Proposal: Hydrosat remote sensing services for the Groundwater Sustainability Plan (GSP) of Madera County

Cover Letter

To: Madera County GSA(s)

Date: June 12th, 2025

The Californian Sustainable Groundwater Management Act (SGMA) is an excellent vehicle to reduce groundwater withdrawals. By defining allocations on the basis of Evapotranspiration from Applied Water (ETAW), two great steps forward are achieved: (i) only the amount of groundwater that has physically left the river basin will be accounted for (not gross withdrawals that includes recoverable water to other users) and (ii) ETAW is measurable from satellites. Hydrosat is therefore pleased to submit herewith a proposal with an action plan for 2025 and beyond. We believe that together with Madera County GSA(s) we can build on continuation of our experiences in the region and work closely with Davids Engineering on presentation of the results to the client and compare the results with field measurements.

Several Governments and Development Agencies outside the USA have expressed interest in copying what's now become internationally known as 'the Madera solution' to reduce groundwater withdrawals. It is with great pleasure we submit this proposal to continue our work with Madera County GSA(s) towards the implementation of their Groundwater Sustainability Plan (GSP) by providing data on water use for the County and its affiliated growers.

Over the past 5 years, we have closely worked with Madera County GSAs to provide our satellite measurement services for calculation of water use based on evapotranspiration from applied water (ETAW). This concept has been tailored to respond to the requirement of the county

Throughout the past few years, we have tailored our product, web portal, and API output to best serve the requirements of Madera County GSA(s) and its growers. In the early years of the program, we made model improvements and aligned the methodologies to make sure the different measurements methods for growers are comparable. In addition, we have revamped our web portal to make it simpler and easier to navigate.

Starting in 2025, the IrriWatch product has access to additional high resolution satellite imagery from Hydrosat which helps improve the accuracy of satellite measurements. Our first thermal satellite was launched in August 2024 and the second is scheduled to launch in June, 2025. Afterwards, additional satellites will be launched in 2026, 2027, and beyond. Access to proprietary high-resolution satellite data ensures more frequency and higher accuracy in the product.

The Hydrosat Team leverages its experience, project understanding, and lessons learned offering the following:

1. Experience in energy balance modeling to provide actual evapotranspiration at 10m pixel resolution.

2. Experience and knowledge about water balance modeling and calculations of evapotranspiration from applied water (ETAW) and from precipitation (ETPR).
3. Quick access to the data and irrigation portal in real-time daily timesteps: IrriWatch provides in addition to the data layers, an online platform at County level as well as at grower level to monitor water use, have access to budget tables for allocations, ETAW, remaining amounts of water, etc.
4. Irrigation scheduling information and crop monitoring is available from the IrriWatch portal for growers with daily updates.

The Hydrosat team is highly experienced and uniquely qualified to provide water use measurements from satellites. We look forward to the opportunity to continue working with Madera County GSA(s) toward sustainable groundwater management.

With kind regards,

Hydrosat Team

Hydrosat

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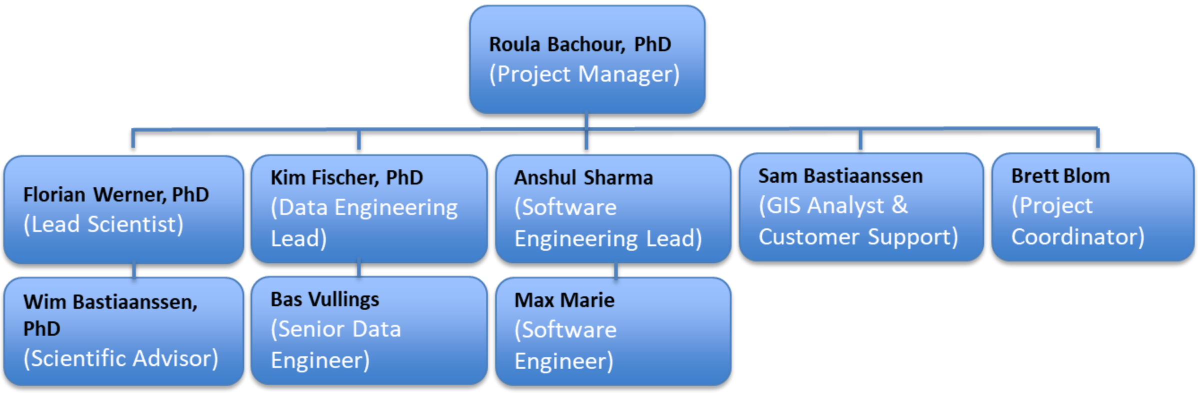
Organization Chart

Hydrosat is the proposed Primary Consultant to provide satellite measurement services.

Hydrosat will work under the administrative direction of Madera County GSA(s)' project manager. The team will be led by Roula Bachour, the Director of Customer Success at Hydrosat. Key tasks leaders include: Florian Werner (Lead Scientist), responsible for the science and modeling of ET and ETAW and water balances; Wim Bastiaanssen will be serving as a scientific advisor for the team; Kim Fischer and Bas Vullings will be ensuring data pipelines and processing of all output are delivered on time and water use estimates are generated both on daily and monthly basis; Anshul Sharma will be leading the portal development and any adjustments required including reporting and data at pixel level, API and graphs.

The proposed key personnel from Hydrosat and organization of the team for this project are presented on the organization chart below:



Qualifications

A short bio of the team members that will be involved in the project is presented below along with their involvement in the project.

Roula Bachour

Roula is the Director of Customer Success at Hydrosat, leading the clients' technical support including understanding of the remotely sensed data provided by the IrriWatch product. She is also coordinating Hydrosat's projects in the MENA region, Asia and USA. She has a PhD in Irrigation Engineering from Utah State University and has over 15 years of professional experience working in agriculture, irrigation and remote sensing. Roula has managed the Madera County GSA(s) project the last two years and she will be leading the project moving forward.

Florian Werner

Florian is Lead Scientist at Hydrosat, leading scientific research and development of Hydrosat's analytics. Florian has expertise in thermal infrared satellite data processing and crop stress detection. He will be leading the quality assessment of the data along with any related research activity at Hydrosat for the project ensuring alignment between the project's technical goals and overall strategy. Dr. Werner holds a Ph.D. in Physics from Leibniz University Hannover and Institute for Solar Energy Research Hamelin, Germany.

Wim Bastiaanssen

Wim is a globally renowned expert in remote sensing and water resource management, with an emphasis on water productivity. He developed remote sensing algorithms for water productivity with his PhD students and conducted over 20 studies for Asian Development Bank and World Bank to identify water productivity gaps in several countries. He helped UN-FAO with various remote sensing studies on water productivity at the global scale for wheat, rice and corn. The global standard framework on Water Productivity Score was developed jointly by Prof. Bastiaanssen and Prof Steduto from FAO. Among his most notable achievements is the development of the Surface Energy Balance Algorithm for Land (SEBAL), which revolutionized remote sensing by enabling the precise estimation of evapotranspiration and energy fluxes at field and regional scale. In addition to his role as Ambassador at Hydrosat, he is a Professor of Earth Observations for Water Resources Management at Delft University of Technology. He has also founded multiple remote sensing companies, including WaterWatch, eLEAF, CropZoomer, and IrriWatch. Dr. Bastiaanssen holds a Ph.D. in Agro-hydrology, Soil Physics, and Groundwater Management from Wageningen University. He has over 26,000 citations to internationally peer reviewed journal papers (as of January 2025). He will be serving as a scientific advisor for this project.

Kim Fischer

Kim is Data Engineering manager at Hydrosat. Kim has 8 years of experience in applied AI, data science, and data engineering. He has worked with Terabyte scale data processing (Real Impact Analytics), created classical and deep learning algorithms for yield forecast, and developed geospatial data pipelines. He has experience in AI and time-series classification, which aligns with project requirements for seasonal crop productivity monitoring. At Hydrosat, Kim is responsible for the architecture and implementation of the large-scale data processing pipelines. He will develop and maintain the large-scale data processing and model training pipelines. Before joining Hydrosat, Kim worked as a Lead Data Scientist at Ferrero, where he managed Ferrero's Agri Competence Center Data Science team. Before that, he held the position of Data Engineer at Ferrero, where he developed yield prediction using predictive analytics techniques as well as precision farming using satellite-, airborne- and UAV-data. Kim holds a double Master's degree in applied geoinformatics and environmental sciences by the University of Trier.

Bas Vullings

Bas is a data engineer at Hydrosat. Within Hydrosat, he mainly works with Python-based models that leverage satellite imagery for irrigation and crop growth management. His primary responsibilities revolve around the design, development, and test of highly scalable and automated data pipelines. He has been working on the pipelines for the Madera County GSA(s) project for the past two years and have made a lot of improvements to ensure stability and scalability of the IrriEngine. Bas holds a Master's degree in biosystems engineering and a Bachelor's degree in agrotechnology from Wageningen University.

Anshul Sharma

Anshul is Software Engineering Manager at Hydrosat, where he leads a team of software engineers developing web and mobile applications. Before joining Hydrosat, Anshul worked at Ankorstore where, as a Software Engineering Manager, he defined and executed the company's

API and integration strategy, enabling third-party partnerships that now drive over 25% of Ankorstore's annual revenue. He also recruited and built four remote engineering teams across Europe. Prior to this role, he held several Software Engineer positions. At Open Assessment Technologies, he developed a large-scale online assessment platform used by Education Ministries across Europe for nationwide school exams and led a team to build an open-source human marking system. At Docler Holding, he designed and implemented highly distributed systems for a live video streaming platform serving over 20 million monthly active users. Anshul holds a Bachelor of Technology in Computer Science from Amity University.

Max Marie

Max is a Software Engineer at Hydrosat, where he develops highly scalable backend and frontend services and designs and implements both customer-facing and internal applications. Before Hydrosat, Max worked at Devoteam where, as a Senior Software Engineer, he implemented and maintained multiple apps for global companies. Prior to this role he held positions at Finalcad as a backend developer, launching and running a cross-platform SaaS in the construction tech, and as a fullstack engineer at CoverGo, an InsurTech, a startup. Max holds a Masters of Engineering (specializing in IT and networking) from INSA Lyon (the National Institute of Applied Sciences of Lyon).

Sam Bastiaanssen

Sam is the Customer Success Manager at Hydrosat leading active user engagement, ensuring users utilize the full potential of Hydrosat's satellite data services by providing dedicated support and being on standby for users' needs with 5+ years' experience as a geospatial data analyst in the international agricultural sector. In this project Sam will support the on-boarding of field boundaries and field information, such as crop type, irrigation method, or soil type into the IrriWatch portal. Besides that, Sam will ensure the administrative parcels and personal privacy data are all safely separated by each individual user.

Brett Blom

Brett is the VP for Sales & Business development at Hydrosat, leading the go-to-market team and ensures coordination with all Hydrosat's client base as well as delivering feedback and recommendations to the company based on customer feedback. Brett has worked in the remote sensing space for almost 10 years and is based in Ripon, California where his family farms almonds. In this project, he will be coordinating the client interactions with the Madera County GSA(s) team.

Project Understanding and Approach

Hydrosat understands that the purpose of Madera County GSA(s) desired measurement program is to contribute to achieving reduction in groundwater water use by providing information to the GSA's, landowners, and growers on field level crop water use from irrigation. Additionally, measurement of crop water use will allow the GSAs to monitor groundwater use relative to sustainability targets. Beyond these two main purposes of the measurement program, Hydrosat envisions additional potential uses of the IrriWatch platform by growers for daily monitoring of water use via graphics and budget tables to compare their consumption to allocations. The

IrriWatch platform also helps growers with irrigation scheduling and crop monitoring throughout the season, which can provide an additional incentive for growers to use the portal and optimize their water use.

Hydrosat's technical approach is described below with more technical details attached in Annex 1.

Land use

Land use maps of the Madera County GSA(s) will be acquired from publicly available maps especially from the Department of Water Resources (DWR). These land use maps are updated every couple of years by LandIQ. Hydrosat's approach will be to update these maps on annual basis based on 1) fallow analysis that will be done during summer to detect fallowed land that has moved into cropping systems and cropped areas that have turned into fallow. This will affect the ETAW of these fields; and 2) throughout the season, growers also indicate the change of crop, by informing the County about these changes. We will coordinate with the County team to access the changelog from the data management system to implement the crop changes as well as ownership changes, parcel moves and measurement methods changes.

Actual Evapotranspiration and Actual Evapotranspiration from Applied Water

Hydrosat uses energy balance modeling, specifically its proprietary version of the SEBAL algorithm to calculate consumptive use based on thermal and VNIR satellite measurements. SEBAL (Surface Energy Balance Algorithm for Land) was developed by Dr. Wim Bastiaanssen of The Netherlands (Bastiaanssen et. al., 1998a, 1998b and 2005). SEBAL uses spectral radiances recorded by satellite-based sensors, plus ordinary meteorological data, to solve the energy balance at the Earth's surface. SEBAL computes actual evapotranspiration (ETa) for each pixel in a multispectral satellite image by applying radiative, aerodynamic and energy balance physics in 25 computational steps.

SEBAL offers distinct advantages compared to the generally accepted "Kc x ETo" method for computing ET including 1) computing actual evapotranspiration (ETa), inherently accounting for the effects of salinity, deficit irrigation, disease, poor plant stands, and other factors, on crop ET. These influences in the standard Kc x ETo computation requires considerable additional data (typically unavailable) as well as substantial time and effort; and 2) the acreage of water-using land is observed directly from the satellite image, so accurate irrigated area is implicit to the process. This feature avoids the typical difficulty of assembling accurate records of irrigated areas and cropping patterns; and 3) SEBAL does not need crop type to solve the energy balance, however, cropping patterns are important for the water balance and calculation of ETAW as the root depth plays an important role in the water storage computations.

The latest version of SEBAL includes an integration between the surface energy balance and soil water balance where actual ET is the common denominator for both. Because ET is a large component of the water balance, it provides great insights in the magnitude of the various terms. The soil water balance model has been employed to acquire a spatially distributed estimation of every term of the balance for every pixel. The soil water balance computes surface runoff Rs following a soil moisture deficit and presence of roots. This is a modified version of the Soil Conservation Service equation that has fixed infiltration capacities described by means of Curve Numbers. Water that percolates from the root zone is no longer available for ET and reduces soil water storage. In line with Darcian flow in unsaturated soil, the mathematical expression for percolation is a non-linear function of the degree of soil moisture saturation. In California, it is common to allocate groundwater on the basis of ET from Applied Water or ETAW. Hydrological background studies have determined the maximum volume of ETAW to realize a new equilibrium situation with zero-overdraft for different sub-aquifers. To accommodate ETAW as a basis for allocation and compliances, the IDC model (https://data.cnra.ca.gov/dataset/idc-version-2015-0-77/resource/238d3e2b-a985-4db7-9793-933ba6d525af) is used for the assessment of ETAW from ET. More technical details about the SEBAL methodology, the water balance modelling and IDC model are presented in Annex 1.

It is important to note that Hydrosat will implement on annual basis, initialization of soil moisture and root depth based on previous years data (water years) to ensure the "rainfall and soil moisture storage buckets for each parcel-field is correctly set.

While the proposal indicates monthly timesteps of ET and ETAW, Hydrosat will be calculating the data on daily timesteps using daily thermal satellite measurements. This will improve the accuracy of ET calculations and avoids challenges of interpolating between two satellite imagery acquired every 8 days (from Landsat). Hydrosat has developed a fusion model to provide 10m resolution daily thermal imagery which has been validated in several countries over the past 4 years. Hydrosat's new constellation of thermal satellite will also be integrated into the modelling to improve the accuracy more.

Precipitation maps

One of the main components into the IDC model to get ETAW is the precipitation. Hydrosat uses global weather services to get the precipitation maps. For this project, the weather data including rainfall will be acquired from the National Weather Service (NWS). NWS precipitation maps do rely on data from a network of weather observation stations across the U.S., including in California. These stations include Automated Surface Observing Systems (ASOS), Cooperative Observer Program (COOP) stations, Remote Automated Weather Stations (RAWS), California Irrigation Management Information System (CIMIS), Airport weather stations, other specialized sensors and radar systems.

Precipitation maps will be acquired on an hourly basis, which are then integrated into daily timesteps and precented on our web portal. At the end of each month, Hydrosat will generate Monthly precipitation maps at 10m pixels to share with the Madera County GSA(s).

Deliverables

The project deliverables will include the following:

1. Annual update of the land use raster files which will be also aggregated to parcel-field level to determine the majority crop of each parcel-field.

2. Daily ET and ETAW raster files at 10-meter spatial resolution (real-time via portal and API).

3. Monthly ET and ETAW raster files at 10-meter spatial resolution (provided within 1 week of the end of each month).

4. Daily precipitation data provided at field level (real-time via portal and API).

5. Monthly precipitation maps at 10-meter spatial resolution (provided within 1 week of the end of each month).

6. Full implementation of a tailored version of the IrriWatch platform including the following:

- irriwatch.hydrosat.com platform with viewer access to all fields individually. The fields will be displayed at the County level to monitor all the fields as well as at farmers' level. Hierarchy structure will be created when needed for master accounts (See Annex 2 for more details on how the portal shows the data).
- Setting up the revised shapefiles and crop maps at the beginning of every year and setting the farmers accounts, farm units and master accounts.
- Delivery of all IrriWatch parameters, including irrigation performance and crop production indicators
- Daily monitoring actual evapotranspiration (ET) based on energy balance modelling and calculating actual evapotranspiration from applied water (ETAW)
- Updated IDC model for actual evapotranspiration from precipitation (ETPR) model
- Initialization of soil moisture and root depth based on previous years data (water years)
- Portal customization including farm unit zones layer, aggregation of field-parcels to parcels and farm units and master accounts.
- Customized portal tables for parcel water budgets and farm unit budgets updated monthly
- Customized reporting on monthly basis at parcel level and farm unit level downloadable from the portal
- Regularly updating the County database with changes at farmers level (e.g. change of crops) in coordination with the County
- In-season change of parcel ownerships in coordination with the county
- Mid-season check of fallow fields and assisting in defining the fields that needs on-ground verification
- Crop production and daily irrigation schedule advice for farmers
- IrriWatch trainings and outreach
- Assist the County during technical discussions with farmers

Project Experience and Success

Hydrosat services to Madera County GSA(s) providing water monitoring data from satellite based on surface energy balance modeling. From 2021 to 2025, Hydrosat is providing ET and ETAW daily data for the County along with access to its growers to its IrriWatch online platform to monitor their water use, monitor their fields and access data on soil moisture, irrigation scheduling and more parameters.

Hydrosat services to Madhya Pradesh Water Resources Department in India for the project "Operational Remote Sensing-based Information for Daily Irrigation Management" covering 130,000 ha of irrigated land. The accuracy of the models was measured by flowmeters and soil moisture sensors. The ET daily data and irrigation scheduling was used in SCADA systems to operate the irrigation systems. (2021-2024; a proposal for extension is now approved and the project will continue soon).

Hydrosat services to Water Resources Department in Kyzylorda, Kazakhstan to develop solutions that leverage remote sensing and geospatial analytics to improve water management, ensuring that available resources are used more effectively and sustainably. The project is in collaboration with Geobox and it covers over a 250,000 hectare of irrigated land. Hydrosat was monthly ET, ETAW, Applied Water and several more parameters on a monthly basis for the whole area. The project continues now for the 3rd year. The accuracy of the models was measured with flowmeters.

Hydrosat services to the Punjab Irrigation Department (Pakistan) that is responsible for 22.5 million acres irrigated land. Diagnosing their irrigation performance in the Lower Bari Doab Canal including equity, adequacy, reliability and productivity for 2017 and 2018. The analysis is based on the spatio-temporal patterns of consumptive use. The project is funded by the Asian Development Bank for detecting whether modernized irrigation systems function better and discharge measurements are accurate. Building on this project, a new project was approved in June 2025 to reinitiate the services to measure water use and water sustainability metrics from remote sensing in Balochistan.

Hydrosat service to Grupo Magdalena sugarcane plant in Guatemala with 75,000 acres of land and over 1,250 farmers on soil moisture monitoring, the need to irrigate and the amount of water to apply. In addition, to access to the IrriWatch platform, Hydrosat provides additional analytics to Grupo Magdalena including harvest planning, sugar content estimation, yield estimation and performance of crop compared to references. Model and data accuracy has been tested using soil moisture sensors, soil sampling for gravimetric moisture, yield and sugar data measurement. Grupo Magdalena is a current client of Hydrosat for the 4th year.

IrriWatch service to the Government of Kazakhstan for monthly reporting on consumptive use in an 82,000-ha irrigation scheme in Turkistan for a period of 4 years (2016 to 2019), and provision of suggestions to improve land and water management operations. Fields with low on-farm efficiencies and low crop water productivity are detected for provision of more governmental support. Best practices are copied from well performing fields.

Further to projects, IrriWatch provides operational information to farmers, commodity traders, investors and banks in more than 50 countries globally.

References

SEBAL has been widely tested in USA by various independent research organizations including University of California Davis, California State University Fresno and the USDA. In addition to that, validation experiments have been conducted by private companies including Jain Irrigation (currently Rivulis), Vinduino and Davids Engineering.

These validations have been focusing mainly on almonds, pistachios, grapes, alfalfa, lettuce among others that represent California's main irrigated crops. The validation experiments are described in research papers and reports that are peer reviewed:

- Allen, R.G., W.G.M. Bastiaanssen, M. Tasumi and A. Morse, 2001. Evapotranspiration on the watershed scale using the SEBAL model and Landsat images, ASAE Meeting Presentation, paper number 01-2224, Sacramento, California, USA, July 30-August 1, 2001
- Allen, R.G., A. Irmak, R. Trezza, J.M.H. Hendricks, W.G.M. Bastiaanssen and J. Kjaersgaard, 2011. Satellite-based ET estimation in agriculture using SEBAL and METRIC, Hydr. Processes 25(26): 4011-4027
- Bastiaanssen, W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids and R.G. Allen, 2005. SEBAL for spatially distributed ET under actual management and growing conditions, ASCE J. of Irrigation and Drainage Engineering 131(1): 85-93

- Bastiaanssen, W.G.M., R.G. Allen, H. Pelgrum, A.H. de C. Texeira, R.W.O. Soppe and B.P. Thoreson, 2008. Thermal-infrared technology for local and regional scale irrigation analyses in horticultural systems, Acta Horticultae792 (Mildura Special Issue) ISHS:33-46
- Clark, B., D. Lal, W. Bastiaanssen, R. Soppe, B. Thoreson and G. Davids, 2007. Variability of crop coefficients in space and time – examples from California, Proceedings USCID conference, Sacramento, September 2007
- Ghorbanpour, A.K., S. R. Peddinti, T. Hessels, W.G.M. Bastiaanssen and I. Kisekka, 2025. Enhancing evapotranspiration estimates in composite terrain through the integration of satellite remote sensing and eddy covariance measurements, Science of The Total Environment, Volume 963, 1 February 2025, 178530
- Kisekka, I.,S. Rao Peddinti, W.P. Kustas, A.. McElrone, N. Bambach-Ortiz, L. McKee and W.G.M. Bastiaanssen, 2022. Spatial–temporal modeling of root zone soil moisture dynamics in a vineyard using machine learning and remote sensing, Irrigation Science https://doi.org/10.1007/s00271-022-00775-1
- Thoreson, B., S. Zwart, W.G.M. Bastiaanssen and G. Davids, 2004. Actual crop evapotranspiration without crop classification, USCID, Symp. Salt Lake City, October 2004
- Thoreson, B., B. Clarke, R. Soppe, A. Keller, W.G.M. Bastiaanssen and J. Eckhard, 2009. Comparison of Evapotranspiration Estimates from Remote Sensing (SEBAL), Water Balance, and Crop Coefficient Approaches, World Environmental and Water Resources Congress 2009: Great Rivers, Proceedings of World Environmental and Water Resources Congress 2009

Costs

The financial proposal for IrriWatch data services is based on 220,000 ac.

Our goal with this proposal is to eliminate additional amendments and budget requests as we make necessary adjustments and enhancements to the product delivered. With this proposal, we have offered a discount on the standard IrriWatch subscription costs with a multi-year commitment.

Description	**Price ($/ac/yr)**	**Acreage**	**Total Price**
IrriWatch Subscription / yr	$ 0.83	220,000	$ 182,600
	Total price / yr		**$ 182,600**
	2 yr discount (5%)		-$ 9,130
	3 yr discount (10%)		-$ 18,260
	Total 2 yr price / yr		$173,470
	Total 3 yr price / yr		$164,340

This subscription also includes professional services costs; we have built in the expected hours and time allotment needed to deliver exceptional custom service to Madera County GSA(s) along with its growers. There will be no additional bills or charges, and applicable insurance requirements are included in the cost as well.

Annex 1: Surface Energy Balance Algorithm for Land (SEBAL) Methodology

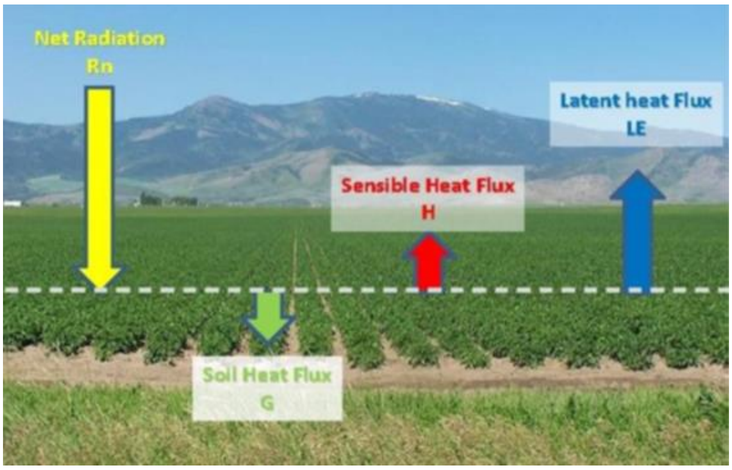
Land Surface Energy Balance Modelling

The Surface Energy Balance Algorithm for Land (SEBAL) computes the actual crop evapotranspiration, soil moisture of the rootzone and the crop dry matter production for every individual pixel (Bastiaanssen et al., 1994; 1998; 2005). Related water flows can be inferred from that, once rainfall is taken from other sources (that source can also be a satellite product). The determination of irrigation water flows will be described in following section "soil water balance modelling".

SEBAL accurately estimates the amount of water evaporated by water and soil, as well as transpired by plants, which is the **actual evapotranspiration** (ET). The principle of a simple residual energy balance is applied. The revolution comes from the fact that crop type, age of crop, soil type, irrigation applications and agronomic management information is no longer needed because ET is based on λE (see later) and λE is determined from other energy and heat fluxes, so not from soil and crop information:

$\lambda E = Rn - G0 - H$

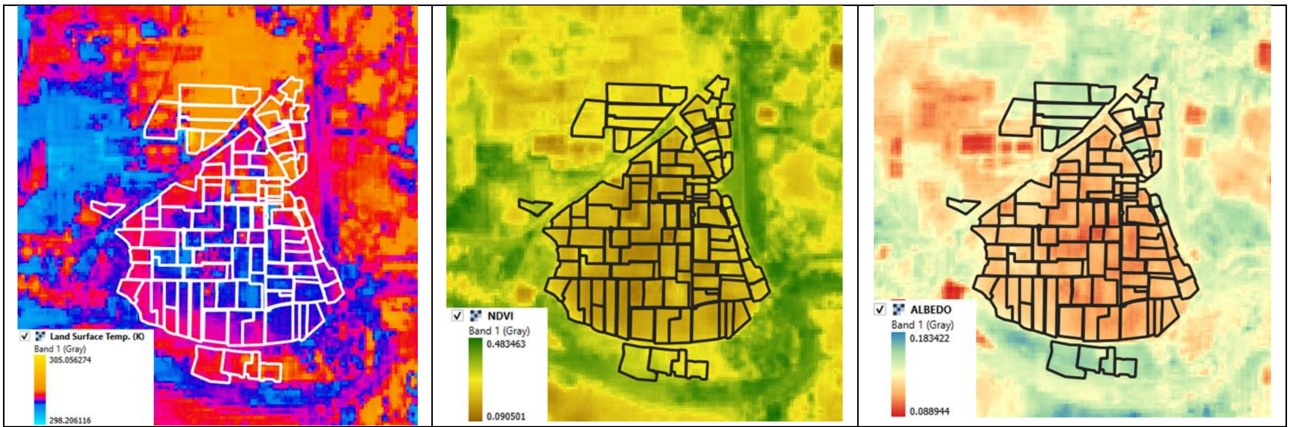
> *(**Rn**): **Net Radiation** – The total incoming shortwave (solar and longwave radiation) minus the reflected and emitted radiation from the surface. It represents the energy available for processes like heating the air, soil, and evapotranspiration.*
>
> *(**G0**): **Soil Heat Flux** – The portion of energy used to heat or cool the soil.*
>
> *(**H**): **Sensible Heat Flux** – The energy used to heat the air above the surface.*
>
> *(**λE**): **Latent Heat Flux** – The energy used in the evapotranspiration process (water vapor flux from soil and plant surfaces)*



SEBAL uses (geostationary) satellite measurements of solar radiation, Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI) and Surface Albedo (see Figure 1) to determine Rn, G0 and H. The source of satellite data is EcoStress, VIIRS, Landsat, Sentinel, MSG and Jacob Van Zyl-1. The data from these satellites is fused and used to generate daily imagery with a spatial resolution of 10m x 10m. The absolute value of Land Surface Temperature (LST) depends on the magnitudes of Rn, G0, H and λE. Solar radiation for instance increases Rn and evaporative cooling increases λE. The latter on return depends on soil water potential in the root zone in combination with a certain canopy development.

A relative cold crop with LST being equal to air temperature will have an ideal soil water potential in the root zone and maximum sapflow leading to maximum evaporative cooling and high λE value. Colder fields in Figure 1 will have a LST of 298 K (25 °C). The fields in the Northern part of the image are in the 305 K range (32 °C) and are thus suffering from access to water. There might be water stored in the root zone at 32^{o}C, but this moisture is retained by soil minerals and not all water are easily available for uptake by roots. In such situation, part of the Rn energy will be converted into H.

The surface albedo has a large impact on the absorption of solar radiation. Darker surfaces absorb more radiation, which increases net radiation values (see Figure 3). Ponded water is a typical example of a surface having a low albedo. More net radiation implies that more energy is available for the phase transition of water from liquid to vapor. The NDVI is another essential crop input parameter to describe leaf development. Pixels with higher NDVI have a higher fractional vegetation cover, a higher Leaf Area Index (LAI) and a higher fraction of Photosynthetically Active Radiation fPAR.



Land Surface Temperature (K)	NDVI	Surface albedo

Figure 1: Example of satellite measurements used as input into SEBAL energy balance model. The data is from Odisha State acquired on 27 January (2024)

SEBAL computes the partitioning into sensible and latent heat for every pixel using anchor points for LST, representing groups of hot and cold pixels. Sensible heat H is very sensitive to LST and SEBAL has an internal calibration procedure with the anchor points to scale H between minimum (cold pixel) and maximum H values (hot pixel). These cold and hot pixels are selected in an automatic manner from the combination of input data demonstrated at Figure 2.

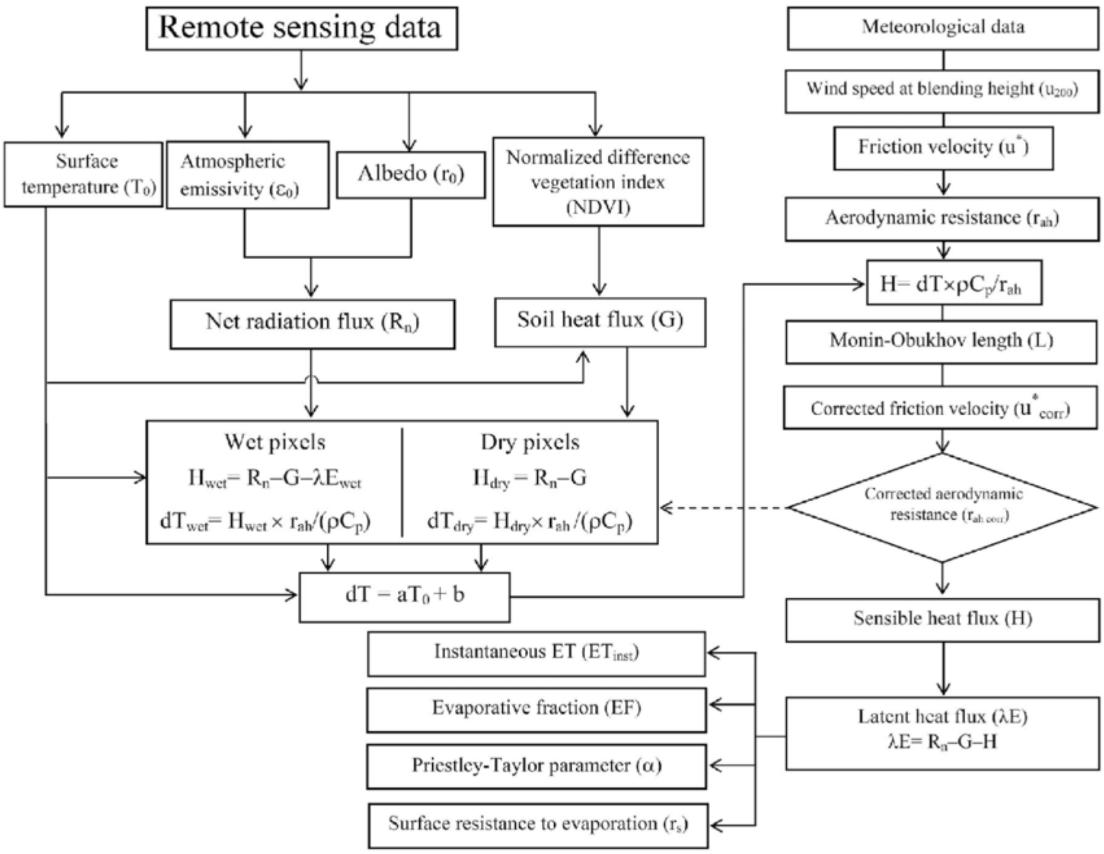
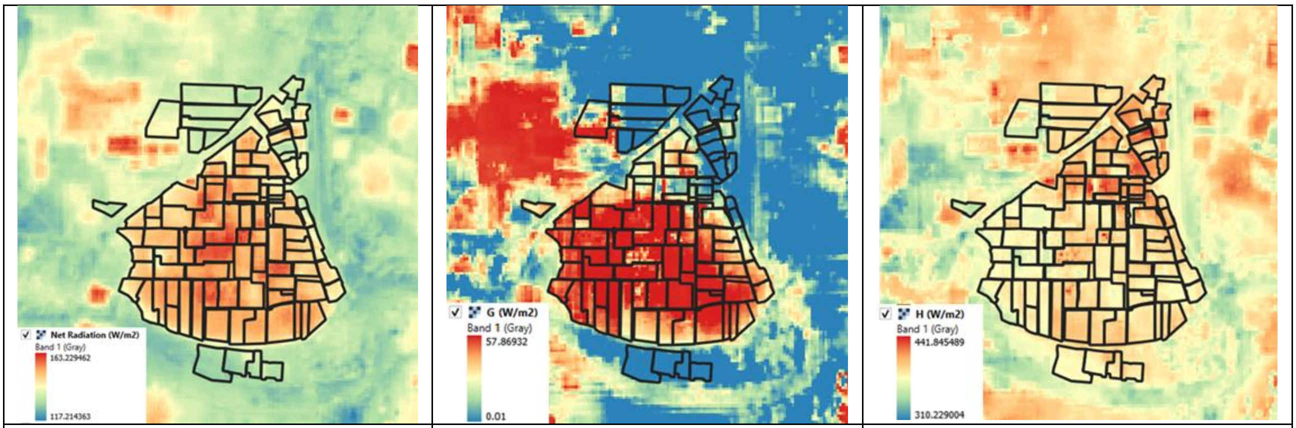


Figure 2: Flow chart of the SEBAL calculation scheme with extreme endpoints of hot (dry) and cold (wet) pixels that forms the basis of self-calibration. LST, surface albedo and NDVI are the major input parameters

This "self-calibration" of SEBAL eliminates propagation of errors on the energy balance partitioning. Simultaneously, the need for radiometric and atmospheric correction of surface temperature becomes less relevant because instantaneous ΔT and H values are forced to certain values at specific hot and cold pixels. The absolute values of thermal imagery LST (or T_0) do not matter. A systematic error of 2K or more in LST is thus not causing any problem. The relative value of LST is much more important. This aspect makes SEBAL very popular because the results are no longer dependent on accurate LST calibrations, atmospheric corrections and available air temperature records. Consumptive use of irrigated crops can be determined without information on the irrigation schedule.



Net radiation Rn (W/m2)	Soil heat flux G (W/m2)	Sensible heat flux H (W/m2)

Figure 3: Example SEBAL energy balance outputs that create the basis for ET mapping. The data is from Odisha State acquired on 27 January (2024)

The **latent heat flux** (λE) forms the basis for determining actual evapotranspiration rate (ET) expressed in mm/d using the following conversion factors:

$$ET = 86.4\ 10^{6}\ \lambda E_{24} / (\lambda\ \rho_{w})$$

Where $\boldsymbol{\lambda}$ *is the latent heat of vaporization (approximately 2.45 MJ/kg for water at typical temperatures) and* ρ_w *is the density of water (approximately 1000 kg/m*^{3}*). In case the 24-hour average value of λE is considered (*λE_{24}*), the factor 86.4 10*^{6} *is used to convert* λE_{24} *directly into an ET rate expressed in mm/d.*

The Surface Energy Balance Algorithm for Land (SEBAL) is developed by Prof. Wim Bastiaanssen from Hydrosat (www.hydrosat.com). Professor Bastiaanssen is also engaged to Delft University of Technology (Netherlands) for continuous updates and improvements of the model. The earlier work at the DLO Winand Staring Centre, Wageningen University, International Water Management Institute IWMI and UNESCO-IHE contributed significantly to the development of SEBAL versions 1.0 to 3.0. The most important co-workers are Prof. Massimo Menenti, Prof. Yasir Mohamed, Ir. Tim Hessels and Dr. Roula Bachour.

A model is never finished. IrriWatch and Hydrosat developed a propriety version (SEBAL4.0) that has several new features being introduced since 2019. They are related to new procedures for hot and cold pixel selection, separation of ET into T and E, soil moisture in the root zone, besides a new routine to describe the behaviour of stomates, being essential to determine the dry matter production

Crop growth modelling

Figure 4 demonstrates that the Transpiration rate T is proportional to daily crop production because T exhalation and CO_2 inhalation occurs via the same stomates. The stomatal aperture is the key regulator for the intake of CO_2. The CO_2 flow is mathematically defined by the stomatal resistance r_s and the difference of CO_2 concentration in air and inside the stomatal cavity. So, knowledge on the λE flux can be thankfully used to determine stomatal aperture and the assimilation of atmospheric carbon. Together with data on the Photosynthetically Active Radiation (PAR) - being also a SEBAL input - it becomes feasible to compute crop dry matter produce from photosynthesis (see Figure 4). More photosynthates are being produced if the crop is relatively cool, being expressed as parameter Ts in Figure 4. Sensible heat flux H is small, and more CO2 is taken by the crop for expansion of roots, stems, leaves and grains.

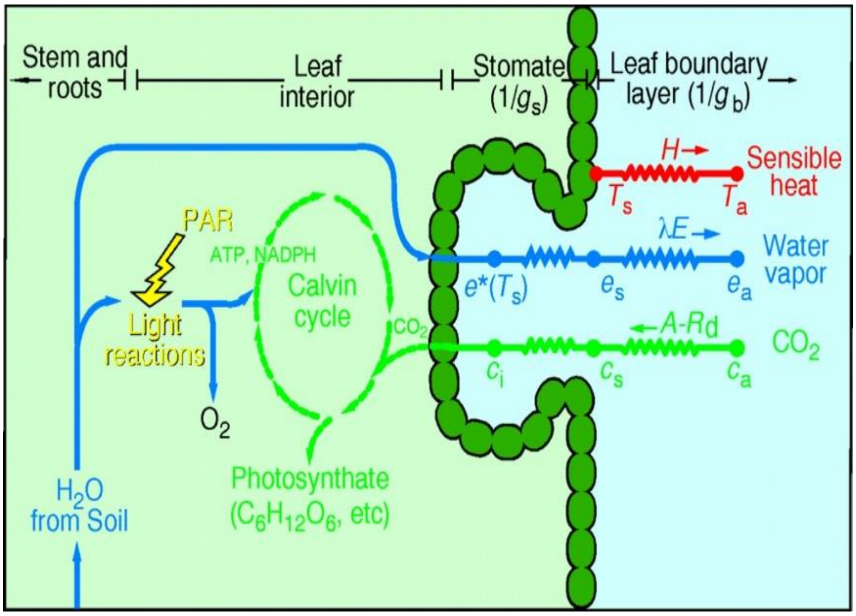


Figure 4: Schematic diagram of the exhalation of water vapour into the atmosphere (λE) as a function of sensible heat flux H and the Inhalation of CO_2 for the generation of photosynthates ($C_6H_{12}O_6$)

Soil Water Balance Modelling

The latest version of SEBAL includes an integration between the surface energy balance and soil water balance where actual ET is the common denominator for both. Because ET is a large component of the water balance, it provides great insights in the magnitude of the various terms. For instance, if ET is high and Precipitation P is low, then there must be another source of water, otherwise large ET rates cannot be explained. Another fact is that if λE is a large fraction of Rn, most available energy goes to ET so the root zone must be moist. This section describes how information on spatial ET can be utilized to infer irrigation water applications.

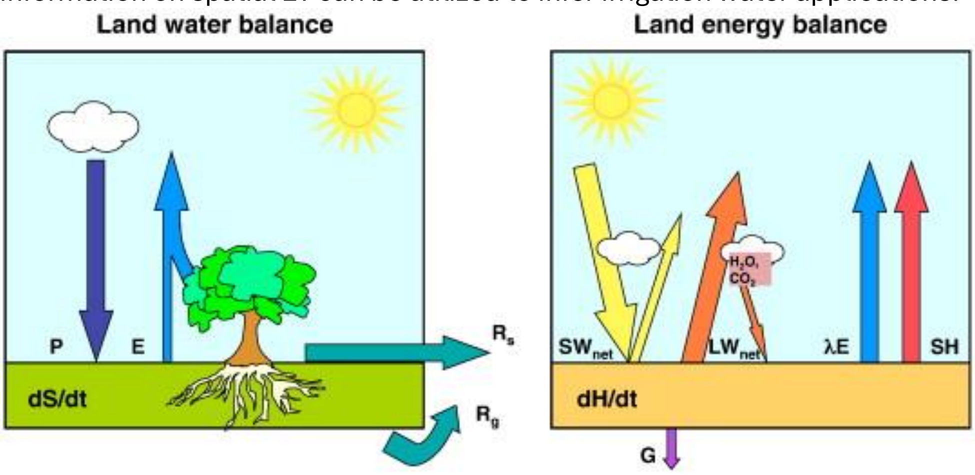


Figure 5: Integrated surface energy and soil water balance modelling. The evapotranspiration process λE and E is part of both balances.

The soil water balance model in Figure 5 has been employed to acquire a spatially distributed estimation of every term of the balance for every pixel. The soil water balance computes surface runoff Rs following a soil moisture deficit and presence of roots. This is a modified version of the Soil Conservation Service equation that has fixed infiltration capacities described by means of Curve Numbers. Water that percolates from the root zone is no longer available for ET and reduces soil water storage. In line with Darcian flow in unsaturated soil, the mathematical expression for percolation $q_{\downarrow}$ is a non-linear function of the degree of soil moisture saturation. The monthly application of irrigation from the farm gate or pumping house express as Applied Water AW can be approximated as:

$$AW = ET + R + q_{\downarrow} + \Delta S - P$$

> *where P is precipitation, AW is Applied Water, ET is actual evapotranspiration, R is surface runoff, $q_{\downarrow}$ is the percolation from root zone and ΔS is the change in storage of water in the root zone. The latter describes the difference between all inflows and all outflows. Applied Water can thus be approximated from remotely sensed ET and ΔS values, in combination with soil moisture (θ) dependent values of R(θ) and $q_{\downarrow}(\theta)$.*

In California, it is common to allocate groundwater on the basis of ET from Applied Water or ETaw. Hydrological background studies have determined the maximum volume of ETaw to realize a new equilibrium situation with zero-overdraft for different sub-aquifers. To accommodate ETaw as a basis for allocation and compliances, the IDC model (https://data.cnra.ca.gov/dataset/idc-version-2015-0-77/resource/238d3e2b-a985-4db7-9793-933ba6d525af) is used for the assessment of ETaw from ET. In short this can be expressed as:

$$ETaw = ET - ETpr$$

Where ETpr is the ET that is related to precipitation values only. While SEBAL provides the storage in the root zone from real world conditions with a mixture of rainfall and irrigation i.e. storage S, IDC model is applied to any pixel of 10m x 10m to compute the storage in the root zone without irrigation Spr. Values for ETpr are approximated from the ratio of the two storages:

$$ETpr = \alpha \, ET$$

with

$$\alpha = Spr / S$$

When the storage from antecedent rainfall is getting negligible small, α reduces to zero and ETpr will fade away. Under that condition all the ET can be ascribed to ETaw. ETaw is a very appealing parameter for the calculation of on-farm irrigation efficiency (ETaw/AW x 100%), but a bit complicated to get to it. The schematic below provides an illustration of how ETpr from rainfall and ETaw from irrigation are computed in parallel. Basically 2 parallel soil moisture buckets for every pixel are parameterized.

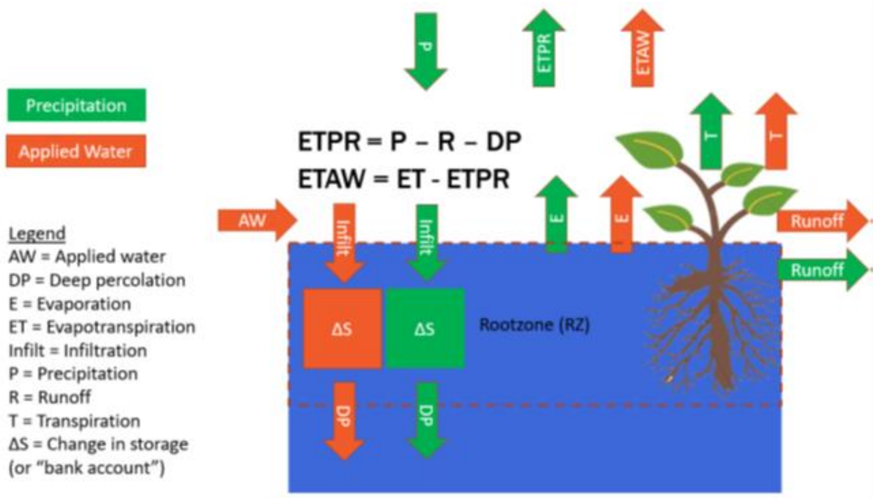


Figure 6: Illustration of how Precipitation P and Applied Water AW have their own impact on ETaw and ETpr calculations (courtesy: J.C. Davids)

Annex 2: IrriWatch Portal Overview

The IrriWatch portal (irriwatch.hydrosat.com) of Hydrosat provides daily monitoring of all the fields within the county. Our energy balance and water balance algorithms are run every day and provide data for every field at 10 m by 10 m spatial resolution.

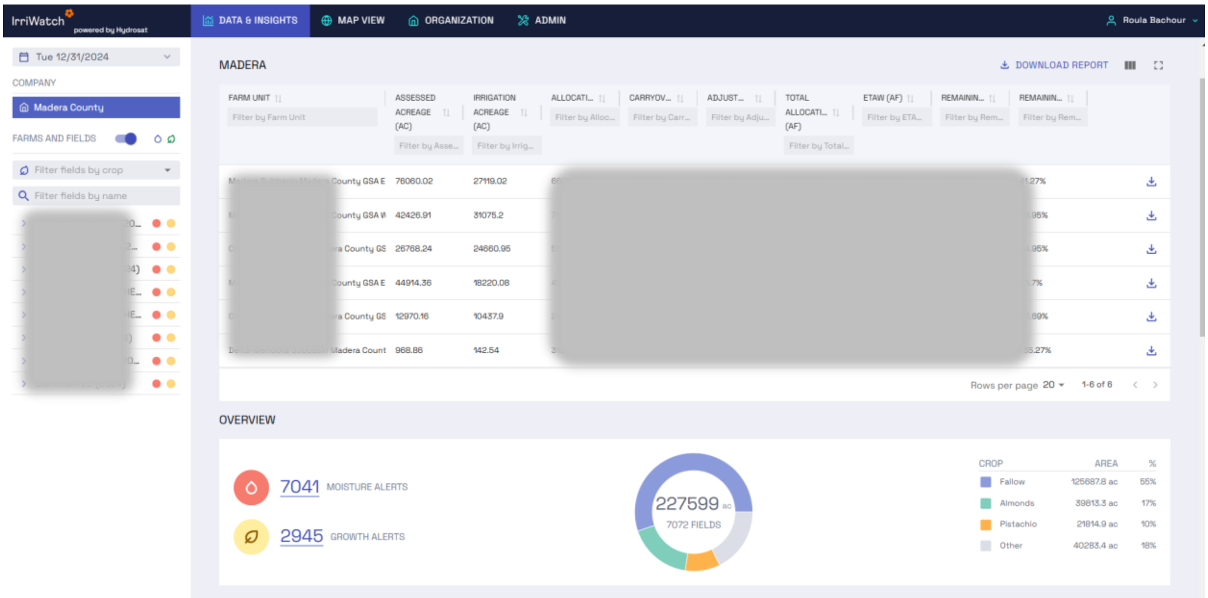
The portal allows data access for the Madera County GSA(s) to see and monitor all fields, while also allowing individual growers or companies to have access to their own parcels and fields.

The standard IrriWatch portal is tailored to farmers to be used for irrigation scheduling, soil moisture, and crop monitoring. However, for water allocation monitoring we have tailored our portal to provide more insights into the actual evapotranspiration from applied water (ETAW) vs Allocations and monitor the remaining allocations. For this budget tables are presented for each farm unit, each sub-basin etc. At the same time, monthly reports are generated at parcel level, farm unit level and master account level allowing maximum flexibility and visibility about data.

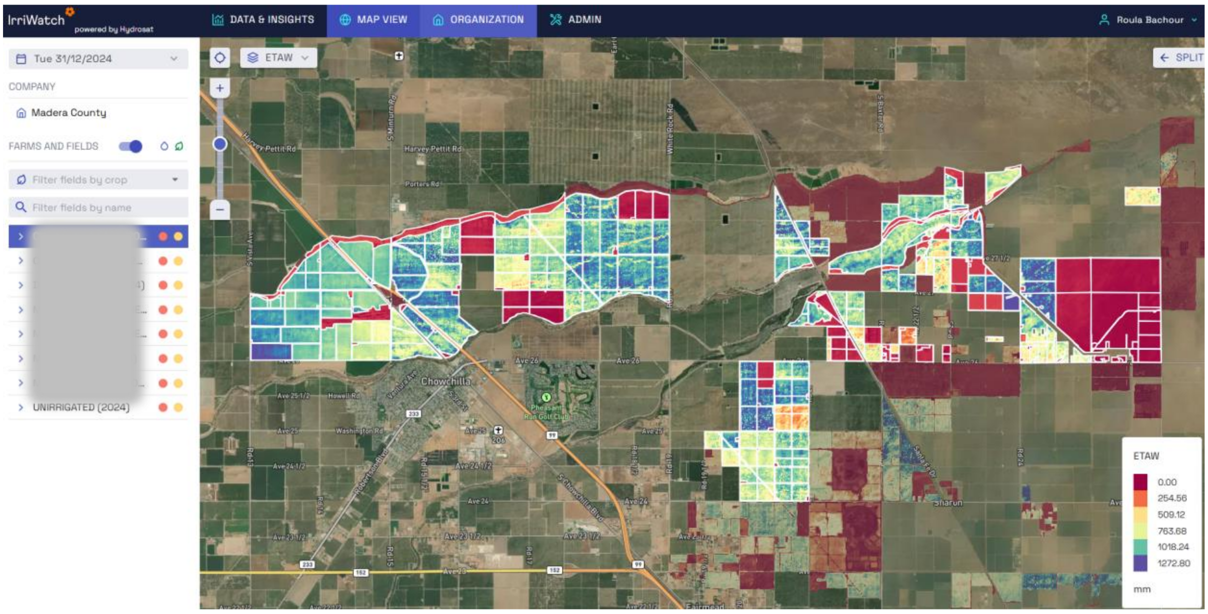
In addition to our web portal, data is also delivered via an API, excel downloads, PDF reports and Mobile App.

In the following screenshots we show examples from our web portal from Madera County (some names/values are blurred out for privacy).

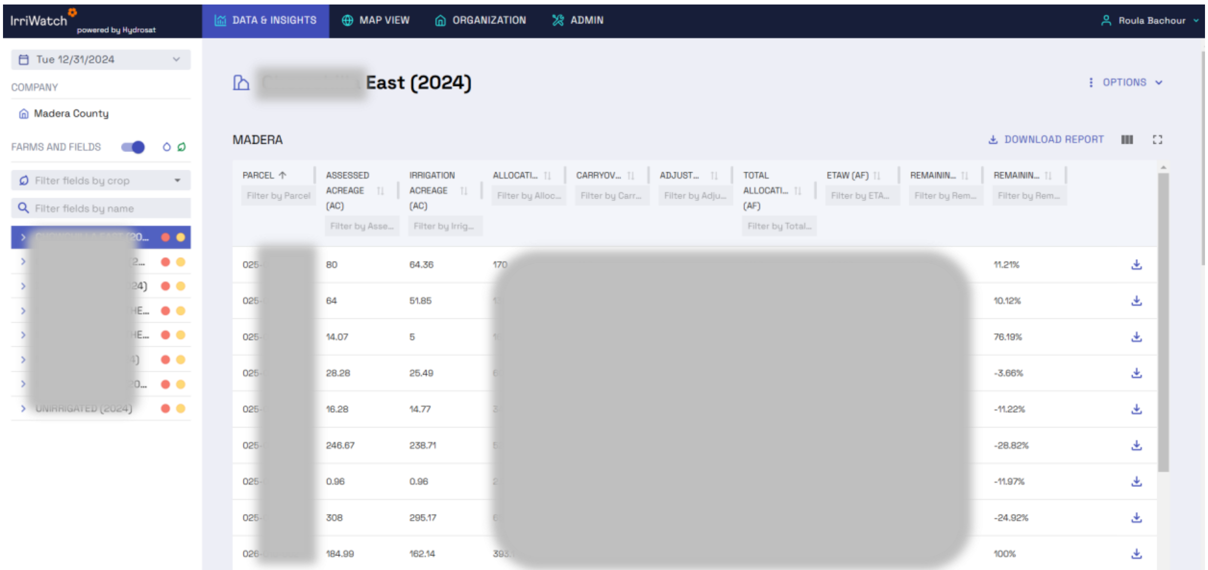
Overview of All County sub-basins and the budget tables



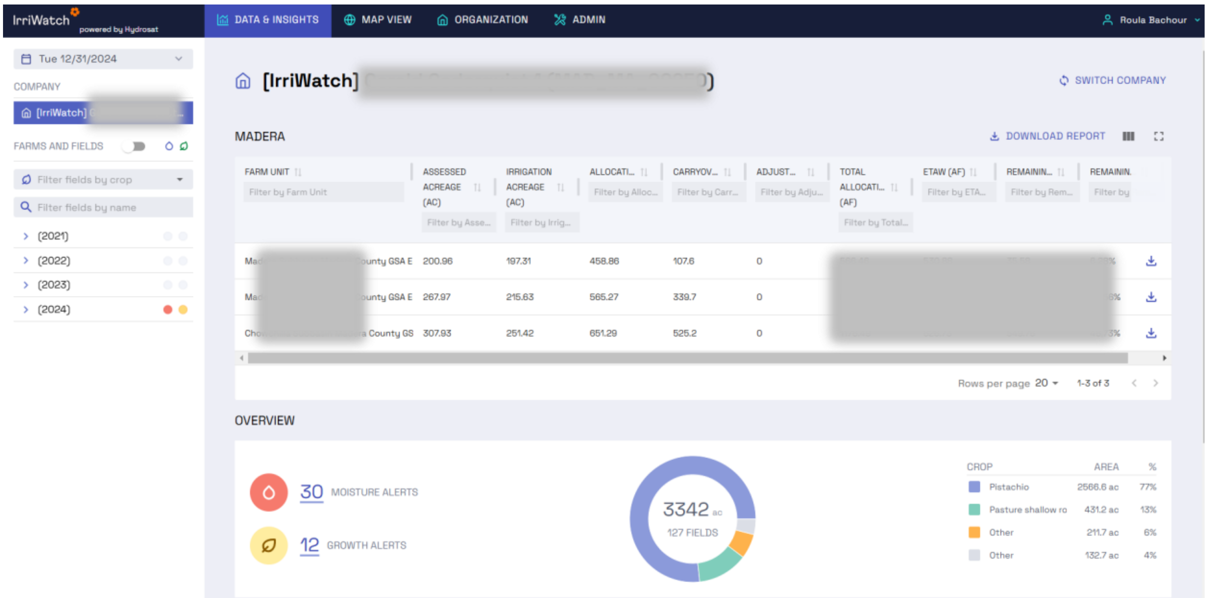
Overview of one sub-basin from the County level (pixel maps showing the ETAW)



Overview of each sub-basin with Budget tables updated on daily basis (Downloadable PDF reports for each parcel generated at the end of each month)



Individual accounts for each grower including their farms units and parcels



Daily monitoring of ETAW vs. Allocation available for each parcel

Thank you!

Hydrosat Team