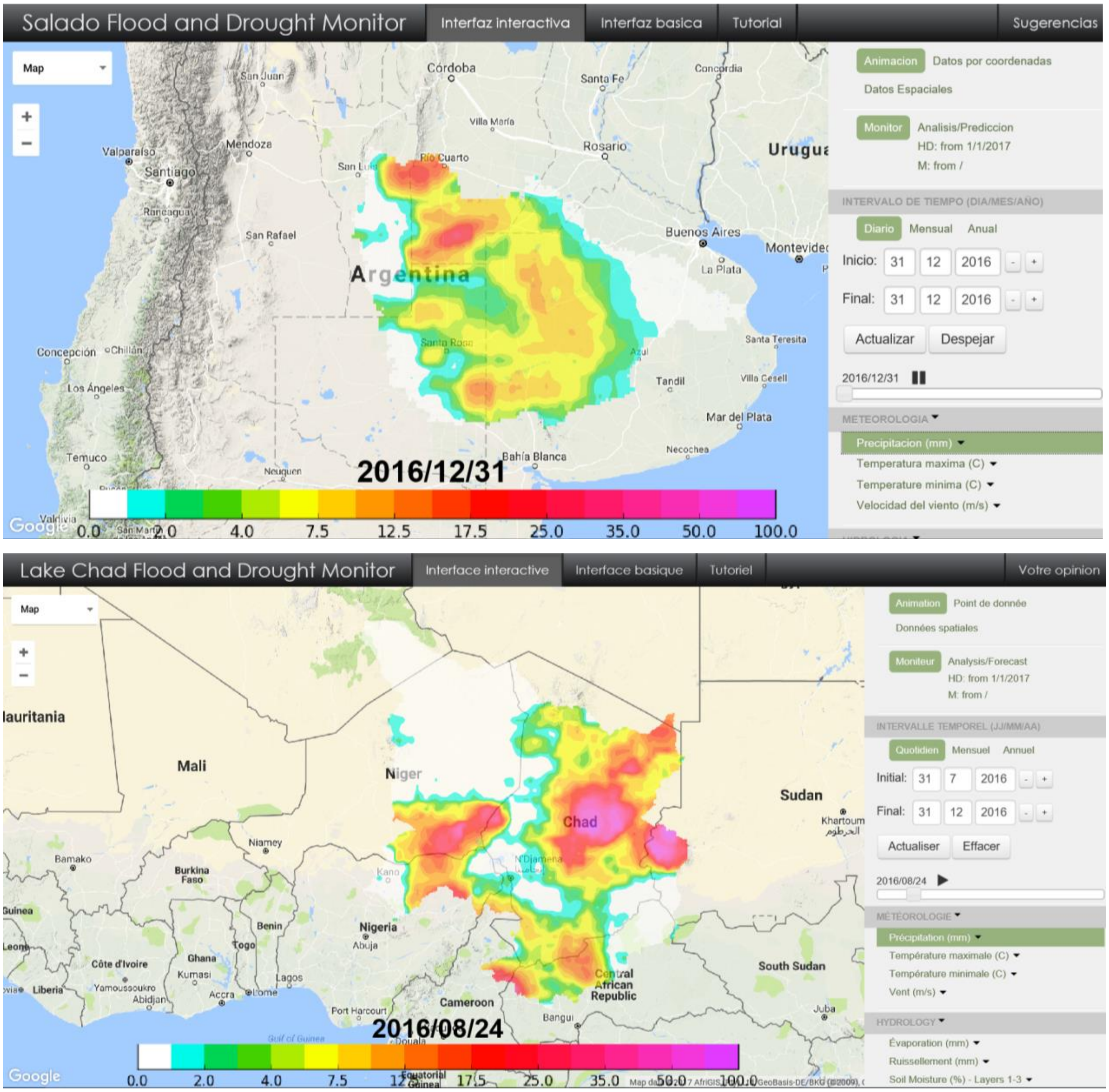


Figure 17. *Internet user interface for the regional Rio Salado basin (top panel) and Lake Chad basin (lower panel).*

The updated soil data in the regional monitors is from SoilGrids, a global collection of updatable soil property and class maps with a spatial resolution of 250 meter (Hengl et al., 2017[13]). Soil

[13] Hengl T, et al. (2017) SoilGrids250m: Global gridded soil information based on machine learning. PLoS ONE 12(2): e0169748. doi:10.1371/journal.pone.0169748.

properties are available from the SoilGrids datasets (ftp.soilgrids.org), and soil texture data was converted into soil hydraulic properties needed by the land surface model and coarsened to 5*km.* The land cover data is obtained from GlobeLand30, which is the world's first open-access, high-resolution maps of land cover covering the globe (Chen et al., 2015[14]). It is generated using an algorithm drawing from more than 20,000 Landsat and Chinese HJ-1 satellite images. The spatial resolution is as high as 30 meter × 30 meter, but for the regional systems, the land cover is aggregated into tiles of different land cover types at the 5*km* modeling grid scale.

Adopted Approach for a Successful Implementation: In order to provide the Agencia Del Agua (ADA, Argentina) and the Lake Chad basin Commission (LCBC, Lake Chad) with operational near real-time monitoring, hydrologic prediction capabilities, and weather and seasonal forecasts, given their current context of low technical and human capacity, the following was done:

1. Starting from basic but operational: Building on past efforts, a continental low-resolution but operational near real-time monitor was taken as a starting point and tailored for the regions by incorporating ground data, additional datasets and increased resolutions.
2. Co-development: The development of the continental applications had previously benefitted from various UNESCO-sponsored regional workshops with river basin organizations and country representatives. For the development of the regional monitors, discussions with the bank team as well as the clients, took place. These included two workshops: one in Buenos Aires, and one in Paris with Lake Chad Basin Commission Representatives, to gather feedback on the monitors. In coordination with other partners, trainings and user-driven validation will continue to take place.
3. Analysis-ready data and good access: the application brings together a range of datasets (otherwise hardly accessible to the end user) and processes them into readily useable products. Intuitive web interface, and open access.
4. Hybrid functionality approach: the platform will be run operationally in Princeton (with online web access) but also available to be installed within the client agencies. This will ensure functionality and internet connectivity for the application at all times to periodically download and process raw data (very poor connectivity in Chad) so that the client can visualize the variables of interest, evolutions over time, and download the data as needed. This approach has been successfully implemented by the AFDM/LAFDM team in installing such data centers in Niamey, Nairobi and Harare in conjunction with UNESCO.
5. Connection with Regional Efforts and Knowledge Networks: this effort has been carried out in synergy with UNESCO who is invested in this process going forward to continue updating the monitors and training the clients, in collaboration with regional centers like *AGRHYMET* (Niamey, Niger, serving 11 states in West Africa) and the regional *Center for Hydroinformatics* in Asuncion (Paraguay).

The detailed report of the Lake Chad and Salado Flood and Drought Monitors can be found in Annex 4.

[14] Chen J, et al. (2015) Global land cover mapping at 30 m resolution: A POK-based operational approach. Isprs Journal of Photogrammetry and Remote Sensing 103: 7-27.

4.3 – Flood extent monitoring and analysis – Rio Salado (Argentina)

Flood extent is very difficult or impossible to document from the ground, and satellite imagery provides a natural vantage point. Using imagery from the last 30 years, we can map the extent of historical flood events and derive flood risk maps (i.e., maps with the probability of occurrence of flooding in each location) and estimating socio-economic vulnerability to floods. Population data and other socio-economic information is then used to estimate the number of people and economic assets exposed to flooding. This can then be used to inform land use planning decisions, designing infrastructure, defining floodable riparian zones as buffers, risk mitigation and disaster response interventions.

The approach used in the Rio Salado combines multiple satellite sensors, parallel cloud computing (Google Earth Engine - GEE), and flood detection algorithms. The past floods of the Rio Salado Basin were mapped, documenting the extent, the duration and frequency of flood water for each pixel, as observed by the satellites, and provided a comprehensive assessment of flood exposure. This was used to produce a flood risk map at 250 and 30m resolutions displaying areas with associated return periods of flooding, from seasonal flooding (likely floods each year) and up to a 5-year return period (likely floods once every 5 years). The results reveal where the major floods have occurred in the watersheds, how long these events lasted, how their extent changed throughout the flood, how extreme flooding compared to frequent seasonal inundation, and the return period flood extent estimates based on the past 30 years. Also, the team produced composites from this full history of flooding to reveal spatial and temporal patterns in flood exposure over the last several decades. Third, this project provided access to a cloud-based database for the maps and a user-friendly online dashboard that visualize all the floods and analytics. The detailed report of this case study application can be found in Annex 3.

Information to decisions context:
The two agencies in the Buenos Aires province are the *Agencia del Agua* (ADA) and the *Demarcación Provincial de Obras Hidráulicas* (DPOH) and they have several flood-related management decisions that can benefit from the information presented here. These are:

e. Land use planning (“*Ordenacion del Territorio”*): spatial flood risk information is essential to plan future land use zoning and development. This includes many dimensions:
    - Establishing the “*linea de ribera”* and the *“mancha media”*: the establishment of this water line separates federal riparian public land (the river and adjacent frequently flooded areas, the “average floodplain”) from private land. A high resolution (30m or 10m) and somewhat statistically robust historical sample is necessary for a fair characterization, and is better enabled by remote sensing.
    - Wetland identification: the mapping, restoration and preservation of wetlands is a priority in the basin aimed at creating flood buffer areas that can retain water during flooding. While the Argentine law definition of “wetland” would define the entire basin as a wetland, the ADA needs a new definition that is

practical for the Basin. Based on the results below, we suggest using a characterization combining the frequency (T=2) and the duration of flooding

f. Designing of hydraulic structures and impact monitoring: understanding flood extents and duration will inform the design of new measures. Satellite images will also help monitor new flood dynamics after project implementation (such as in the current Bank project).
g. Informing tax policy: when 80% of their cropped area floods, farmers benefit from tax breaks, and thus dynamic flood maps can be used as evidence and basis for executing tax policies.

The ADA said they would use this tool to aid land use planning, define the water shoreline (*linea de ribera*), and use the 2 year floodplain as a key variable to include in characterizing wetland extent for the Basin. A follow-up workshop in 6-10 months could give additional support of how to best use the data and tool to achieve these goals. In particular, the engineers identifying the wetland area for expropriation were interested in doing additional analysis with SPOT imagery (5m resolution, private data source ADA can access due to MOU with French government). This dataset could be included into the dashboard presented below and detect floods systematically with Earth Engine, as well as training them how to use the API themselves.

Methods and Results: Google Earth Engine brings together the full libraries of MODIS and Landsat to provide the computational power to integrate these products over the historical stack of imagery. Each of these sensors has different advantages and disadvantages for flood detection as compared to the others. Flood detection algorithms for the two sensors were run for each event over the past 30 years in the flood database and for the full basin. Some of the spatial information produced is as follows:

- Flood detections at a 250m (MODIS) and 30m resolution (Landsat) for ~40 major events over the past 30 years, including: 1) area and population exposed calculated for each event and satellite at district and basin level, 2) duration of the flood in # days calculated (for MODIS detections only), 3) number of "clear views" percent per pixel as a data quality metric, and 3) hyetographs (rainfall over time) for each flood event mapped to compare Landsat image dates with storm date intensity.

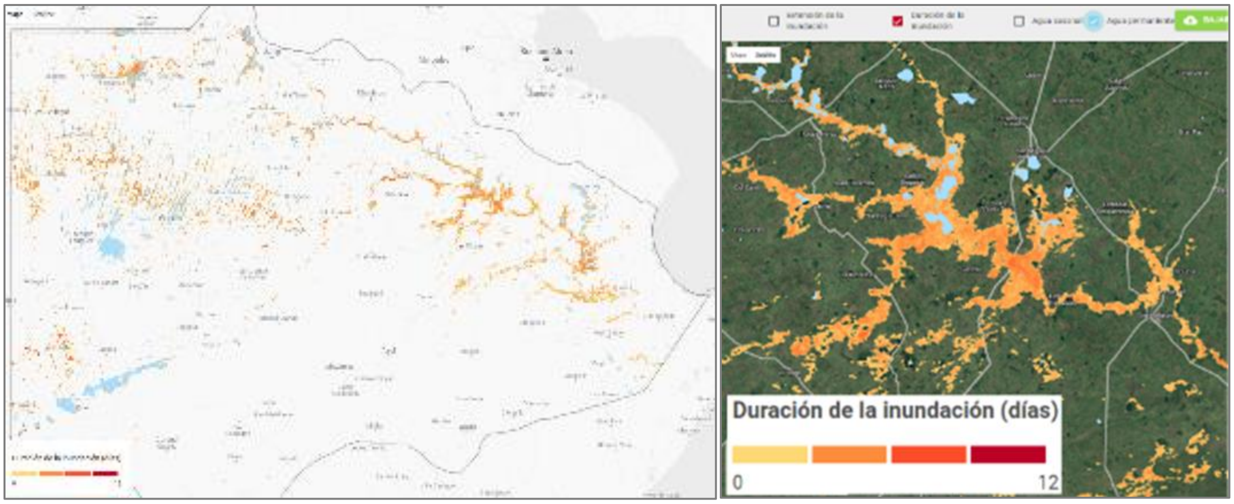


Figure 18. *Flood frequency for the October to December, 2001 flood occurring in the Rio Salado Basin. Flooding followed the Rio Salado and its tributaries (left), detail (right). The flood duration is the number of days an area (e.g. pixel) is inundated during a flood. Permanent water is shown in light blue.*

- Maximum Annual Flood Detections (if the pixel flooded that year at any point) at 250m since 2001: 1) return periods for up to a 5 year event (using MODIS and Landsat) with area and population exposed. We suggest using the 2 year return period from the Landsat dataset as the "*mancha media*" (i.e. the "average flood") to identify pixels that flood in half the years of observation and can be used to determine the "*linea de rivera*" (the water shoreline) and areas of potential expropriation by the government and 2) total number of flooded days across all events at 250m resolution since 2001.

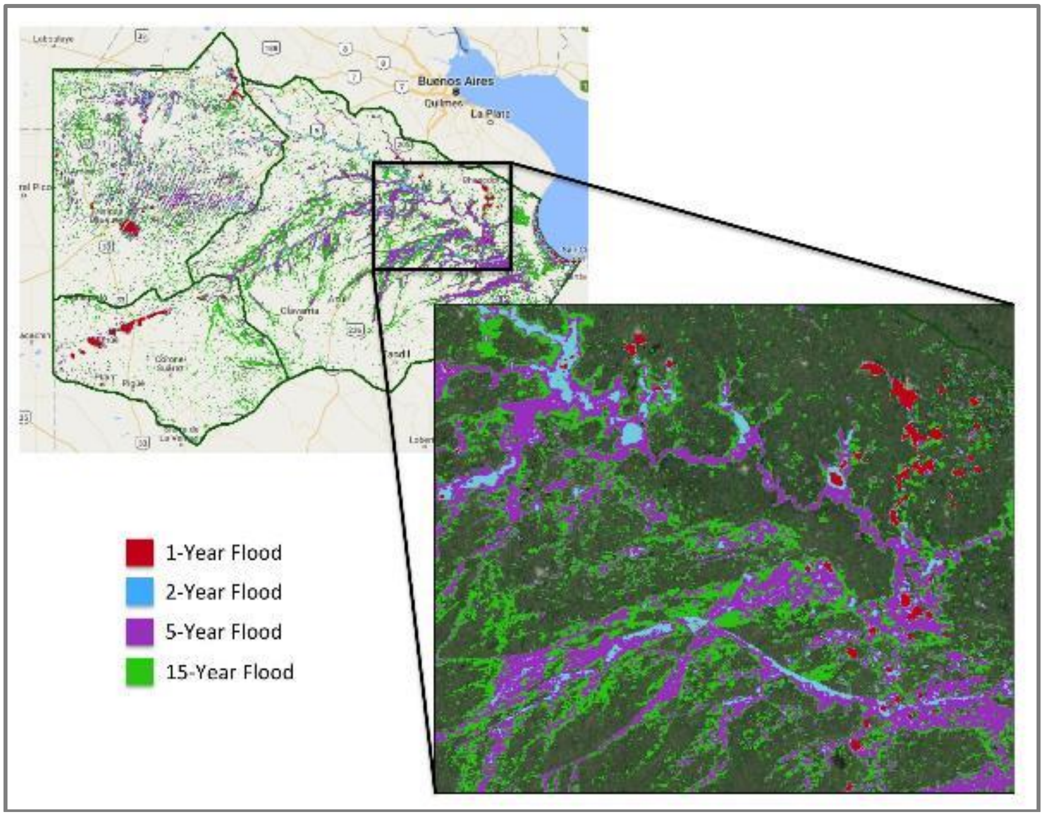


Figure 19: *Estimated flood extent under various return intervals based on 16 years of MODIS data.*

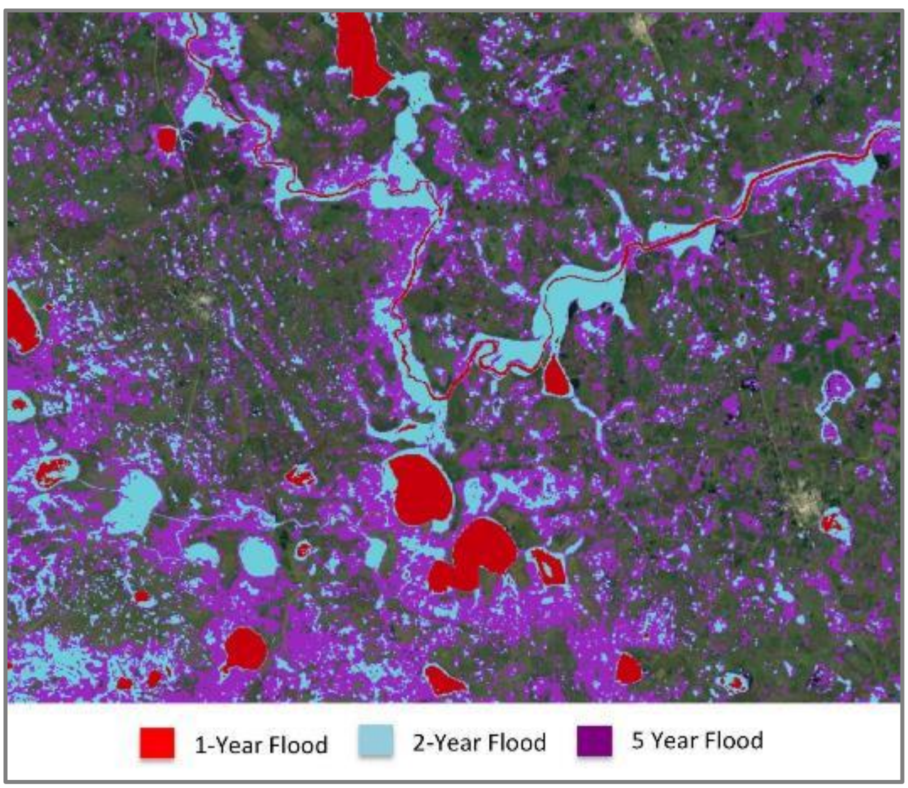


Figure 20 *Flood extent for 1, 2, and 5-year return periods based on 30 years (1985-2015) of Landsat 5, 7, and 8 data in the Rio Salado watershed, Argentina.*

- Comprehensive flood data across the watershed: 1) number of events where flood lasted more than 6 days at 250m resolution, 2) maximum extent observed since 2001, and 3) Maximum extent observed in populated regions.

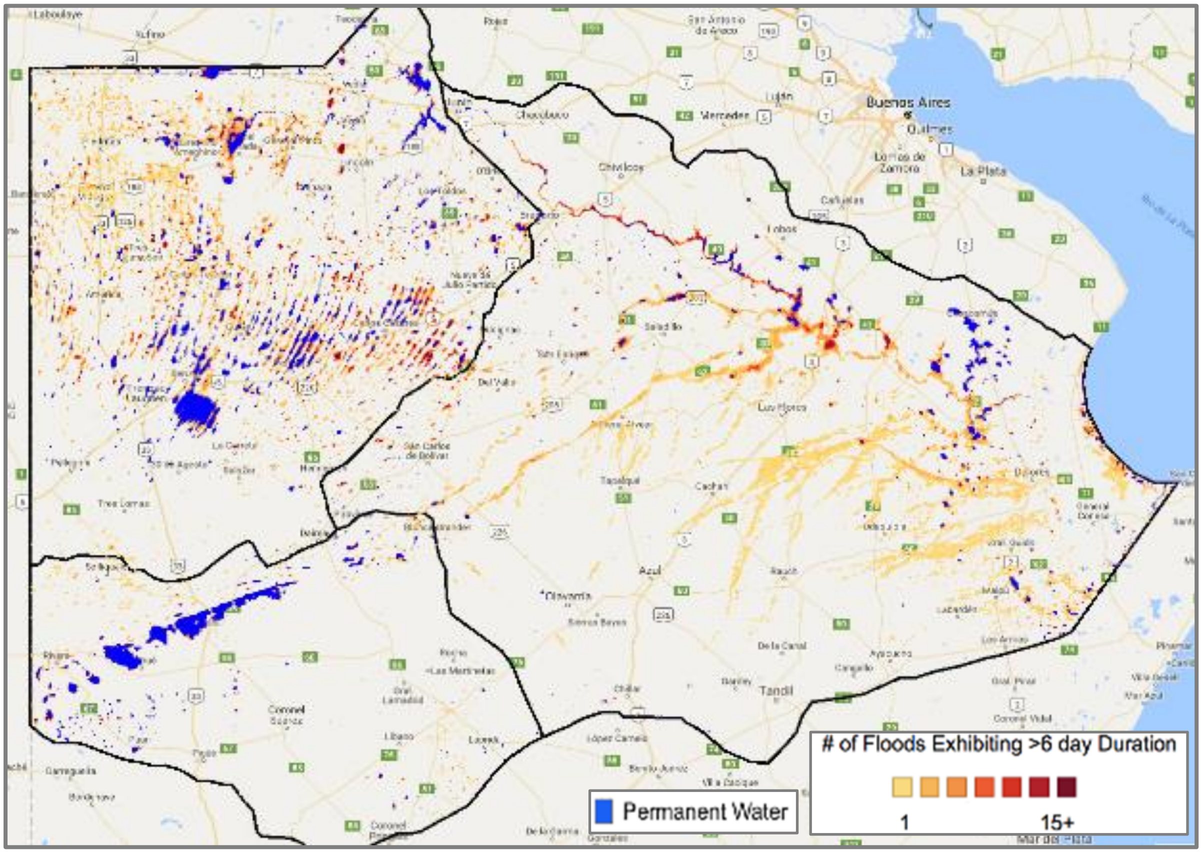


Figure 21. *Composite map showing the total number of flood events with a duration ≥ 6 days in each pixel*

The total flooded area of extent measures over 26,000 km2; according to the WorldPop dataset, area extent has directly affected the homes of approximately 10,000 people. The research includes a spatial representation of population residing in inundated areas. This is represented as a "heat map" where dense areas of population are highlighted versus lower density areas.

Using the daily information from the MODIS observations, a map product signifying the number of composite-days inundated across all events is presented. Additionally, another map composite shows at each pixel the number of events where the flood duration was 6 days or greater (termed the "thresholded flood duration").

Finally, the project provided a user-friendly dashboard that visually displays all the flood data and analytics on the watershed. The dashboard is publicly available at: https://argentina-flood-database.appspot.com.

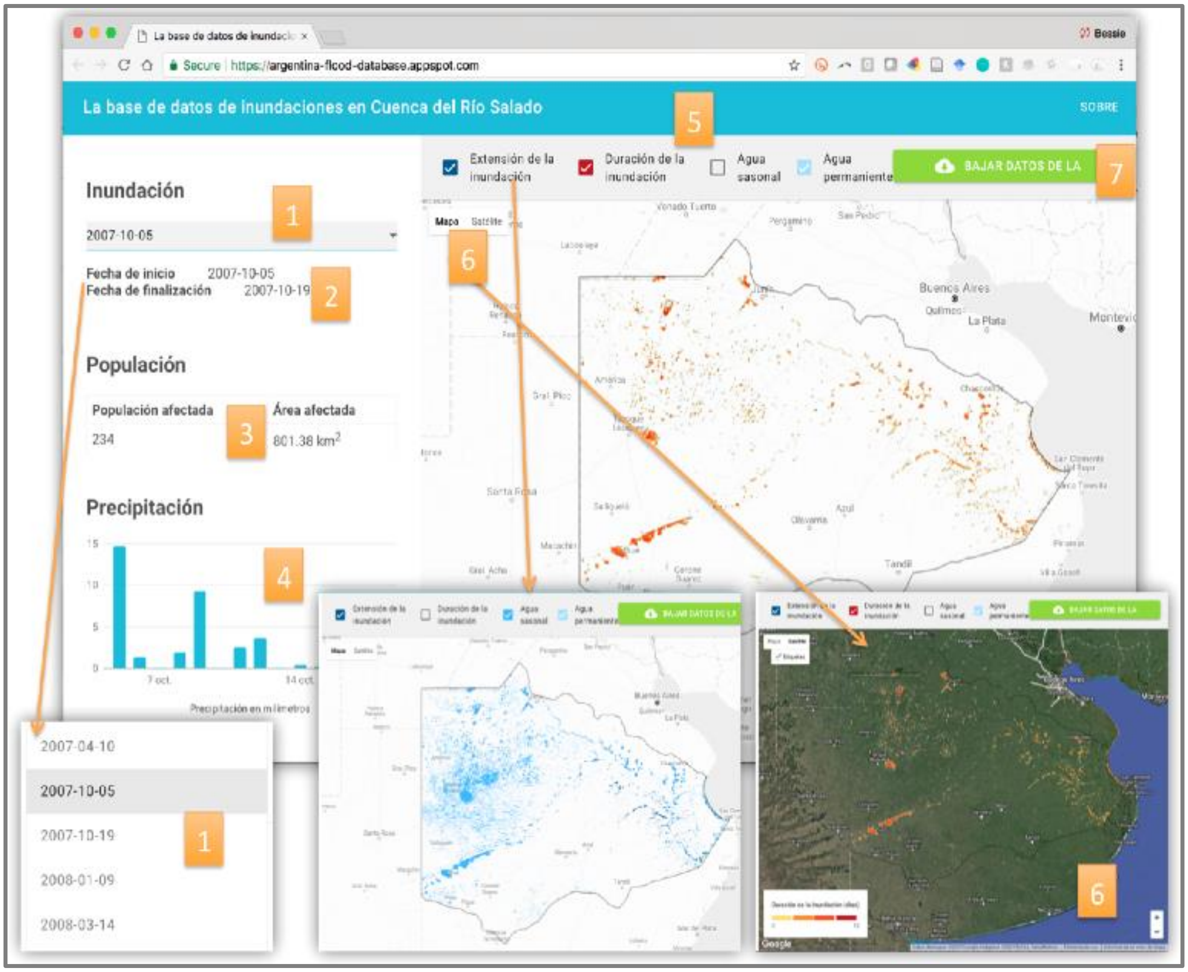


Figure 22. *A composite where each pixel value expresses the estimated population affected at that pixel. As evidenced most flood events occurred in areas of low population density (i.e., a small number of people estimated at each pixel.*

Approach for a successful implementation: Given the lack of appropriate and operational monitoring tools for WRM by the two provincial water agencies, inexistent or very scarce historical ground data of flood extents, the following approach was taken to build knowledge on historical flood events, durations and frequencies, as well as to build capacity to monitor future flooding events as they occur:

1. <u>Create a Retrospective Historical Flood Archive:</u> This is the first step to demonstrate to the provincial water agency the unique advantages of remote sensing to monitor flood extents in a large basin: where there was no spatial data on flood extent, current efforts are providing a detailed historical retrospective look at past flood events over the basin.
2. <u>Produce flood frequency and duration maps for the basin:</u> using the previous historical information, flood frequency and flood duration maps can be produced, showing the probabilities of each pixel being flooded during the year or a specific month, as well as the likelihood of each pixel being flooded for a given length of time.
3. <u>Assessment of flood risk and socio-economic vulnerability</u>: The combination of physical flood data (hazard) with population and economic activities (exposure) allows for a spatial

representation of flood risks that can inform the prioritization of land use planning, investment, and flood response measures.

4. Use of Google Earth Engine (GEE): providing easy access to imagery and computing power, the client does not need to invest up-front in hardware, storage, software and human resources to setup the system. GEE can be used until the client decides to own the system in-house and has the capacity to do so.
5. Implement algorithms for flood mapping in GEE: three flood mapping algorithms are being implemented in GEE to process MODIS, LANDSAT and SENTINEL images, taking advantage of the GEE storage of these satellite archives and of its cloud computing power. As the algorithms can be set up in GEE by the experts and run in the cloud, it is easy for the client to access the output data and results produced, without having to do any complex data processing, until he decides and has the capacity to do so.
6. Creating a Dashboard for the client to access results: For ease of access, a dashboard is being designed for a better user-friendly accessing of the results produced in the cloud.
7. Operational in time: the implementation of automatic processing of new satellite images in near real-time (as they become available in the cloud) is being explored to develop capabilities for continuous operational flood monitoring in the region.

The detailed report of this Flood Monitoring and Analysis application can be found in Annex 3.

4.4 – Water Quality Monitoring – Indonesia, Mexico, Uruguay

Multispectral remote sensing data is an extremely valuable tool to understand water quality dynamics, due to its synoptic view, multiscale and systematic data collection, and immediate transmission of the data. A range of key water quality constituents can be estimated using remote sensing, including total nitrogen, total phosphorus, chlorophyll-a concentration, colored dissolved organic matter (dissolved organic carbon or total organic carbon), harmful algal blooms (e.g., cyanobacterial toxins or microcystin concentrations), and descriptors of ecosystem states, such as total suspended sediment (or turbidity), transparency (e.g., Secchi disk depth), and temperature.

Within the Remote Sensing Initiative, four case studies in three countries were developed at the request of the Bank's local clients: **Lake Toba** in Indonesia, **Valle de Bravo Reservoir** (supplying water to Mexico City) and **Lagunas de Montebello** (environmental site degrading at the expense of agriculture) in Mexico, and the **Santa Lucia River Basin** in Uruguay (severe nutrient problems due to human activities) through a collaboration with CEOS. Only the Lake Toba case study will be presented here as it provides a good overview of a multi-sensor approach to understand a water quality issue at the basin scale. The detailed water quality report on the three case studies can be found in Annex 5.

Lake Toba is the largest volcano-tectonic lake in the world and one of Indonesia's prime tourist destinations. Since the 1990s the Lake has suffered from a continual decline in water quality that threatens both the unique tourism potential and the long term ecological sustainability of the lake. The 87km long lake drains a catchment area of 3,658 km^2 that includes more than 366 villages with more than half a million people. A range of point and non-point sources of pollution contribute to the deterioration of water quality: land use practices and deforestation, industrial development, poor investment in basic infrastructure and services resulting in poor water supply and sanitation, and unregulated expansion of caged aquaculture, among others.

Information to Decisions Context:
The Government of Indonesia is preparing an Integrated Tourism Masterplan, intending to be a strong framework for sustainable tourism development. The masterplan will guide future growth, as well as establish policies and practicies to ensure key economic and environmental assets are protected and environmental impacts properly monitored and managed.
To address this increasing water quality problems in Lake Toba, the government is preparing a Roadmap for Improving the Water Quality in Lake Toba, but must first understand the water quality dynamics and processes, to direct measures and investments to address the problem. Given the lack or scarcity of historical water quality data, the government requested assistance to the Bank team to learn about remote sensing monitoring and analysis approaches. The decision-support goals of this application were to help understand the spatial and temporal dynamics of water quality in the Lake, and provide advice on operationalizing a monitoring system integrating remote sensing and ground data. The team used multiple sensors to relate

land use changes and other data with water quality dynamics, to inform the planning of future measures and investments.

Methods and Results:

The tropical climate of the Lake Toba region, paired with its high altitude location, presents particular challenges to remote sensing because of the prevailing atmospheric conditions of high cloud and haze cover. A combination of multiple sensors is therefore needed in order to increase the probability of obtaining a high enough temporal coverage of good quality, unobstructed observations. To this end, data from the relatively higher spatial resolution and lower temporal resolution "land sensors" (Landsat and Sentinel 2A) were combined with data from the relatively lower spatial resolution and higher temporal resolution sensors (Sentinel 3A, MODIS and Himawari-8) as shown in Figures 23 and 24.

Satellite (Instrument)	**Agency**	**Temporal Coverage**	**Revisit Frequency [1/days]**	**Resolution [m]**	**Notes**
Landsat-8 (OLI)	USGS / NASA	2013 - present	~1/16	30	pan ~15m
Sentinel -2A (MSI)	ESA	2015 - present	~1/10	10	
Sentinel -2B (MSI)	*ESA*	*2017 - present*	*~1/10*	*10*	*2A+2B ~5days*
Envisat (MERIS)	ESA	2002 - 2012	~3	300	
Sentinel-3A (OLCI)	*ESA*	*2016 - present*	*~2*	*300*	*3A+3B ~1day*
EOS Aqua/Terra (MODIS)	NASA	2000 - present (T) 2002 - present (A)	1~2	250~500	3hrs offset
SNPP-JPSS (VIIRS)	NOAA / NASA	2015 - present	~1	~375	
HIMAWARI - 8 (AHI)	JAXA	2015 - present	~60 (10mins)	~1000	geostationary

Figure 23: *Suite of Satellite sensors used in the Lake Toba water quality and land use change analysis (Red frames indicate sensors for which atmospheric and Rayleigh corrected images and movies were produced, top of the atmosphere images and movies of example dates were produced for sensors in blue frame).*

The combination of data from these sensors was used to construct time series estimates of turbidity and chlorophyll in the lake and vegetation cover in its surroundings. To address data quality challenges, in addition to combining data from multiple sensors, a marine layer cloud glint mask was designed and applied. For monitoring water quality dynamics on a very short timescale, data from the geostationary Himawari-8 were used.

The remote sensing-based analysis of Lake Toba suggests the presence of complex water quality dynamics driven by nutrient-oxygen-light mixing. Although Lake Toba is a large and deep water mass, surface mixing appears to be driven by hydrologic transport (i.e, inflow and outflow), while vertical mixing in the lake is limited by a very weak thermocline.

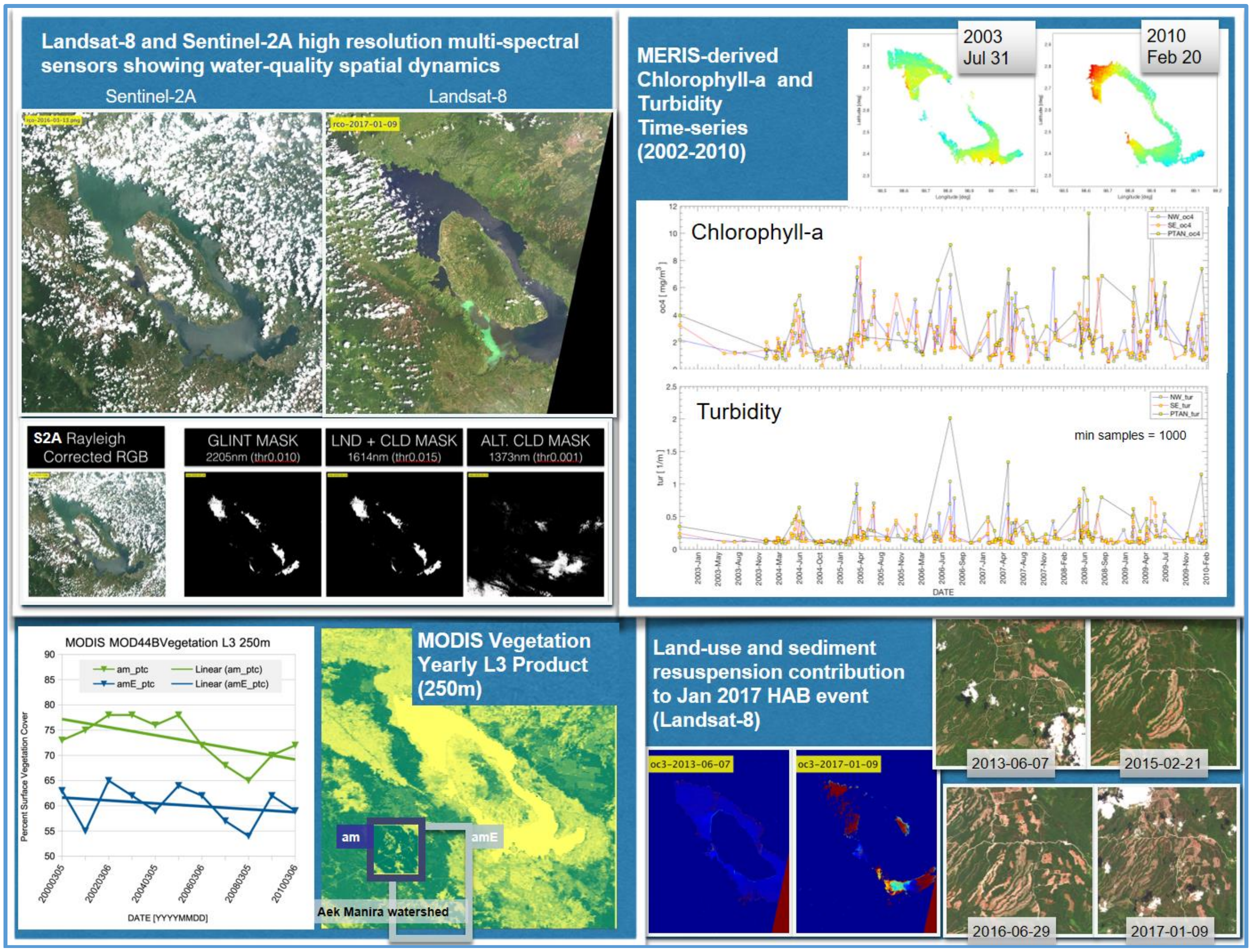


Figure 24: *The use of multiple sensors allowed a better understanding of land use change dynamics in Lake Toba sensors*

Evidence of eutrophication is apparent in long-term (MERIS) time-series data starting around 2006. An approximately two-fold increase in regionally-averaged chlorophyll-a from 1~2 mg/m^3 to 2~6 mg/m^3 and corresponding two-fold increase in light attenuation at 490nm (turbidity) were observed. In localized areas, chlorophyll-a concentrations and turbidity are much higher. Mesotrophic to eutrophic lake conditions with chlorophyll-a concentrations of 4 ~ 30mg/m^3 were also evident from Landsat-8 and Sentinel-2A imagery with complex local variability. In addition to the overall increase in those two parameters, a significant increase in spatial and temporal variability was observed for both.

A visual analysis of land cover change in the Lake Toba watershed showed limited regional changes; however, loss in vegetation cover in the Aek Manira region is estimated to be around 1% / year over period of 2000 to 2010, and accelerated in the period 2013-2017 covered by Landsat-8 imagery (Figure 25).

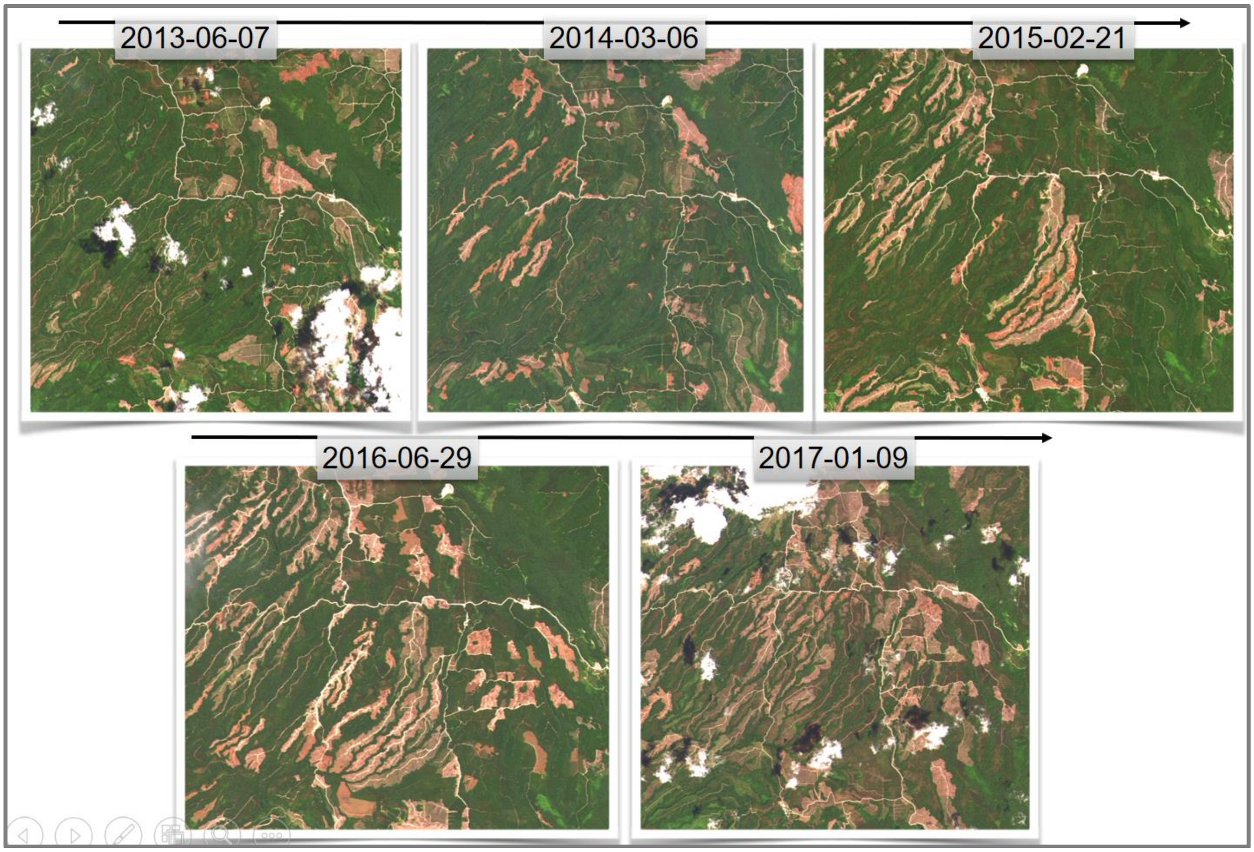


Figure 25: *Land Use Changes in the Aek Manira/Silang watershed as seen by Landsat-8 (2013-2017).*

A water-quality event on January 9th 2017 in the SE of Lake Toba in Bakara/Baktiraja region, which led to hypoxia and aquaculture loss, is visible in Landsat-8, Himawari-8 and Sentinel-3A images. Chlorohyll-a levels reaching > 10mg/m^3 (and >30 mg/m^3 locally) and evidence of benthic sediment re-suspension can possibly be explained by significant precipitation and discharge from the Aek Manira/Silang into the lake, such discharge likely being rich in organic matter from its agricultural watershed. Meteorological reports from the ground preceding the significant precipitation event are not available, but meteorological conditions are visible from Himawari-8 during first week of January (Figure 26).

A detailed remote sensing monitoring approach would need to be defined as part of a comprehensive water quality management strategy, which would not only include specific sensors and processing chains, but also a sampling strategy for in-situ observations, which would inform and be informed by findings from the remote sensing data. Accurate monitoring and understanding of water quality dynamics going forward (including suspended particulates, nutrient content and algal-bloom dynamics) would highly benefit from regionally-tuned models incorporating data from Sentinel-2A+2B, Landsat 8, MERIS, Sentinel-3A and VIIRS, integrating available in-situ sampling data.

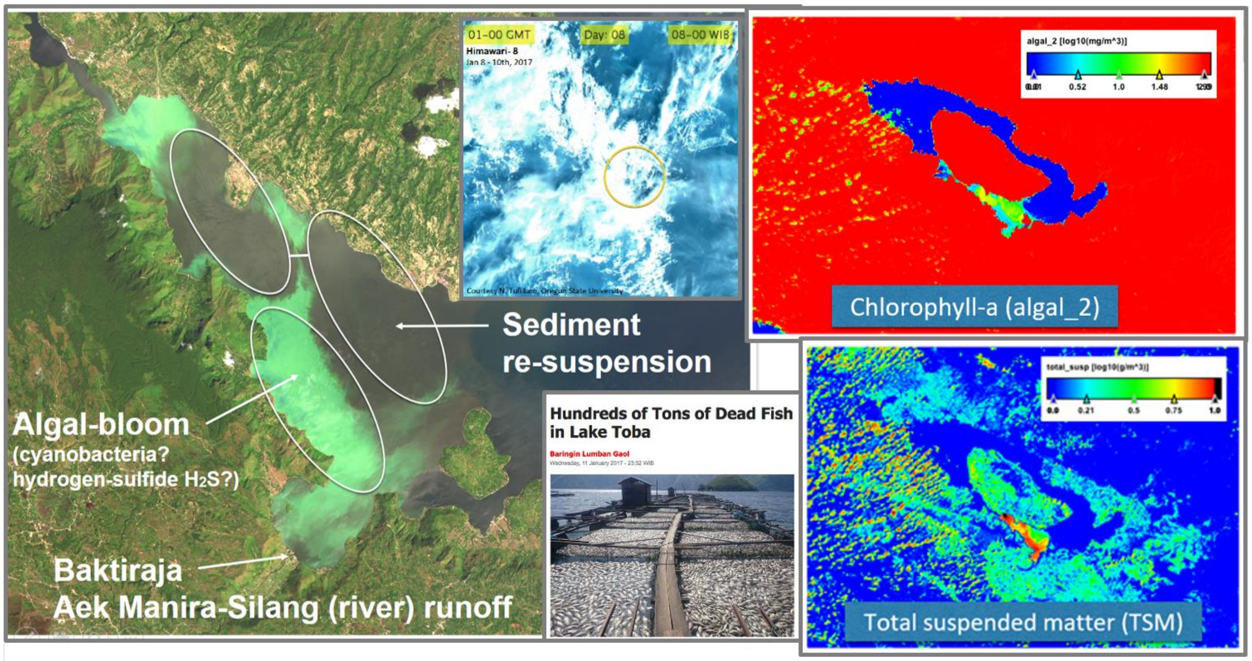


Figure 26: *Landsat-8 and Sentinel-3A Images of the Hypoxia and Harmful Algal Bloom (HAB) event occurred in January 9th of 2017, resulting in hundreds of tons of dead fish in Lake Toba, and the satellite derived images of chlorophyll-a and total suspended matter. The Himawari-8 sensor enabled understanding the context of meteorological conditions leading to the event.*

Approach for a successful implementation: This work was answering to an exploratory request from the client to see what could be done with remote sensing to better understand water quality issues in Lake Toba (and Mexico and Uruguay) and was not an effort to operationalize a system. However, a few points from our approach can be highlighted to emphasize the potential of operational monitoring of water quality for better management and planning:

6. Compound Eye of Sensors: A combination of sensors was used to observe changes in several different parameters: various water quality parameters, as well as land use change, and meteorology. In addition, the study tried to maximize the number of sensors observing similar parameters in order to maximize cloud-free images, as well as to relate current with historical imagery.
7. Make imagery accessible, videos: all of the imagery was made easily available online to the client and the project team online. Videos were produced showing the historical evolution of land cover, the variability and frequency of cloud cover, and the spatial-temporal variation in water quality patterns. The presentation of imagery through videos of temporal sequences is an intuitive way of delivering information.

The detailed report on water quality monitoring in Lake Toba (Indonesia) as well as the case studies in Mexico and Uruguay can be found in Annex 5.

4.5 – Water Point Functionality Monitoring – Africa

The World Bank, along with other international, governmental and non-governmental organizations, funds the construction of millions of water points every year in order to help provide clean water to communities in the developing world. Monitoring the sustained functionality of those installations has rarely been part of the project design, but recent findings have indicated that a systematic and efficient monitoring approach would be invaluable for ensuring the longevity of the water points.

The increasing availability of Very High Resolution (VHR) optical satellite imagery, combined with advances in machine learning algorithms, holds some promise for the systematic and efficient detection of small features. Its potential for the automatic identification of people, such as for detecting crowd congregations and migration movement, had already been discussed in a number of studies, which will be briefly outlined below. VHR earth observation could be conceived as a useful means of detecting human activity, or the lack thereof, at water points of known location, which in turn could be used as a proxy for the state (functional or dysfunctional) of the water points. While investigating the potential of VHR earth observation and machine learning, it is also important to recognize and address potential drawbacks as well as limitations of the currently available technology for our target application (see Annex 6 for detailed report).

Methods and Results – An Exploratory Study

A desk study was initiated through a request for technical assistance from the Water Expert Team (WET) to assess the potential of very high resolution remote sensing for monitoring water point functionality. This study project was highly exploratory in nature and engages with the fast evolving fields of very high resolution remote sensing and machine learning. The tradeoff between temporal and spatial resolutions had been one of the hallmarks of remote sensing technology since its beginnings, limiting applications that require detail in both the spatial and temporal domain, such as this monitoring project. However, with recent advances in sensor technology and cloud computing capabilities, remote sensing datasets that simultaneously offer high spatial and high temporal resolutions are increasingly becoming a reality.

Figure 27: *Livestock at a borehole in Tessekré, Senegal, as seen on Google Earth from imagery provided by Digital Globe*

The landscape of commercial providers of very high resolution remote sensing imagery is dynamic and continually evolving. Industry norms have been changing fast from single, massive, multi-billion dollar satellites to constellations of smaller, cheaper, and easier to replace satellites in a low Earth orbit. These micro- and nano-satellites, which include the so-called CubeSats with a mass of no more than 1.33 kg per 10x10x10cm cubic unit, are being deployed in constellations of multiples, allowing for more complete coverage of the Earth and more frequent revisit times, in a Low Earth Orbit. Digital Globe offers the currently highest spatial resolution data from its Worldview-4 satellite, which at 30 cm in the panchromatic band rivals that of aerial photography. On sub-meter resolution images, features such as individual trees and shrubs, buildings and infrastructure, and even crowds of people and animals can be clearly distinguished. Such level of detail offers potential for monitoring human and livestock activity around water points from space, but the actual feasibility of this application also depends on a number of other factors:

Timing: An important consideration is the time of day that water is typically fetched at the pump, and its coincidence (or not) with the satellite overpass time. In order to optimize sun angle and minimize shadow cast and cloud cover, the local overpass time of satellites is between 10:30 am and noon anywhere. At this time, satellites are unlikely to capture most water point activity, which typically takes place much earlier in the morning, before it gets too hot and before farmers tend to their fields.

Figure 28. *Two images from Ethiopia of sample water point locations. Left: with the water point concrete structure clearly visible, but no people in the subset (image subset provided by Digital Globe). Right: a dense crowd of people or livestock (outlined in red) as well as some individuals (outlined in blue) can be identified.*

Frequency of observations: In order to monitor activity around water pumps, weekly image acquisitions would be desirable. The frequency of image acquisition over a particular area – WorldView-4 images the entire globe once every year – is currently too low to make monitoring viable. However, in the near future, more frequent coverage is expected, as several new constellations of CubeSats are being launched, with expected revisit frequencies of multiple times daily in important economic centers. It remains to be seen, however, how frequently remote areas will be imaged.

Causality: Depending on the depth and accessibility of the water table, in some places water points are installed in relatively remote locations, where they are the only point of “attraction”. In these cases, presence of people around the water point is highly likely to indicate that the water point is being used and functional. Other water points were installed in central locations, near markets and shops, where people congregate for various reasons. In these cases, the correlation between presence of people and water point functionality is expected to be weaker. In either case, the non-use of a water point does not automatically indicate the non-functionality of the pump.

Activity around water points could be detected from satellite data by alternative approaches to the identification of the presence of people, which would make the monitoring slightly less time sensitive. One possibility would be to focus on livestock rather than people, since herds tend to be larger than congregations of people and also stay around the water point longer.

Other alternatives, which have already proven viable where installed, are in-pump sensors, which record sensor flow data inside the pump and transmit it through the cellular/satellite network. While retrospective installation of such in-sensor pumps in already established water points would be a large undertaking, including them in new pump installations might be the most promising approach for the time being.

To conclude, the current technology is not ready for satellite remote sensing-based monitoring of water point functionality today, mainly due to the time of overpasses not overlapping with time of use, and the frequency of satellite re-visits. However, the technology could become ripe within the next 2-5 years, given the rapid advances in the field and planned new satellite constellations maximizing both spatial resolution and revisit frequency.

The detailed report on very high resolution imagery to monitor water point functionality can be found in Annex 6.

5 – Reflections on the Sustainability of Applications

The sustainability of computer models (hydrologic, or other) and data applications is an old problem: often developed within the setting of a Bank Project by specialized technical teams, a large percentage falls in disuse as client agencies may not have the means to update or maintain them. Remote sensing applications merging complex data and models are part of the same category. In the same way that we need a mechanic to service and fix our car when it breaks down, we also need arrangements with technical teams when our data and modeling applications need fixing or updating when our environment and our systems evolve (and they do, very rapidly). In developing regions, these arrangements to ensure sustainability have not been yet established, but some promising venues exist.

At the Global Level, a range of products using freely available remote sensing data can provide useful and accessible information. However, and since water security is site-specific and is mediated by the behavior or local actors and institutions, many applications will need to be locally customized (adapted, calibrated, validated with ground data, etc.) to address the local needs of management. Thus, while global applications are a public good, but they can't always cover the local needs at the required level of accuracy.

At the regional and local level, country hydromet agencies, water management institutions and transboundary water commissions face a range of responsibilities including monitoring water conditions, data collection, archiving, reporting, regulatory, planning and management. On one hand, institutions may not have enough resources to cover all of these needs, resorting to drastic prioritizations obeying to immediate needs; and on the other hand, these responsibilities may cut across agencies resulting in the challenge of coordinating information and efforts. Human, technical and financial capabilities may vary widely in each context, and will determine the sustainability of models and applications in each case. In order to build long term capacity to strengthen institutions in client countries, synergies with educational and training programs must be found, as well as ways to provide some level of funding support, or internal agency, ministry budgeting, over the long term to grow and maintain in-house capabilities in client agencies (by the government or other). While this goes beyond the duration of a project, it is at the core of building capacity, and should be included within lending operations along with longer-term arrangements. Other institutions and programs, such as UNESCO, have promoted initiatives that develop knowledge networks spanning sectors (academia, data producing agencies, end-users, water managers). These networks are efficient in disseminating new ideas and applications, and creating knowledge overspills. An example is the GWADI Program of UNESCO.

For example, in the Rio Salado and Lake Chad, as in any other setting, there is the challenge to make data systems and the monitors sustainable. The following are insights from past experiences:

1. Managing the systems: Past experiences (from the African Flood and Drought Monitor, AFDM) with establishing data centers in Niamey (Niger), Nairobi (Kenya) and Harare (Zimbabwe), is that data systems are fragile. Agencies like NASA, NOAA or ESA change their file structures or formats without notice, and systems using this data must adapt. In many operational agencies, the capacity to adjust is limited. Currently, the AFDM/LAFDM data centers receive processed data from the AFDM/LAFDM central computer system, and when there is a data system change the team can address this at the central computer and all local data centers are corrected and updated. In the past, the ADFM/LAFDM team has been doing this for the greater good and using

piece-meal project support when available, but it is not a sustainable model going forward. An alternative model would be a data license and service agreement, established with local end-user agencies, which would be less expensive and specially more reliable than each agency/country doing this ‘in house’. In addition, such a license agreement or “subscription” model would also enable the following point.

2. Adding new capabilities: The Latin American and the African Flood and Drought Monitors are the product of extensive research and development efforts over many years. As these efforts advance to improve the monitors (a unique operational application that fills an important gap), a sustainable mechanism to periodically update the regional monitors and applications is needed. As new remote sensing and modeling capabilities get developed, they should be added to the continental and regional systems. Some, like high resolution evapotranspiration or flood inundation products from remote sensing will be central to the interest of operational agencies, but their capacity to effectively adopt and incorporate these can often be limited.
3. Strengthening local institutions and their technical capabilities: Increasing human and technical capacity is a long-term effort which can hardly occur without a local financial commitment to support it. This may or may not be best addressed with the Bank’s main current supporting mechanisms (loans and accompanying TAs), but one would need to invest in education and training, incentivize synergies with knowledge networks and support/enable staff trainings through academic and professional exchanges. Such strengthening of local institutions at a human and technical level would also contribute to building capacity to develop and add specific models and analytic tools to the regional systems, targeting site-specific needs .

Many of the above challenges for the sustainability of systems could be met if funding mechanisms existed that resulted in global water data information systems, as well as associated regional capabilities for assimilation and integration with local data (and local platforms as those developed within this initiative for the Rio Salado and Lake Chad). It would certainly be cost effective and very helpful for operational agencies in most of the world.

Mechanisms should also be found to align long-term technical training with the implementation of Bank projects, in order to create a solid human capacity foundation. The “*consultant model*” used by the bank in the implementation of its projects may not work in terms of sustainability of human capacity. Trained consultants in the setting of a project are not likely to stay within the local agencies and management settings where the project was implemented.

6 – Main outcomes of the Remote Sensing Initiative

The main contributions to date of the RS Initiative to different RS application fields for World Bank projects, client countries and beyond can be summarized as follows:

1. **Advancement of operational field-scale evapotranspiration ET monitoring capabilities over very large areas with the use of Google Earth Engine:** With Bank leadership and support and through synergies with a range of key partners including developers of ET products, USDA, Desert Research Institute, the University of Wisconsin-Madison, the Water for Food Institute (University of Nebraska), Google Earth Engine and others, the DisALEXI algorithm to estimate field-scale evapotranspiration has been implemented in Google Earth Engine and is in the process of validation (with estimates computed offline). The algorithm will initially run to cover the project areas in Mexico and India, with future aims at running many other regions of interest on Google Earth Engine. In addition, a new product being developed at the USDA at 375m resolution would substitute in the future the 5-km ALEXI product currently used by DisALEXI, making the 30m ET estimates more accurate. The US has been selected as a pilot region by the USDA to test the new 375m product (at our request they will also cover Northern Mexico to include Irrigation District Rio Colorado 14) because of the availability of ET products for comparison in the region. Overall, this contribution will ultimately allow regular and periodic ET monitoring across all of the Bank's operating regions and projects. As a broader context of efforts, we have coordinating with other partners to implement all of the main field-scale ET algorithms (METRIC, SEBAL, DisALEXI, SSEBop, etc) into Google Earth Engine through the ***OpenET Framework Project*** and work with end-users to operationalize the use of multi-product ET estimates within their management systems. The Remote Sensing Initiative has supported a consortium of partners in securing significant funding ($6M) from private foundations and convinced them to adopt a global scope in their first round of case studies. The Irrigation District 014 *Rio Colorado* in Mexico will be the first international case study.

2. **Retrospective historical flood archive in ungauged basins:** The Rio Salado case study demonstrated a low cost method for creating spatially explicit historical flood archives in ungauged basins, building on flood detection algorithms used on MODIS, LANDSAT, and SENTINEL data, implemented in Google Earth Engine, and accessible to agency staff through a user friendly Flood Monitoring and Analysis Dashboard. These historical flood archives will reveal spatial and temporal patterns of flood exposure over the past several decades, and can be used to extract spatial statistics on flood frequency and duration per pixel. In combination with ancillary data (such as population density and socio-economic data), they form a basis for flood probability and vulnerability assessments.

3. **Historical flood monitoring and analysis application, potentially near real-time:** In addition to historical flood extents, the Rio Salado case study will lead to near real-time flood extent monitoring applications, leveraging near real-time image data availability, specialized flood detection algorithms and parallelized cloud computing in Google Earth

Engine. Near real-time flood extent monitoring is key for rapid and immediate disaster assessment and response planning. For client country agencies, the capability to spatially monitor floods while they are occurring (and shortly after) with algorithms running operationally in the cloud and producing results and maps in near real-time will be an important step forward. The time and labor demands on the client are very low, and the opportunities for easy replication across projects and regions are very high.

4. **Hydromet monitoring and prediction**: The development of operational and near real-time Lake Chad Flood and Drought Monitor and the Salado Flood and Drought Monitor, provides hydromet monitoring, weather forecasts (10-15 days ahead), seasonal forecasts (6 to 9 months ahead) and the resulting hydrologic predictions. The models within the application integrate high resolution remote sensing and spatial data with ground data, and are accessible through a user friendly online platform. Thus, for the agencies in Argentina and the Lake Chad Basin Commission, without access to near real-time hydromet spatial data, and ground data, have now functioning monitors requiring almost no operating resources from them (technical and human, resources that they may not be able to dedicate).

5. **Linkage with international hydrologic knowledge networks:** The RS Initiative team has made an effort to connect the efforts within each of the project applications with broader international knowledge networks of partners and parallel efforts. While many partners have gathered around the implementation of field-scale ET estimates in Google Earth Engine, vested and willing to contribute to these efforts, we have also coordinated closely with UNESCO-IHP efforts in LAC and Africa, as well as with its GWADI Program and the IWR's International Center for IWRM (ICIWaRM-UNESCO). This UNESCO network is working at the continental scale with similar case studies in other countries to improve hydromet monitoring capabilities using remote sensing. We believe that coordination with such parallel efforts is key for the long term benefits in the regions and for benefitting from future opportunities, such as joint capacity building activities, other funded projects and initiatives, and knowledge spillovers.

6. **Adaptation of remote sensing-derived products and tools to settings with low human and technical capacity:** Owing to the rapid advancements in cloud computing and the universal accessibility of the internet and its clouds and data repositories, such as the Google Earth Engine platform, the remote sensing-derived products and tools created in this initiative are all adapted to low-tech settings, where computing and storage capacity are generally low, as are also human and technical capacity. All data is stored and processed in the cloud, thus evading the need for expensive software and high volume data processing capabilities in-country. Data and ad-hoc processing are made available in intuitive web interfaces and easy-to-use dashboards. Stakeholder interaction and training has and will help fine-tune the presentation and usability of the products to best respond to user needs.

7. **RS reaching the project portfolio through WET requests**: As another vehicle for the RS initiative to influence the Water GP project portfolio, we identified those requests for assistance to the WET that could benefit from relevant remote sensing expertise. The RS Initiative and WET teams have worked together to explore solutions to best address the challenges within projects in the operational portfolio, or relating to overarching issues with high potential across regions and projects (see Annex 6 on RS applications for water point functionality monitoring, advancing the thinking and finding the right expertise to develop innovative solutions to an old, unresolved problem).

7 – Going Forward: Remote Sensing Applications for Water Resources

A number of strategic insights are possible given the current water resources challenges, or threats to water security, and the recent technological advances such as the wealth of raw data, cloud computing power, and well established science applications. A range of applications, until now complex or costly to implement and operate, are currently able to produce periodic results over large areas by taking advantage of the following facts:

a) Large archives and ongoing mission imagery is currently being stored in public clouds. Cloud storage is very low cost, developers and now users have relatively easy access to cloud space.
b) Cloud computing allows the processing of large amounts of data and the running of complex algorithms over large areas.
c) Many complex computing algorithms are freely available or open source (ET, flood extent, water quality).
d) Internet access from developing regions, and user-friendly interfaces, enable a window into the cloud to obtain only relevant outputs (of very small size, insignificant, in comparison to all input files).

The Water and Earth Observations of the future will routinely combine ground measurements with remote sensing, weather predictions, seasonal and climate projections, and models. In addition, most applications will consist of a ***compound eye*** using various sensors to monitor relevant variables, all contributing to gain a holistic perspective on a specific management challenge.

The following six strategic investments are proposed as valuable applications that should be part of the Water GP project portfolio toolkit. They would have a significant impact in the Bank's portfolio across different sectors, as mentioned in each strategic application.

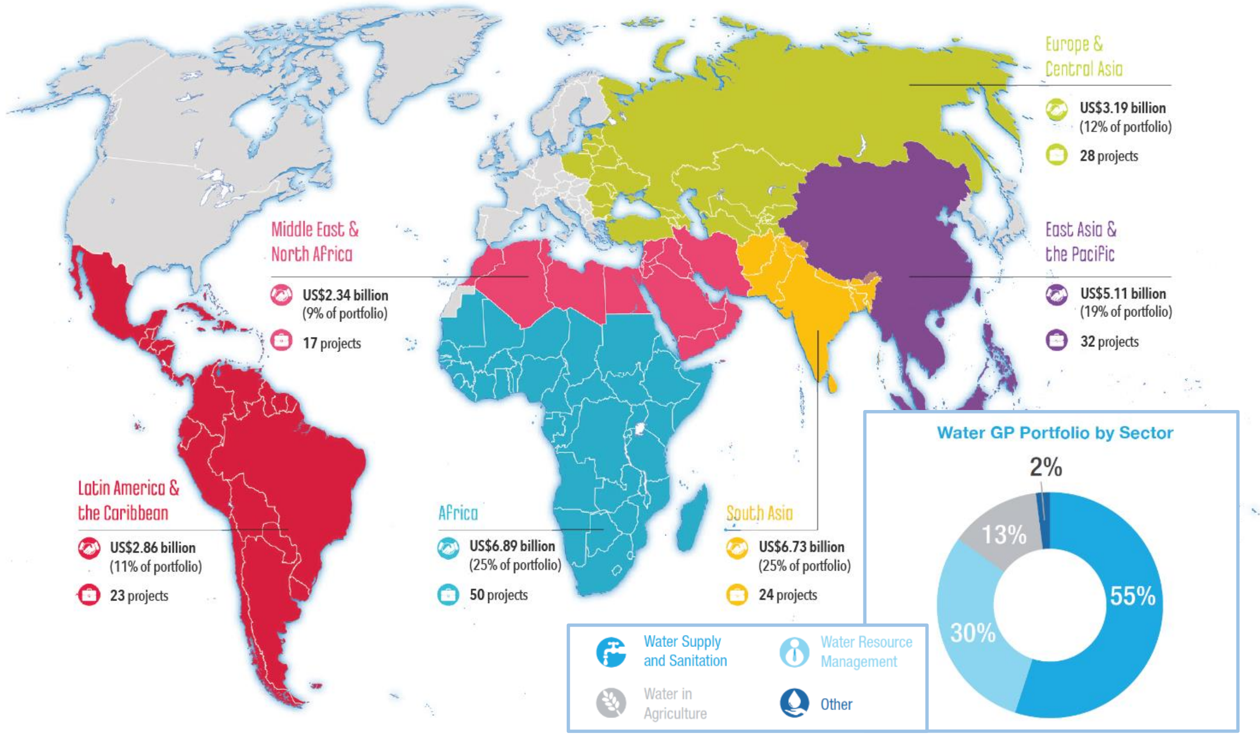


Figure 30: The Water GP portfolio and its distribution by sector.

1. **Periodic Evapotranspiration (ET) and Crop monitoring at the field scale (resolution ~30m):**
   - Evapotranspiration: We have produced a Google Earth Engine function for one ET estimation algorithm (DisALEXI) which we will be contributing to a broader multi-partner initiative named *The OpenET Framework*, in order to put all the main algorithms in Google Earth Engine with a range of partners (i.e. we are not endorsing one product over others, but contributing a piece of the puzzle within a coordinated effort).
   - Crop monitoring: The use of EVI and NDVI at 30m, easily computed in the cloud from the Landsat and other mission imagery enables, with an easy validation of crop types from the ground, the periodic monitoring of crop evolution during the growing season.
   - ***Compound Eye: Combining ET and crop variables (Veg. Indices) provides a powerful tool to monitor irrigation districts in near real-time globally.***
   - *Building on the ET and Crop monitoring work of Chapter 4.1 (Annexes 1 & 2), a multi-product platform to periodically estimate field-scale ET over large areas would directly impact 13% of the portfolio (Water in Agriculture) and indirectly 30% (Water Resource Management)*

2. **Flood Extent Monitoring and Analysis:**
   - Retrospective Flood Archive and Flood Area Analysis: the work in Argentina presented here demonstrates that using flood detection algorithms within the Google Earth Engine

database is an efficient and very cost-effective way to produce historical analysis on past floods, using all available imagery from Modis, Landsat and Sentinel. Thus, for regions and projects without a historical spatial perspective on flood history, this is an easily accessible tool to gain an understanding of flood dynamics. In addition, this provides a very low cost tool to monitor the effects of newly built infrastructure and other types of interventions, on the flood dynamics and areas flooded. In other words, the changes of spatial flood risk in the basin.

- Recent and real-time flood monitoring: With the launch of the Sentinels and their 10m resolution imagery complementing Landsat at 30m, the frequency of observations increases. Capabilities to monitor flood extents in real-time would provide additional benefits to national agencies and inform flood mitigation and recovery decisions.
- Rainfall estimates over the basin are helpful to understand the context of the rainfall event and the timing of the overpass of the flood detecting satellite sensor within the event. Rainfall estimation products are operationally available at sub-daily aggregation periods (3h and less), thus much more frequently than flood-detection satellite sensors.
- ***Compound Eye: Combining increasingly frequent satellite sensors, with historical imagery, and using satellite rainfall products to understand the spatial dynamics of rainfall and observed flooding.***
- *Global flood monitoring capabilities would inform and support projects ranging from water resources management (30% of the portfolio, including disaster risk reduction and land use planning) as well as all of the Transport GP portfolio (all linear transport is likely to cross flood areas), poverty, environment and other portfolios.*

3. Hydrometeorological Monitoring and Prediction (Including Floods and Droughts):

- An easily accessible monitor integrating historical datasets, real-time satellite rainfall, evapotranspiration and soil moisture estimates, meteorological forecasts (7-14 days ahead), seasonal forecasts (6 to 9 months ahead) and ground data, is a baseline tool, beneficial to all countries to monitor the state of their basins in near real-time, for water balance accounting purposes and to inform management and planning. A land surface atmosphere model can be used to assimilate different real-time input data and produce other variables in a predictive way. Currently only the Latin American and African Flood and Drought Monitors exists as continent-wide platforms running operationally and freely available online, albeit at low resolution, merging limited ground data, and using only rainfall estimates and forecasts.
- The inclusion of actual evapotranspiration estimates at a moderate resolution (~5 km), available in near real-time, would greatly improve hydrologic modeling. Estimates of soil moisture data would also be beneficial to constrain and update model runs and improve flood predictions.
- For streamflow monitoring and prediction, the above hydrologic modeling can also be coupled with hydrodynamic modeling to transform streamflow predictions into river

stage and flood propagation predictions. In that regard, river altimetry measurements are a great complement for river stage applications, and the projects with lidar surveys of the river channels are ideal candidates for implementation.

- ***Compound Eye: Satellite estimates of rainfall, basin-wide ET, soil moisture (+model outputs such as weather forecasts and seasonal forecasts) to monitor the state of the basin and constrain model runs. Also, Lidar for detailed Digital Elevation Models and altimetry estimates for river stage discharge.***
- *The basic and real-time hydromet monitoring tools presented in this report should be the baseline for any hydromet or water related agency in any country as the foundation of water management (supporting all of the water portfolio of the World Bank, including water supply). This application would also support downstream riparian states in transboundary basins.*

4. Monitoring of Riparian Ecosystems and the Environment

- Natural riparian ecosystem monitoring through vegetation indices and the estimation of riparian ET are a good way to monitor changes in the area and the health of such ecosystems. In arid and semi-arid areas, riparian systems may rely for part or all of the year on the proximity of shallow groundwater which they tap with their roots. Water abstractions upstream in the basin or in the vicinity will directly affect the eco-hydrologic balance of these systems, resulting in decreased groundwater recharge, lesser dry-season flows, and a decline in groundwater tables, resulting in a reduction of ecosystem area and even disappearance.
- ***Compound Eye: Vegatation monitoring (area and health) and evapotranspiration estimation.***
- *This application will enable the monitoring of impacts on riparian environments from projects and other interventions: water for agriculture and the environment portfolios.*

5. Water Quality Monitoring Systems

- Remote sensing can provide a much needed spatio-temporal view of water quality dynamics and relate it to other processes such as land use change and meteorology (rainfall, temperature, etc). In regions with observable water surfaces such as lakes, reservoirs or large rivers, capabilities to complement ground measurements of water quality with remote sensing will provide key information to inform the prioritization of measures and investments to improve and protect water quality.
- ***Compound Eye: Satellite sensors for water quality parameters, vegetation indexes and land use change observations, and meteorological satellite estimates.***
- *The Bank's Environment GP stated recently that pollution reduction will be its main priority. This application will enable the monitoring of a range of water quality parameters related to pollution in waters and watersheds. Also, it will directly inform*

30% of the portfolio (Water Resource Management) and indirectly 13% (Water for Agriculture) and 55% (Water Supply and Sanitation).

6. **Transboundary Reservoir Systems Monitoring:**
   - In large transboundary basins with upstream and downstream states, with challenges of information-sharing, transboundary flood risks, water flow allocation issues, and the operation of reservoirs in each country, remote sensing can level the field by providing a transboundary view of the state of the basin, its flows, and the observed operation of reservoirs.
   - Digital Elevation Models from available topography (SRTM) can provide approximate reservoir volume-to-area curves, which combined with altimetry observations of reservoir levels, enables the estimation of water storage changes. Rainfall and other met estimates over the basin region, with hydrologic models, provide a quantification of inflows into reservoirs. Then, combining all of the above, we can infer the reservoir releases and derive the operation policies. This system can inform downstream states about the state of the basin and reservoirs in upstream states, and vice-versa, making water information more public.
   - ***Compound Eye: Digital Elevation Models, Altimetry estimates, Rainfall and other hydromet parameters for hydrologic modeling.***
   - *This application has relevance for any transboundary basin with reservoirs where riparian states do not share sufficient information regarding reservoir operations. In transboundary basins without dams, application investment #3 would be sufficient.*

Water Information as part of the Strategic Vision for WRM in the Water GP:

Water Security can only be achieved through Knowledge-based Management and Planning. Water resources management investments should fall into place under a unifying and practical paradigm and strategy to achieve water security, sustainability and resilience. We propose a strong focus to anchor interventions in the promotion of hydrologic knowledge and knowledge-based decision-making, as a unifying theme to accompany all WRM interventions in the Bank's portfolio. Information from applications integrating remote sensing and ground information needs to integrate well with planning and management cycles so that a good understanding of water resources dynamics can enable knowledge-based decision-making and achieve water security. Hydromet is the basis to inform water security.

Strong and Knowledgeable Hydromet Institutions and Water Agencies are the basis for knowledge-based decision-making. Institutions with capabilities for periodic and ongoing monitoring of water resources across its basins, and with the ability to perform analysis of such data, gain understanding of the evolution in the dynamics of its basins, and institutionalize the accumulation of that knowledge, are the foundation of knowledge-based management in regards to the three pillars of water security: water resources management, service provision and risk management. The accumulation and growing of human, technical and institutional capital will directly influence the management and planning processes within the basins, and consequently the effects and impacts of such management.

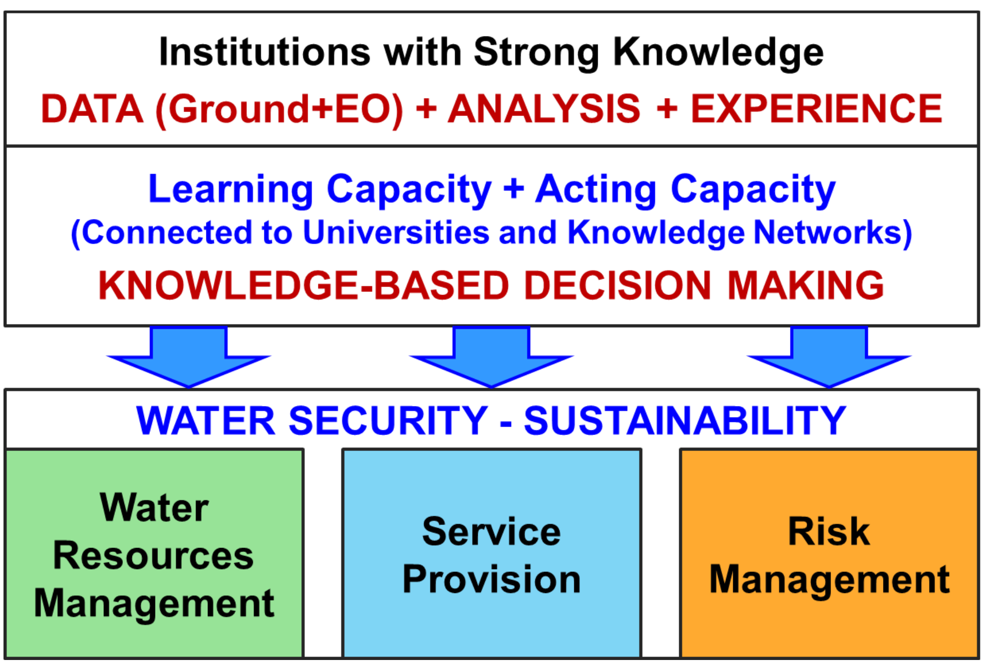


Figure 31: Water Security is Site Specific, and information and understanding is the foundation for knowledge-based decision making.