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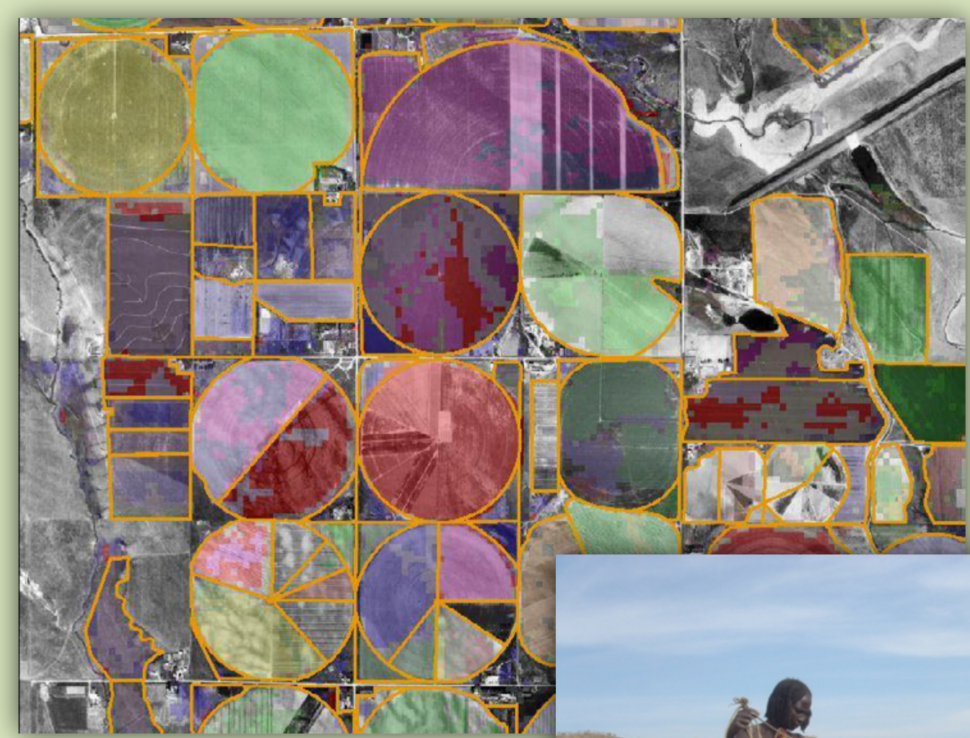
Landsat and Water—Case Studies of the Uses and Benefits of Landsat Imagery in Water Resources

By Larisa Serbina and Holly M. Miller



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Contents

Figures

Table

Acronyms

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DMC	Disaster Monitoring Constellation
METRIC	Mapping EvapoTranspiration at high Resolution with Internalized Calibration
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
SPOT	Système Pour l'Observation de la Terre (System for Earth Observation)
SRTM	Shuttle Radar Topography Mission

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Executive Summary

The Landsat program has been collecting and archiving moderate resolution earth imagery since 1972. The number of Landsat users and uses has increased exponentially since the enactment of a free and open data policy in 2008, which made data available free of charge to all users. Benefits from the information Landsat data provides vary from improving environmental quality to protecting public health and safety and informing decision makers such as consumers and producers, government officials and the public at large. Although some studies have been conducted, little is known about the total benefit provided by open access Landsat imagery.

This report contains a set of case studies focused on the uses and benefits of Landsat imagery. The purpose of these is to shed more light on the benefits accrued from Landsat imagery and to gain a better understanding of the program's value. The case studies tell a story of how Landsat imagery is used and what its value is to different private and public entities. Most of the case studies focus on the use of Landsat in water resource management, although several other content areas are included. A brief list and description of the case studies is as follows:

Introduction

- **Space Policy**: explores the requirement of the government to provide moderate resolution satellite imagery. Possible alternatives are mentioned along with their costs and characteristic differences.

Federal Use of Landsat Imagery in Water Resources

- **United States Bureau of Reclamation (Reclamation)**: highlights uses of Landsat by Reclamation along with cost savings realized by the agency. Projects and products that would not be accomplished without the use of Landsat imagery are also discussed. The case study illustrates the critical contribution of Landsat imagery in assessing consumptive uses and losses in the southwestern United States, the use of Landsat imagery as a supplemental tool for monitoring and measuring consumptive use within the Lower Colorado River Basin; the use of Landsat imagery in monitoring land cover, land change, and consumptive water use in riparian and agricultural areas of the southwest United States; and the agency's work in water conservation plans using Landsat imagery to help determine present and historical irrigation practices.

Intrastate and Interstate Water Management

- **Wyoming State Engineer's Office and Riverside Technology, inc.**: highlights the use of Landsat imagery to monitor and measure state consumptive water use for compliance with the Upper Colorado River Compact.
- **Hydrologic Modeling, Idaho Department of Water Resources**: focuses on the ability of the state of Idaho to use Landsat in conjunction with METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration) to monitor consumptive use change within the state.

- **Consumptive Use Mapping, Nevada Division of Water Resources**: illustrates the frequent use of Landsat to verify irrigation on land in various parts of the state. Landsat imagery serves as an independent source of information which helps to confirm or deny claims.
- **Use of Landsat Imagery for Water Accounting, State of Colorado**: captures the use of Landsat imagery to measure and monitor water in various basins throughout the headwater state.
- **StateCU and Landsat, Colorado Water Conservation Board and Riverside Technology, inc.**: compares the use of Landsat imagery and the METRIC model to the use of the StateCU model for estimating consumptive use within the state.
- **Colorado South Platte Decision Support System, Riverside Technology, inc.**: uses the Landsat platform for decision making regarding water resources and agricultural crop production along the South Platte River.
- **Sonoma County Water Agency, California**: describes the continuous use of Landsat imagery in Sonoma County for water budgeting and accounting, particularly as it pertains to the viticulture production in the area.
- **Russian River Normalized Difference Vegetation Index (NDVI) Methodology and Use, California:** shows the updating of field maps using Landsat imagery in California's northern grape growing region.

Irrigation in Agriculture

- **E. & J. Gallo, California**: explores ways in which a winery is using Landsat imagery during the growing season to improve yield and grape quality while decreasing the amount of water applied.
- **Vineyards, Apple, and Olive Orchards, Chile**: looks at the use of Landsat imagery for yield and quality optimization of grapes, apples, and olives along with water application savings due to water crop coefficient estimates.
- **Irrigation Improvements, Australia**: shows the progress in the improvement of yield optimization conducted by the State of Victoria government using Landsat imagery to increase "crop per drop" ratio.
- **Morocco Irrigation Improvements, Riverside Technology, inc.**: focuses on the work done in Morocco by Riverside on improving irrigation methods through the use of Landsat imagery and irrigation technology.

Streamflow Water Rights

- **Salmon Basin, Idaho**: exemplifies the use of Landsat imagery for in-stream flow rights and promoting the recovery and health of streams and endangered species by looking at evapotranspiration mapping with Landsat and METRIC.
- **Klamath Basin, Oregon**: highlights the use of Landsat imagery for water-rights assessment for basin-wide management.
- **Walker River Basin, Nevada**: similar to the use of Landsat data in the Klamath Basin, Landsat data are used as additional information in helping assess consumptive use prior to purchase or transfer of water rights.

Water Dispute Settlements

- **A&B Irrigation District, Idaho**: describes a restriction on water allocation from the river for low-priority users that was dismissed by the courts by using Landsat imagery and METRIC data as evidence.
- **Clear Springs Foods Inc., Idaho**: a case of a curtailment order enacted when Landsat images and METRIC showed harm had been caused to senior water-rights holders.

Water Exploration

- **Radar Technologies International, Darfur**: shows that Landsat imagery has contributed to saving thousands of lives in dire circumstances by providing refugees with quick access to water in an arid climate.
- **Exploration Signatures, Venezuela**: highlights the use of Landsat imagery in identifying potential well sites in the State of Falcón in order to provide water to rural and urban populations that previously required water trucking.

Flood Mapping and Monitoring

- **Flood Extent and Disaster Mapping, Australia**: describes various uses of flood extent mapping from forest management for emergency response use of Landsat imagery.
- **Flood Extent Monitoring in Riparian Forests, Australia:** inputs Landsat imagery as an independent source used for calibration of hydrological models. Model outcomes are used to carry out best forest management practices in areas of high flood risk.
- **National Flood Risk Information Program, Australia:** illustrates the use of Landsat imagery for flood insurance purposes.

Land Cover Mapping

- **Mapping Africa, Radar Technologies International**: highlights the many errors and inconsistencies in colonial era maps of Africa that have been corrected with the use of Landsat imagery.
- **Land Cover Mapping, Australia**: shows the use of Landsat imagery for mapping agricultural and riparian areas of the country to monitor current and historical land cover change.

Landsat and Water—Case Studies of the Uses and Benefits of Landsat Imagery in Water Resources

By Larisa Serbina and Holly M. Miller

Introduction

Landsat satellites have been operating since 1972, when the first Landsat satellite, Earth Resources Technology Satellite 1, was launched. In February 2013, the National Aeronautics and Space Administration (NASA) successfully launched Landsat 8, and in May 2013, operational control was handed over to the U.S. Geological Survey (USGS). Recently, the program also decommissioned Landsat 5, the longest operating Earth observation satellite after 29 years of operation. Currently, two Landsat satellites are operational: Landsat 7 and 8. Landsat 7 has a technical issue that results in missing data in each scene, which at times limits data uses. Landsat 8 is currently providing hundreds of complete scenes a day of high quality data to users.

Landsat imagery is available in an archive from present time dating back to 1972, making it the longest continuous archive of satellite imagery. At the end of 2008, the entire archive of Landsat imagery became available online at no cost to all users. The free and open data policy had a significant impact on users, resulting in a tenfold increase in the number of users registered with USGS, as well as a more than hundredfold increase in the number of scenes distributed annually.

Landsat imagery has a vast number of users and uses. The benefits of information that Landsat data provide vary from improving environmental quality and protecting public health and safety, to informing decision makers, such as consumers and producers, government officials, and the public at large. Although some studies have been conducted, little is known about the total benefit provided by open access Landsat imagery.

In general, the value or benefit of the information largely depends on four factors:

1) “how uncertain decision makers are;
2) what is at stake as an outcome of their decisions;
3) how much it will cost to use the information to make decisions; and
4) what is the price of the next-best substitute information” (Macauley, 2005, p. 3).

There are various approaches for estimating the value of information using quantitative economic models and qualitative descriptors. In 2009 and 2012, Landsat users were surveyed by USGS (Miller and others, 2013). The surveys quantified the economic benefits direct users received from Landsat imagery, based on the contingent valuation method.

The contingent valuation method could not be used in a single study to cover the broad range of applications presented in this report. The case studies provided here take a more qualitative approach, exploring each particular use of the imagery and its benefits and challenges as seen by the users. The case studies provide a story of users and uses while focusing on the four factors that influence the value of information. They enrich our understanding by complementing the economic benefit modeling and shedding more light on the value of Landsat imagery.

The majority of the case studies in this report focus on the use of Landsat data in the area of water resource management, including both U.S. and international uses and benefits. The report begins with a broad examination of laws and policies supporting the Landsat program and best available alternatives, as well as the implication of the free and open data policy. The report then moves into uses and benefits of Landsat imagery specific to water resources.

Space Policy

The USGS is required by the Federal government to provide and archive remotely sensed data such as Landsat imagery. The National Space Policy of 2010 (p. 12-13) states that:

> "The Secretary of the Interior, through the Director of the United States Geological Survey (USGS), shall:
>
> - Conduct research on natural and human-induced changes to Earth's land, land cover, and inland surface waters, and manage a global land surface data national archive and its distribution;
> - Determine the operational requirements for collection, processing, archiving, and distribution of land surface data to the United States Government and other users…"

The Landsat program has played a key role in meeting this policy requirement. However, the data are not mandated to be Landsat imagery and may come from other sources that meet the policy requirements and standards. In 2009, given a certain degree of uncertainty regarding the operational lifespans of Landsat satellites 5 and 7 and the length of time before the scheduled launch of Landsat 8, the USGS Land Remote Sensing (LRS) Program began purchasing SPOT imagery in order to ensure continuous data coverage over most of North America. In this case, SPOT was chosen as the most cost effective option available to the Landsat program. Between December 2009 and June 2013, SPOT data were acquired through a series of purchase orders; each order was completed by the USGS Office of Acquisition and Grants (OAG). The total award amount for SPOT imagery varied from year to year. The cost and conditions for five acquisition installments for continuous coverage are as follows:

- Period covered: November 5, 2009 – through June 30, 2013
- Approximate number of scenes acquired: More than 256,000
- Total cost: $3.63M
- Per scene cost: $14 (nine SPOT scenes cover the area equivalent to one Landsat scene)

The USGS has not acquired SPOT data since June 30, 2013, as Landsat 8 was operational by that time. However, these purchases provide insight into the actual cost of a substitute product that could be bought in the absence of functioning Landsat satellites. These costs can be extrapolated for multi-year estimates. Additionally, it can be anticipated, based on economic theory, that without Landsat data availability, the increased demand for SPOT imagery would lead to an increase in the price of SPOT imagery.

Although SPOT has been identified as a data stream that could augment and perhaps partially mitigate a loss of Landsat data, several trade-offs exist in this scenario. For instance, SPOT data is acquired under various contracts, each one having a different set of rules and systems for keeping track of the data and its eligible users. Additional processing of the imagery is also necessary in order to provide data which is equivalent to the standard Landsat product now available. The management and processing of the SPOT data require time and costs that are not accrued with the Landsat program. Due to the difference in the swath dimensions, it would require approximately nine SPOT scenes to cover an area equivalent to a single Landsat scene. This has additional processing and time costs for users. Additionally, the bands on SPOT are not identical to that of Landsat. For example, SPOT does not have a thermal band, the presence of which on Landsat allows for extensive applications in water resources.

In fact, the majority of the case studies in this report focus on the benefits in water resources, most of which would not be possible without the presence of the thermal band on the satellite instrument. The cost of the SPOT imagery purchase reflects only the coverage of North America. If this data-acquisition plan was followed, the opportunities for benefits through the use of Landsat global coverage would no longer exist. Furthermore, the substitute data would be available to civilian Federal government, State government, local government, and Tribal users, and everyone partnering with those entities, leaving out the private sector and academic users and uses. This indicates that the benefits acquired by private, academic, and international entities from no-cost Landsat imagery would not exist. More so, SPOT data can be purchased more than once when purchases are made by different agencies or users. For example, Department of Defense, civilian Federal government, State government, and local government could all purchase SPOT data under different contracts, with constrained user access. This structure could result in the government paying the cost of imagery multiple times.

Landsat in Water Resource Management

Water availability and allocation are issues gaining a great deal of attention, particularly in arid climates. Increases in population growth and recent droughts bring urgency to measuring and monitoring water use in areas such as the western United States, where the majority of the water has already been allocated.

In the world of water resource management, Landsat has played a key role in providing objective and continuous data for the United States, particularly in the arid west. Water-related benefits of Landsat imagery are also reaped far beyond the United States' borders in countries such as Chile, Australia, Morocco, Sudan, and Venezuela, which are using Landsat data to make informed decisions regarding natural resource allocation and use.

Federal Use of Landsat Imagery in Water Resources

U.S. Bureau of Reclamation

The Water Accounting and Verification group of the U.S. Bureau of Reclamation (Reclamation) uses Landsat data for various tasks. These include mapping, monitoring, and quantifying crop and riparian vegetation types and associated acreage for water resource and other management activities. The monitoring area includes the Colorado River from the Hoover Dam to Mexico and the adjacent agricultural areas. This represents approximately 870,000 acres of irrigated lands and approximately 500,000 acres of riparian area, totaling 1,370,000 acres. Landsat imagery is used as an input in a variety of analyses including:

- Annual estimation of evapotranspiration from irrigated areas for monitoring of agricultural water use,
- Annual estimation of evapotranspiration from riparian vegetation for monitoring water use,
- Estimation of evaporation from the channel and reservoirs of the lower Colorado River and evaporation from canals, lakes, lagoons, and other open water areas, and
- Identification of types, locations, and acreages of crops, irrigated lands, and riparian vegetation, as well as fallow land, both current and historical.

Reclamation projects require detailed current and historical land-use data. Although programs such as National Agricultural Statistics Service (NASS) cropland mapping provide land-use data, the data is presented for large scale analysis to identify trends at state or national scales. State- and national-level statistics are insufficient in addressing the many requirements for the uses listed above and described below. However, the results of Landsat-based analyses can be summarized at the individual agricultural field level, within irrigation district boundaries, outside of irrigation district boundaries, within wildlife refuges, by river reach, and within any site specific geographic area on the system (for example, a conservation unit). Additionally, many fallowing programs, drought studies, groundwater studies, and so on, require historical and current data to establish both baseline and current conditions. Historical data and current data at the smaller scale are often times non-existent outside of data derived from satellite imagery. Generating comparable data without Landsat would require an increased amount of fieldwork and time costs, and would hinder the accuracy and temporal consistency in the data.

Landsat imagery is unique in that it comes from a series of satellite sensors that have been continuously and consistently monitoring the Earth's surface since the 1970's. Leveraging these data to provide products such as estimates of land-use change and evapotranspiration through time (using energy balance algorithms) represents a significant cost savings as the examples below demonstrate. Even more so, Landsat imagery makes it possible to generate these types of data sets at a level of accuracy not possible without Landsat data (Jeff Milliken and Paul Matuska, Bureau of Reclamation, oral commun. and written commun., 2013).

Agricultural and Riparian Evapotranspiration

Reclamation is responsible for multi-year riparian and irrigated acreage analysis and associated water use for planning and projecting future water needs. They use calculation methods based on crop-coefficient curves with crop data generated from Landsat imagery to estimate evapotranspiration from irrigated lands. Reclamation is also in the process of actively testing energy balance algorithms such as METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration), which uses Landsat imagery, as a supplement to the current methodology. Based on comparable spectral and spatial resolutions, SPOT or DMC satellite data could be used for mapping agricultural types without the availability of Landsat. However, because these sensors do not have a thermal band, energy balance algorithms such as METRIC could not be used for estimating evapotranspiration. For riparian and agricultural monitoring alone, access to no-cost Landsat data represents an annual cost savings of approximately $40,000. Another alternative would be to conduct 100 percent field-based monitoring as opposed to the 10 percent field sample required for the current Landsat-based methodology. This method would see a ten- to twentyfold increase in costs per year. In order to accomplish this sampling task, two federal term employees would be needed for 10 months to sample everything currently sampled now at the same frequency. The costs for data collection alone would be around $580,000, based on an $80/hour burdened rate for two people and travel expenses. Additional costs for data processing would follow data collection (Paul Matuska and Jeff Milliken, Bureau of Reclamation, oral commun. and written commun., 2013).

Consumptive Uses and Losses Reports

The Colorado River Basin Project Act of 1968, Public Law 90-537, Section 601 (b)(1), dated September 30, 1968, directs the Secretary of the Interior to "make reports as to the annual consumptive uses and losses of water from the Colorado River System after each successive five-year period, beginning with the five-year period starting on October 1, 1970." Reclamation is investigating the use of historic Landsat data with energy balance methodologies such as METRIC, to improve estimates of agricultural evapotranspiration estimates for both historic and current periods. These efforts will provide agricultural estimates of consumptive use in the Lower Basin's tributaries to the Colorado River. Ultimately, the natural flow model of each tributary will assist in modeling the water supply for the Colorado River (Paul Matuska, Bureau of Reclamation, oral commun. and written commun., 2013).

In order to complete this task using energy balance algorithms, frequent (usually monthly) multi-spectral and thermal imagery is needed. Without the availability of archived Landsat data from 1972 to 2012, this would not be possible. Although SPOT satellite data could be used to estimate evapotranspiration using a vegetation index or other methods (no thermal band), the SPOT 1 satellite was launched in 1986, preventing any analysis prior to that year. Considering that for this project 1 million acres of agricultural land are assessed with 8 analysis periods since the 1970's (every fifth year), and using a monthly time step needed for an energy balance algorithm, a total of $450,000 in image costs ($75,000 per analysis period) would have been incurred if SPOT imagery had been purchased since the 1980's when it first became available. Commercial satellite systems would be more expensive than this, while MODIS would not be a suitable substitute due to its resolution being too coarse to provide the needed accuracy for the field-level consumptive use measurement (Jeff Milliken, Bureau of Reclamation, oral commun. and written commun., 2013).

Water Conservation Plans

Reclamation evaluates water conservation plans by using Landsat data to determine present and historical irrigation practices. This helps in the decision-making process to determine which conservation activities result in water savings to the system. Landsat data is also used to verify conservation under the Inadvertent Overrun and Payback Policy (IOPP), Intentionally Created Surplus (ICS), and System Conservation (SC) programs. The imagery is used for verification of land fallowing activities for these programs. Landsat infrared imagery easily lends itself to be used for identification of fallow and irrigated land. Figure 1 shows a clear distinction between irrigated (in red) and fallow (in light green) land, making the identification and verification process easy. Landsat imagery helps with the determination of authorized and unauthorized land use, analysis of land-use change over time, and estimation of future land-use demands. Only 5 percent of fields are visited in person, while the rest are verified through Landsat imagery review. In the case that Landsat data is not available, the percent of field visits would increase to 100 percent for all fields that require monitoring per particular fallowing agreements. Additional time and costs would be associated with the latter approach. Landsat imagery is also used to determine past and current cropping patterns and associated water use in potential habitat conservation areas for the Multi-Species Conservation Program (MSCP) as well as water balances for MSCP. Archived and current Landsat data make the analysis possible at the field level. Although other historical data for crops exists (such as data produced by NASS), the geographic scale is often limited to counties, which makes analysis of land change on a smaller geographical scale impossible without satellite imagery (Paul Matuska, Bureau of Reclamation, oral commun. and written commun., 2013).

Reclamation's Customers

Many of the reports and data sets produced by Reclamation are used by other entities, including Federal agencies, State agencies, universities, and private businesses such as agricultural producers and contractors. The USDA uses the Landsat-derived data as control data for their cropland data layer. The USGS and the Arizona Department of Water Resources (ADWR) use the data to estimate annual groundwater withdrawals in the Lake Mohave, Parker, and Yuma Basins. The ADWR also uses the data for agricultural monitoring and evapotranspiration estimates for the Phoenix and Tucson adaptive management areas. The California DWR uses the data to meet California Water Plan requirements and to map agriculture for the Land Cover Mapping and Monitoring Program. Without the information Reclamation produces from Landsat imagery, these organizations would have to either produce the data themselves or find alternatives, both of which may result in additional costs through increased time or money spent.

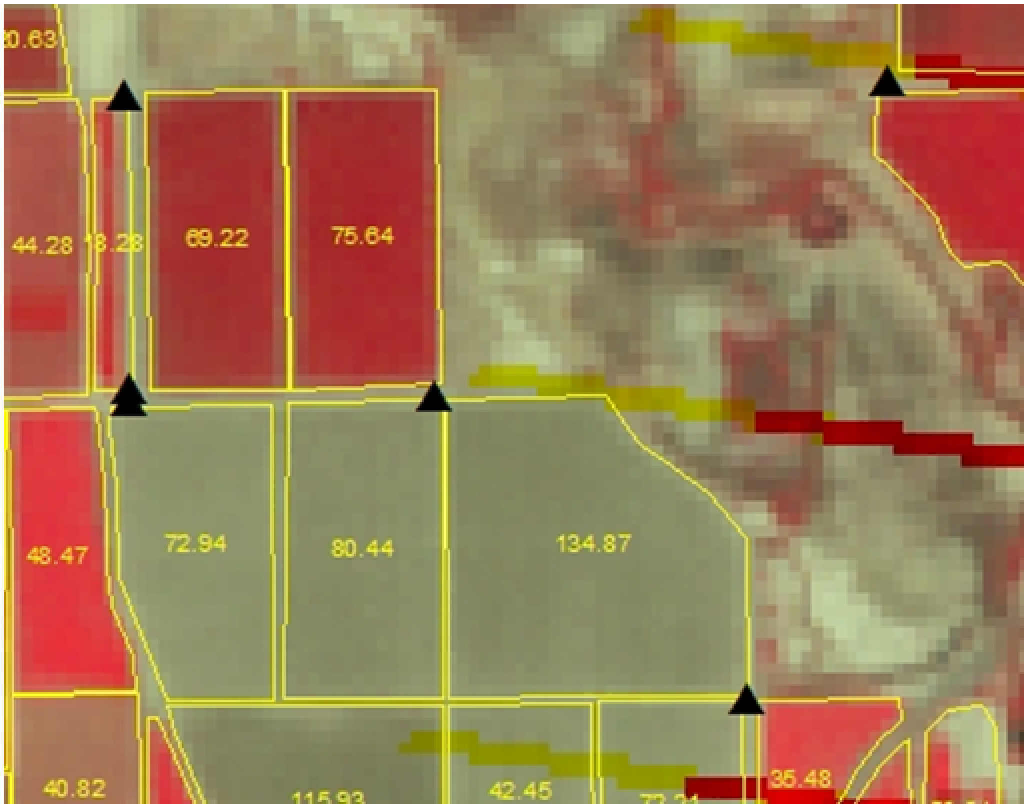


Figure 1. GIS agricultural field border database displayed with Landsat imagery showing the difference between a cropped field (in red) and a fallow field (in light green). Numbers represent acreage of individual fields. Courtesy of U.S. Bureau of Reclamation.

State and Local Water Accounting: Measuring and Monitoring with Landsat

Interstate compacts influence water availability within a given state. In order to stay within the appropriated allocation, water use must be measured and monitored. The Upper Colorado River Compact, which spans across Wyoming, Utah, New Mexico, and Colorado, is a great example of the vast area that must be assessed yearly/seasonally to uphold the Compact. Landsat thermal imagery is a very efficient tool for accomplishing this task. It offers consistency in measurements across the multi-state area, as well as time and cost savings compared to other measurement and monitoring approaches. Federal, State, and county agencies have been identified as users of Landsat imagery in water resource monitoring.

Wyoming State Engineer's Office and Riverside Technologies, inc.: Consumptive use Monitoring for Colorado River Compact

The Colorado River provides water to seven states as well as the Republic of Mexico. The seven states which receive water from the river system are Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming. Water is divided between these entities primarily based on three documents. The Colorado River Compact signed in 1922 allocates water in the basin between the lower basin states (Arizona, California and Nevada) and the upper basin states (Colorado, New Mexico, Utah and Wyoming). The International Treaty with Mexico signed in 1944 guarantees annual delivery of 1,500,000 acre-feet of Colorado River water to that country. Finally, the Upper Colorado River Basin Compact of 1948 divides the water allocated to the upper basin states between those states on a percentage basis. Language in the Upper Basin Compact requires each upper basin state to determine and report their annual consumptive use of water.

For the State of Wyoming, this reporting obligation has historically presented a considerable challenge. The vast majority of water use in Wyoming, as with most western states, occurs due to irrigation. The portion of Wyoming that drains to the Colorado River includes the Green River Basin (fig. 2) and has over 330,000 acres of irrigated lands spread out over 17,000 square miles (mi^2). In addition, water is withdrawn from surface water sources at over 2,000 individual headgates. Under these conditions, accurate on-the-ground measurement of the consumptive use of water is not only costly, but nearly impossible. In 2009, the State of Wyoming turned to the use of remotely sensed data from Landsat and a process developed in Idaho termed METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration; Allen and others, 2007), to assess evapotranspiration from irrigated lands in the Green River Basin (figs. 3 and 4). The METRIC model was originally developed at the University of Idaho to compute and map evapotranspiration using Landsat images. The recent Landsat satellites (5, 7, and 8) contain the necessary spatial resolution and thermal data to conduct an energy balance calculation to determine evapotranspiration at the field scale. The use of Landsat and METRIC has yielded consistent savings from a third to potentially as much as a half of the total costs compared to on-the-ground methods.

The use of Landsat data to assess the consumptive use of water across a large basin provides a savings in time and money for the State. The use of Landsat data in METRIC to estimate evapotranspiration is more efficient and accurate, as well as relatively inexpensive, when compared to traditional methods in use (Allen and others, 2005; Morse and others, 2008). The Landsat thermal band and relatively high spatial resolution are necessary for conducting energy balance analysis and determining consumptive use. Riverside Technology, inc., a private consulting firm, is currently working with the State of Wyoming by helping the state engineer's office map consumptive use in the Green River Basin. This work is done to meet the obligation of the State of Wyoming to the Colorado River Compact administration program.

Despite the efficiencies associated with Landsat imagery use, concerns about potential problems exist. Currently there are two operating satellites: Landsat 7 and Landsat 8. Each satellite has a revisit time of 16 days, providing Landsat imagery as frequently as every 8 days. Landsat 7, however, returns an image with some missing data. Relying on imagery from Landsat 8 only, provides imagery every 16 days at best. Cloud cover on days of satellite overpass may render an image unusable, increasing the gap in imaging intervals to less than what is needed to measure evapotranspiration during a growing season. Therefore, the State of Wyoming is currently moving ahead with a program to continually measure water diverted at as many headgates as possible to ensure the state will have a "back-up" process to measure consumptive use in case of any failures in the Landsat program. This effort is expensive but necessary until an operational Landsat program can be guaranteed. Such a program would need to meet the criteria outlined by the Western States Water Council, which include ensuring the continuity of no-cost global imagery in perpetuity while retaining or improving the existing spectral bands, spatial resolution, and temporal resolution (Willardson, 2012).

Finally, although each of the upper basin states currently uses a different methodology to calculate their consumptive use, there is a study under way by the Upper Basin Commission to evaluate what it may take to conduct some monitoring of all irrigated lands in the upper basin using Landsat imagery. A consistent method across all states will hold each state accountable at the same level of accuracy and efficiency. A decision to move forward with such an effort will be based on the confidence in or certainty of a long-term Landsat program (Steve Wolff, Wyoming State Engineer's Office, oral commun. and written commun., 2013).

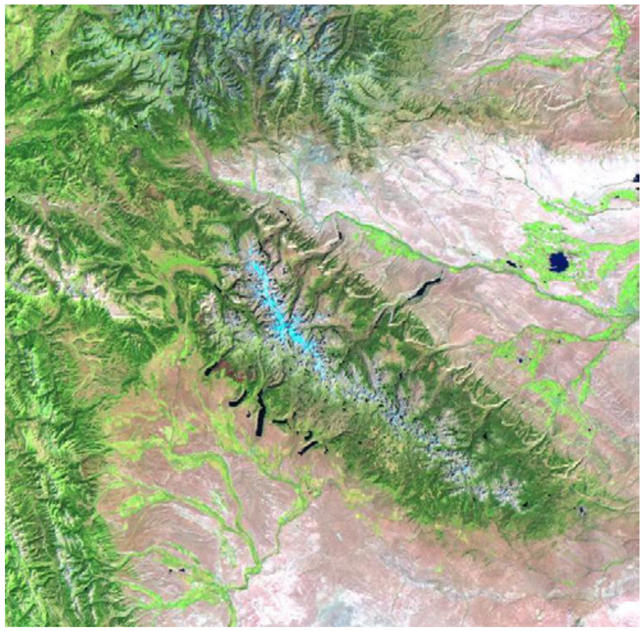


Figure 2. Landsat image of the Upper Green River Basin. Courtesy of Wyoming State Engineer's Office.

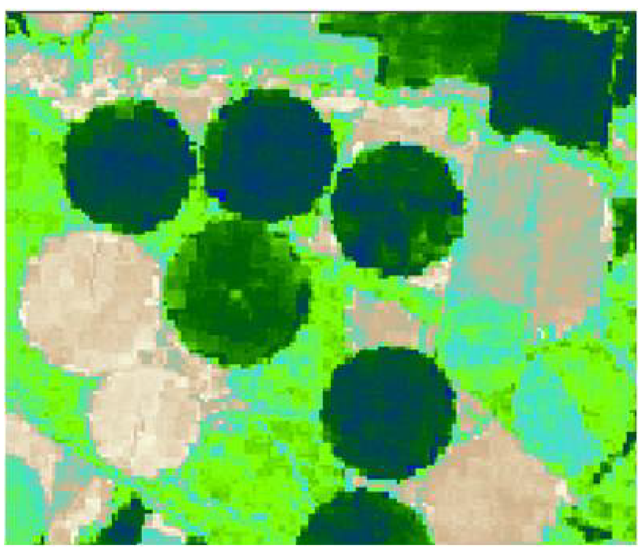


Figure 3. Landsat 5 thermal image processed in METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration) of center pivot irrigated fields in Wyoming. Courtesy of Wyoming State Engineer's Office.

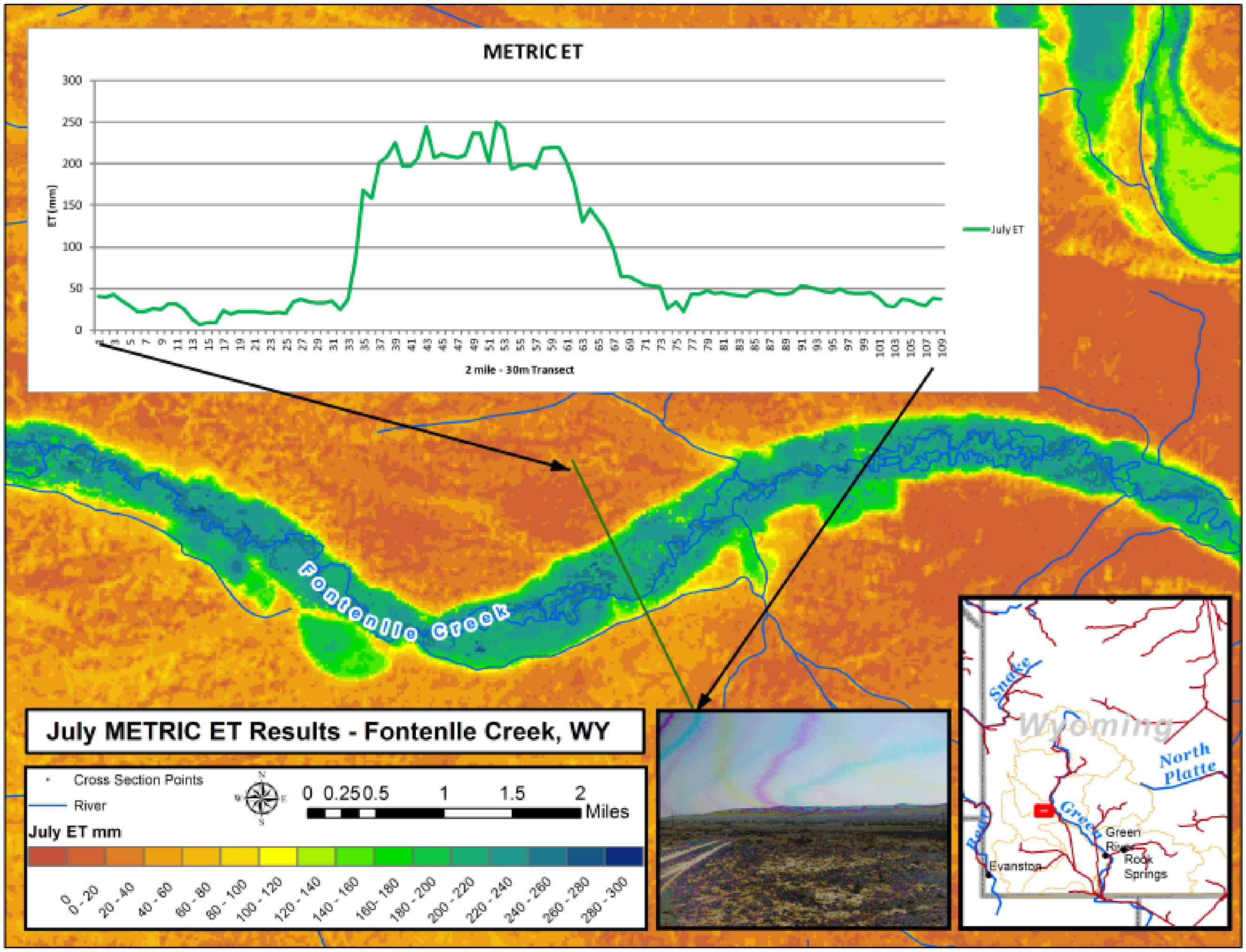


Figure 4. Preliminary monthly evapotranspiration estimation results for the month of July along a narrow river corridor of the Green River Basin when irrigation is applied using surface water deliveries. Courtesy of Wyoming State Engineer's Office. (METRIC, Mapping EvapoTranspiration at high Resolution with Internalized Calibration; ET, evapotranspiration; mm, millimeters)

Hydrological Modeling, Idaho Department of Water Resources

Idaho water law is based on the Doctrine of Prior Appropriation. The doctrine states that a water right is authorized for beneficial use based on priority date: "first in time, first in right." Senior water-rights holders, established before the junior water rights-holders, get priority in fulfilling their water rights. In order to meet senior holders' allocation amounts, actual and historical consumptive water use data are needed. Thus, measuring and monitoring consumptive water use in agriculture becomes an important task for Idaho hydrologists and water engineers.

In order to accomplish the task, hydrologists start by using monthly and seasonal Landsat data processed in METRIC to estimate evapotranspiration on the Eastern Snake Plain Aquifer and the Boise

Valley Aquifer. Estimated evapotranspiration is an input during calibration of a groundwater model called MODFLOW. The improved accuracy of estimation of water depletions from the aquifer caused by crop evapotranspiration provided by METRIC improves model calibration. The METRIC model is also used to compute incidental recharge to the aquifer from surface water irrigation diversions (diversions – evapotranspiration – returns = recharge). The more accurately calibrated groundwater models have been used in litigation involving conjunctive use of groundwater and surface-water resources (Kramber and others, 2012). Landsat data were also used to update the Eastern Snake Plain Aquifer model. Cloud-free Landsat images from 1996, 2000, 2002, 2006 and 2008 were used to estimate monthly and seasonal evapotranspiration (fig. 5). Additionally, evapotranspiration estimates from as early as mid-1980s are being developed with the use of Landsat data. This will allow for the analysis of long term trends in irrigation, evapotranspiration and their impact on the aquifer (Kramber and others, 2012).

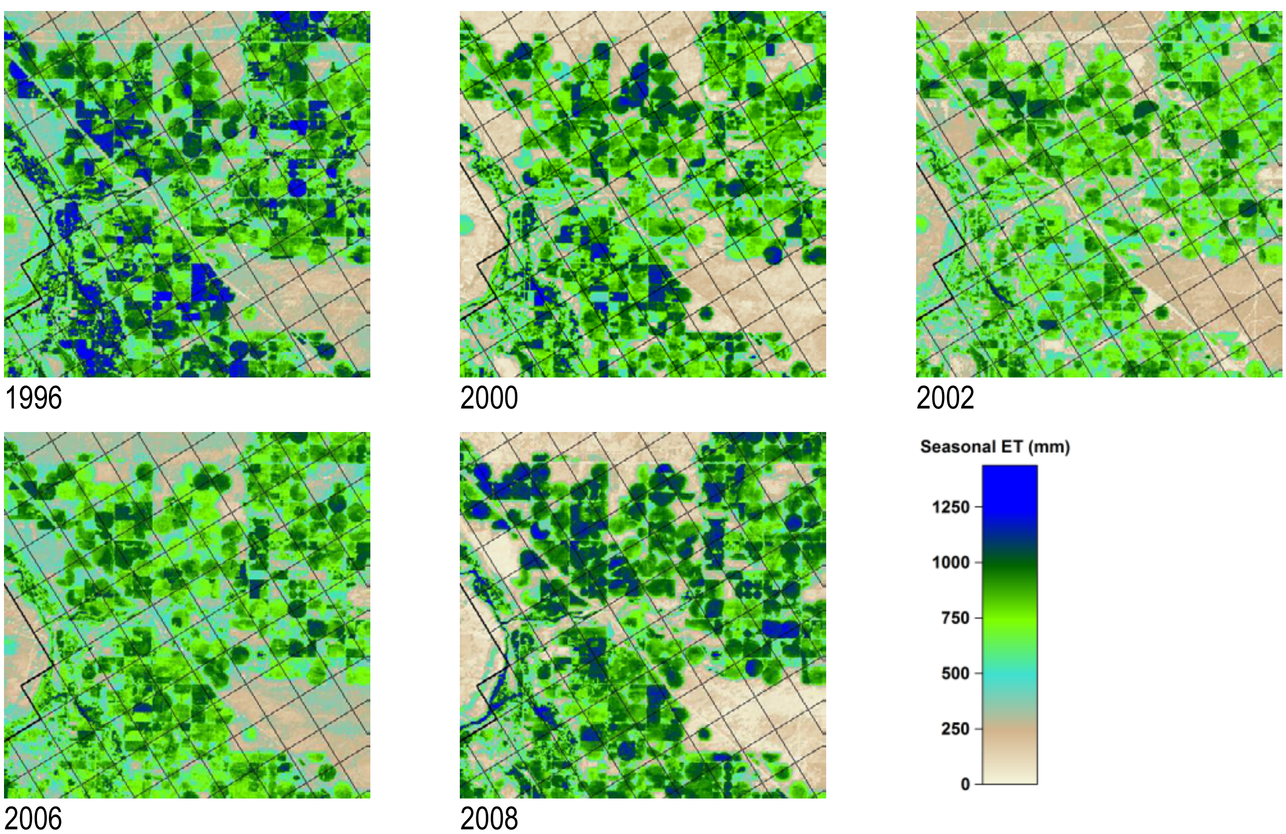


Figure 5. Trends in evapotranspiration over time on the Eastern Snake Plain Aquifer, Idaho. Courtesy of Idaho Department of Water Resources. (ET, evapotranspiration; mm, millimeters)

State Consumptive Use Mapping, Nevada Division of Water Resources

The Nevada Division of Water Resources uses Landsat imagery as one source of independent data to meet their responsibilities regarding the measurement and monitoring of agricultural water consumption within the state. Within Nevada, Landsat imagery serves as either a source of independent confirmation or as a baseline. Since Nevada has less than 3 million residents, only one state water engineer/hydrologist is responsible for monitoring a very large area of land. When questions regarding beneficial use of water in the state arise, it is the state engineer's job to verify water use on the plot of land. Typical practices include meter readings or field investigations, which can take several days to conduct, considering travel time. The Normalized Difference Vegetation Index (NDVI) derived from Landsat imagery greatly increases the accuracy and defensibility of historic water-usage records without additional cost or time commitments (fig. 6). In many cases, documentation of water use from meters or field investigations is not available, and Landsat is the only independent source of data to support or refute word of mouth. Landsat imagery is pulled at least once a month by staff at the Nevada State Engineer's Office. Landsat data are also commonly used by applicants or protestants of water-right applications for the purpose of quantifying water use.

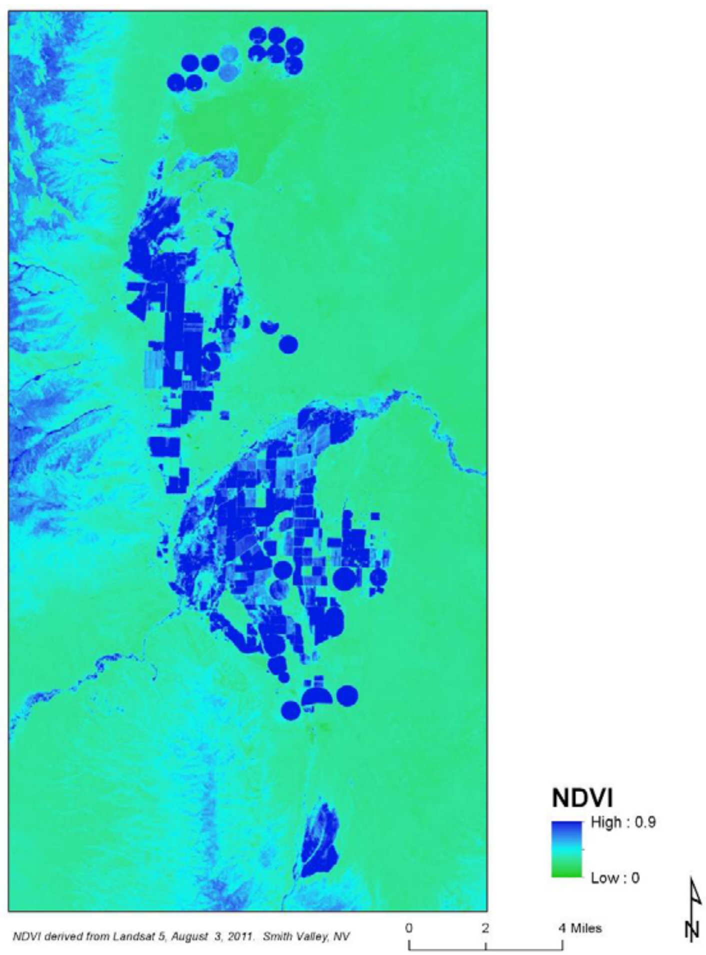
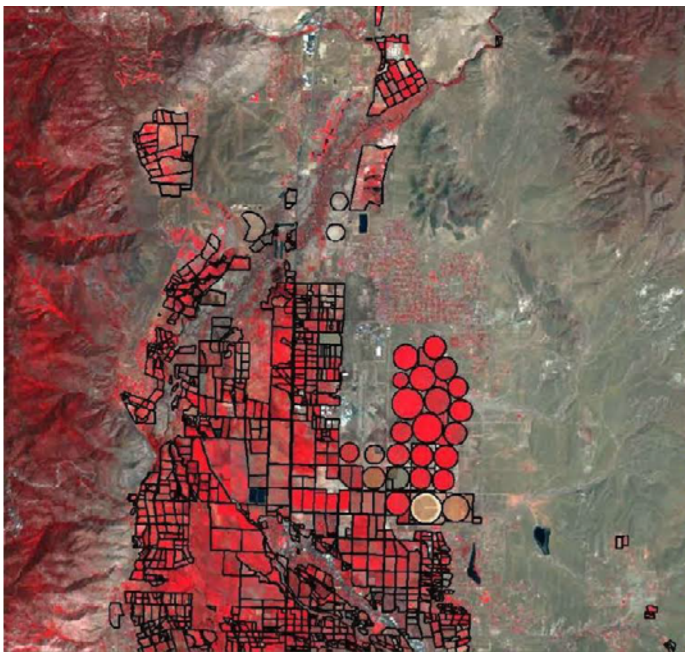
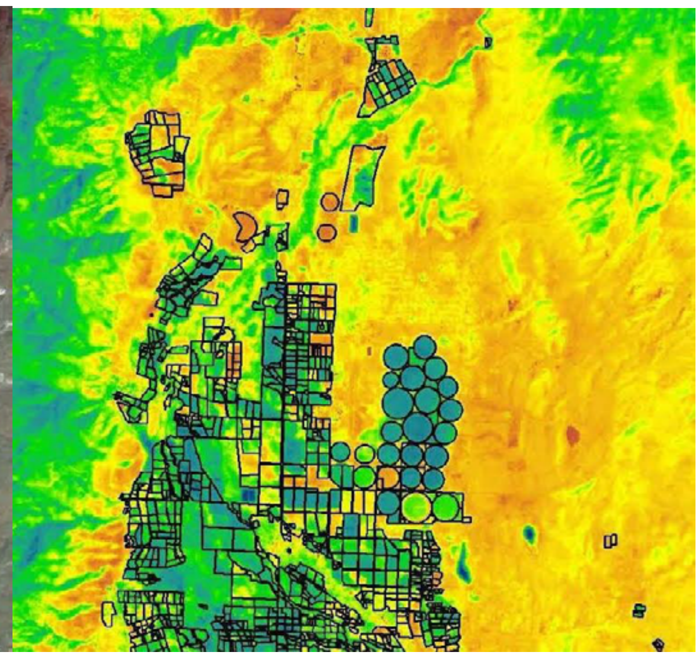


Figure 6. Normalized Difference Vegetation Index (NDVI) derived from Landsat 5 image, August 3, 2011, Smith Valley, Nevada. Courtesy of Nevada Division of Water Resources.

The State is working in conjunction with the Desert Research Institute (DRI) and the University of Idaho to implement the METRIC model with Landsat data to quantify actual consumptive use of water in agricultural areas. The State is in the fourth year of a five-year grant from the Bureau of Reclamation to complete this project. The results of the project can be used to estimate seasonal and monthly agricultural water use at the basin- and field-scale and to improve water budgets and hydrologic modeling. At this time, METRIC results have not been used in any water right transfers in Nevada. Figure 7*A* is a false color infrared derived from Landsat for Northern Carson Valley, Nevada (prepared by Justin Huntington, DRI). Figure 7*B* shows evapotranspiration using energy balance in the valley. These images allow the viewer to easily delineate between irrigated and non-irrigated land (Adam Sullivan, Nevada Division of Water Resources, oral commun. and written commun., 2013).



A Landsat false color infrared image showing irrigated lands in red, Northern Carson Valley, Nev., August 3, 2009.



B Landsat image showing evapotranspiration using energy balance (irrigated lands in blue), Northern Carson Valley, Nev., August 3, 2009.

Figure 7. Images of Northern Mason Valley, Nevada, showing irrigated and non-irrigated lands. Courtesy of Desert Research Institute.

State of Colorado's Use of Landsat Imagery for Water Accounting

The Colorado Water Conservation Board (CWCB) has been using Landsat imagery for the last 20–25 years in the State of Colorado to assist in its various water planning activities. Currently, Landsat imagery is used in almost every basin to delineate between irrigated and non-irrigated land. The imagery is also used for crop signatures: identifying various crop types that are produced in a given growing season using the NDVI approach (figs. 8 and 9). Areas of phreatophytes (high consumers of water that are often invasive species) are also identified and delineated using the satellite imagery (fig. 10).

Landsat data are used to help estimate actual consumptive use by applying energy balance algorithms. Landsat's TM (Thematic Mapper) data has also been used as an independent verification source for the traditional estimation models of crop consumptive use within the South Platte River basin. Additionally, the uses of the imagery in assessing irrigated acreage and water use by irrigated crops has extended from data gathering for within-basin water management to providing information for some of Colorado's interstate water compact accounting needs.

The imagery has great benefit in areas where there is no diversion or pumping records available. For example, along the Front Range of Colorado, Landsat imagery has been used to help estimate agricultural pumping of water for irrigation where no pumping records are available, thus helping the CWCB with its water-planning activities. In the Rio Grande River basin, the imagery is primarily used to delineate irrigated lands and crop type, but the data is also used to help estimate consumptive use directly as part of the basin's water management strategies. Landsat imagery is also being used indirectly in the support of the creation of Colorado's Water Plan, as directed by Governor Hickenlooper's executive order.

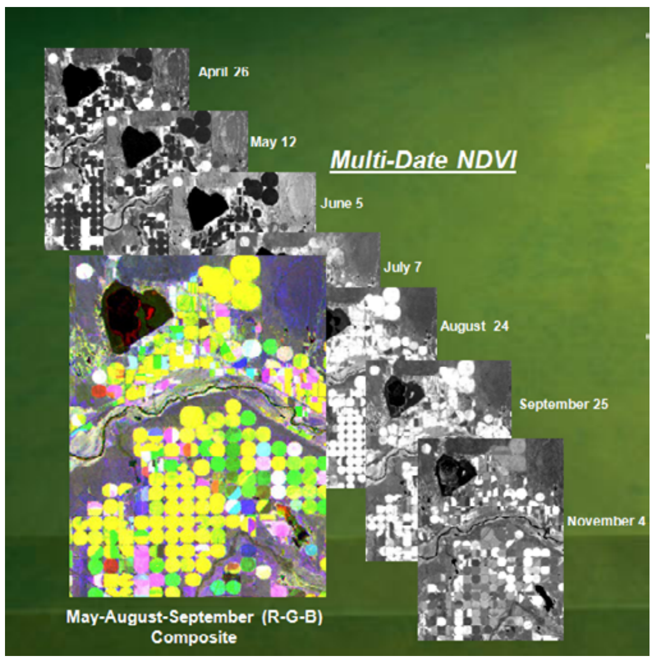


Figure 8. Classification of irrigated lands in the State of Colorado using Landsat imagery. Courtesy of Colorado Water Conservation Board. (NDVI, Normalized Difference Vegetation Index)

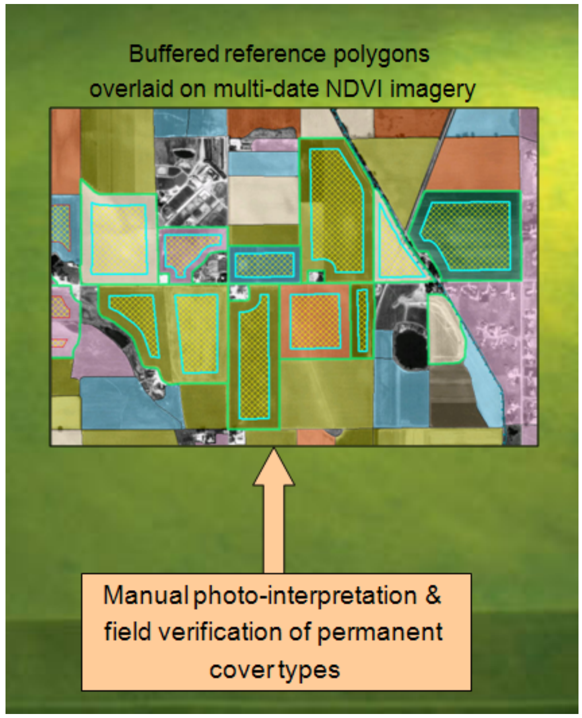


Figure 9. Evaluation and validation of crop classification in the State of Colorado using Landsat imagery. Courtesy of Colorado Water Conservation Board. (NDVI, Normalized Difference Vegetation Index)

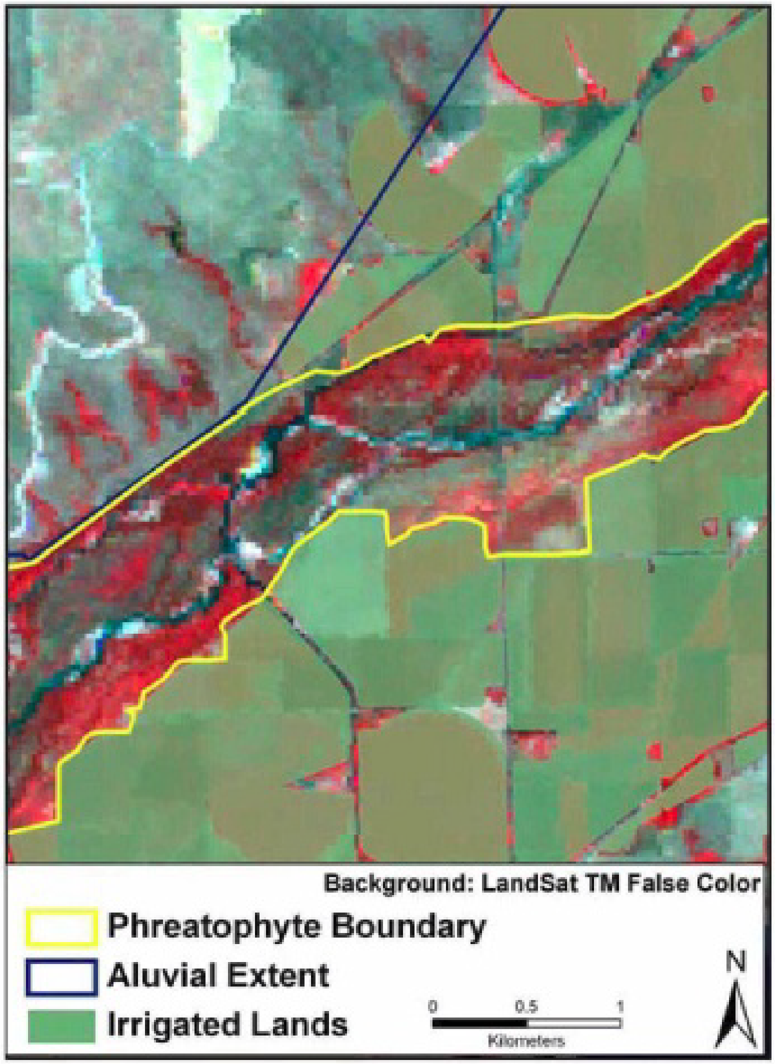


Figure 10. Landsat image showing the area used to estimate evapotranspiration in one area in the State of Colorado. The boundary of the mapped alluvium is indicated by the dark blue line. Only phreatophyte cover (yellow boundary) inside the alluvial boundary was considered for the estimation of evapotranspiration. Hence, the springs visible above this boundary were not counted in the evapotranspiration estimate. Courtesy of Colorado Water Conservation Board.

On average, eight usable Landsat scenes are downloaded during the growing season, from April to the end of October. Cloud cover at times limits the number of usable images; more frequent Landsat coverage would help with cloud-cover issues. More frequent Landsat coverage would also provide additional information that would help in crop typing, by getting strong crop signatures at different growing stages. However, the current availability of the information remains extremely beneficial to the State of Colorado. In some cases, higher resolution would be helpful, particularly in areas where there are smaller field sizes and (or) acreage in production. However, Landsat's current spatial resolution is able to meet many of the state's water-accounting needs.

If Landsat imagery were no longer available, the State of Colorado would suffer various consequences. The options for moving forward would include seeking alternative sources of thermal data or conducting time-consuming fieldwork to collect information normally obtained from the imagery. Either option would be costly and lead to the decrease in quality and (or) frequency of certain reports or activities. The report on irrigated-acreage delineation would most likely no longer be produced at the current level of detail and accuracy. Alternative sources of data might include MODIS, though the spatial resolution would be too coarse to produce quality products, beyond the point of generalization. Third party vendors that may offer thermal band imagery would be sought, although it is speculated that the price for the service, if available, would either eliminate them as an option, or limit the use of this service to every 5 years instead of annually. Without thermal band data, more site visits would need to take place in order to identify the irrigated crop types. This work would most likely be added to the task list of the Division of Water Resources, which currently collects data on water diversions at head gates; if not assigned there, the CWCB would mostly likely have to contract the work out. The task would be extended to complete "window surveys" (from a vehicle) of what is being irrigated in a field. Most of these surveys are completed by hourly, part-time labor, meaning that an increase in tasks would require more funds to pay for part-time employees, and the results would lack the consistency of satellite-based analyses. More importantly, the information would be received with a tremendous lag in timing. The quality and frequency of reports would be reduced, while higher costs would be accrued for their production. Data collected from the use of imagery during drought seasons, like the one in the summer of 2012, may not be available without Landsat. The lag of getting timely information, due to data acquisition and processing, would set back the production of current information and limit its usability and benefits to the state and public (Ray Alvarado, Colorado Water Conservation Board, oral commun. and written commun., 2013).

StateCU and Landsat, Colorado Water Conservation Board and Riverside Technology, inc.

In the State of Colorado, Riverside Technology, inc. conducted a project, in collaboration with the CWCB, to compare traditional consumptive-use estimates from Colorado StateCU decision support system (DSS) and Landsat thermal data processed in METRIC (fig. 11). The results showed that application of METRIC model on Landsat thermal imagery provides more consistent output than that of the StateCU model (figs. 12 and 13). The METRIC model in conjunction with Landsat data is also able to identify consumptive use variation along the river reach. This type of precision is not generally estimable with the StateCU model. The CWCB is using the results to evaluate decisions regarding future water use, through alternative methods of consumptive use measuring and monitoring and potential modeling cost savings.

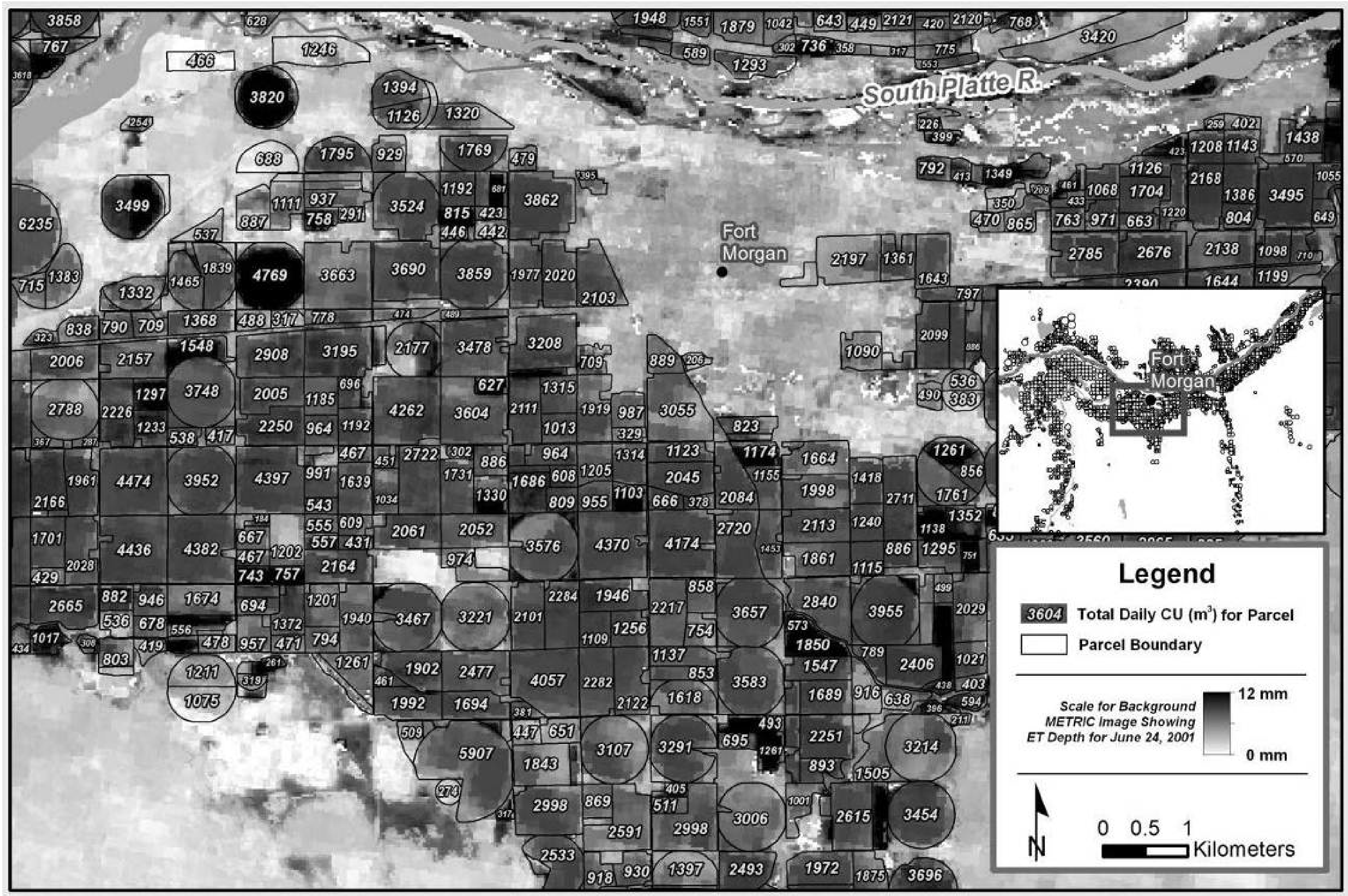


Figure 11. METRIC-derived evapotranspiration estimates for irrigated fields in eastern Colorado. Courtesy of Riverside Technology, inc.

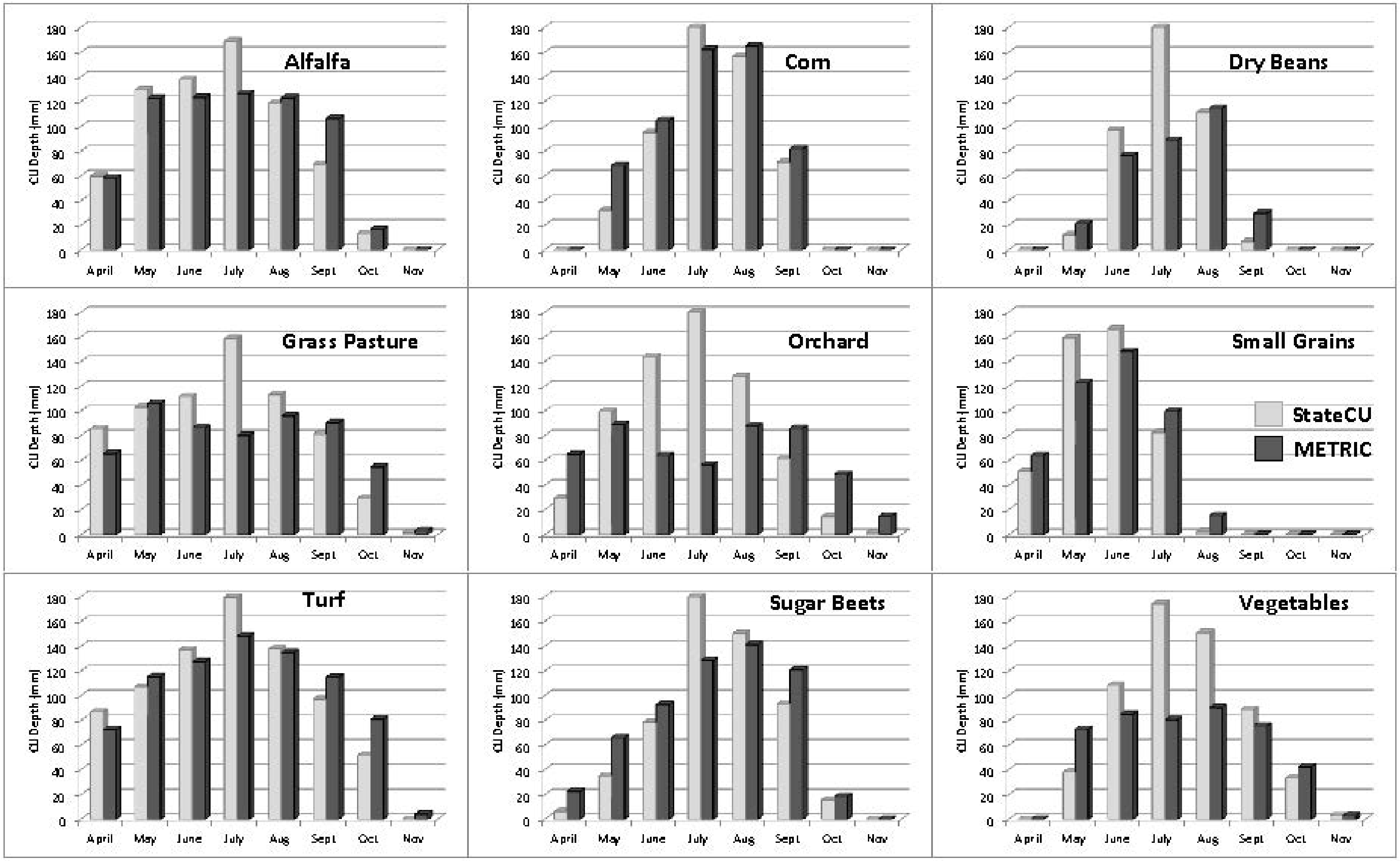


Figure 12. METRIC-derived evapotranspiration estimates for specific crops in eastern Colorado. Courtesy of Riverside Technology, inc.

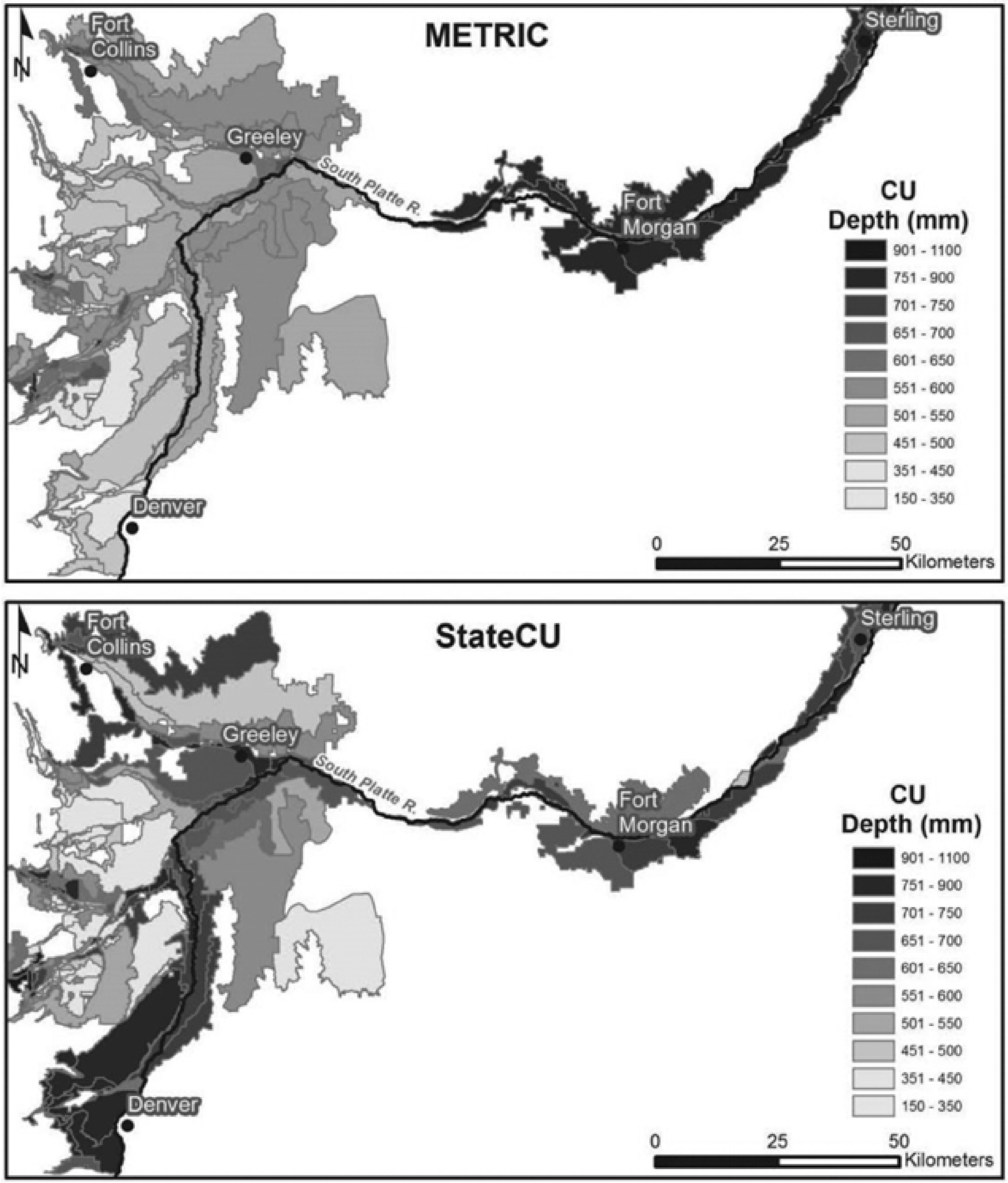


Figure 13. Comparison of evapotranspiration estimates in eastern Colorado from METRIC (top) and the Colorado StateCU model (bottom). Courtesy of Riverside Technology, inc. (mm, millimeters)

Colorado South Platte Decision Support System, Riverside Technology, inc.

Riverside has also worked with the CWCB to develop a DSS for the South Platte River in Colorado. An important component of the DSS is to perform irrigated lands delineation utilizing the Landsat platform and to provide information for decision making regarding water resources and agricultural crop production in the South Platte. The objectives of the South Platte DSS are as follows:

- Develop accurate, user-oriented databases helpful in the administration and allocation of the waters of the South Platte River and its tributaries,
- Provide data and models to evaluate alternative water-administration strategies,
- Accurately represent current and potential federal and state administrative and operational policies and laws, and
- Promote information sharing among government agencies and water users.

Riverside has provided the spatial information systems component of the South Platte DSS, beginning with a comprehensive GIS database and spatial-analysis tools. Thirty-meter (m) multi-temporal Landsat satellite images are used to map an estimated 1.5 million acres of irrigated lands in the basin and to estimate the consumptive water use for each irrigation diversion and for irrigation wells in the basin (figs. 14 and 15). The mapping was completed in consultation with State of Colorado water resource managers, water conservancy districts, and hundreds of irrigation ditch companies and water users.

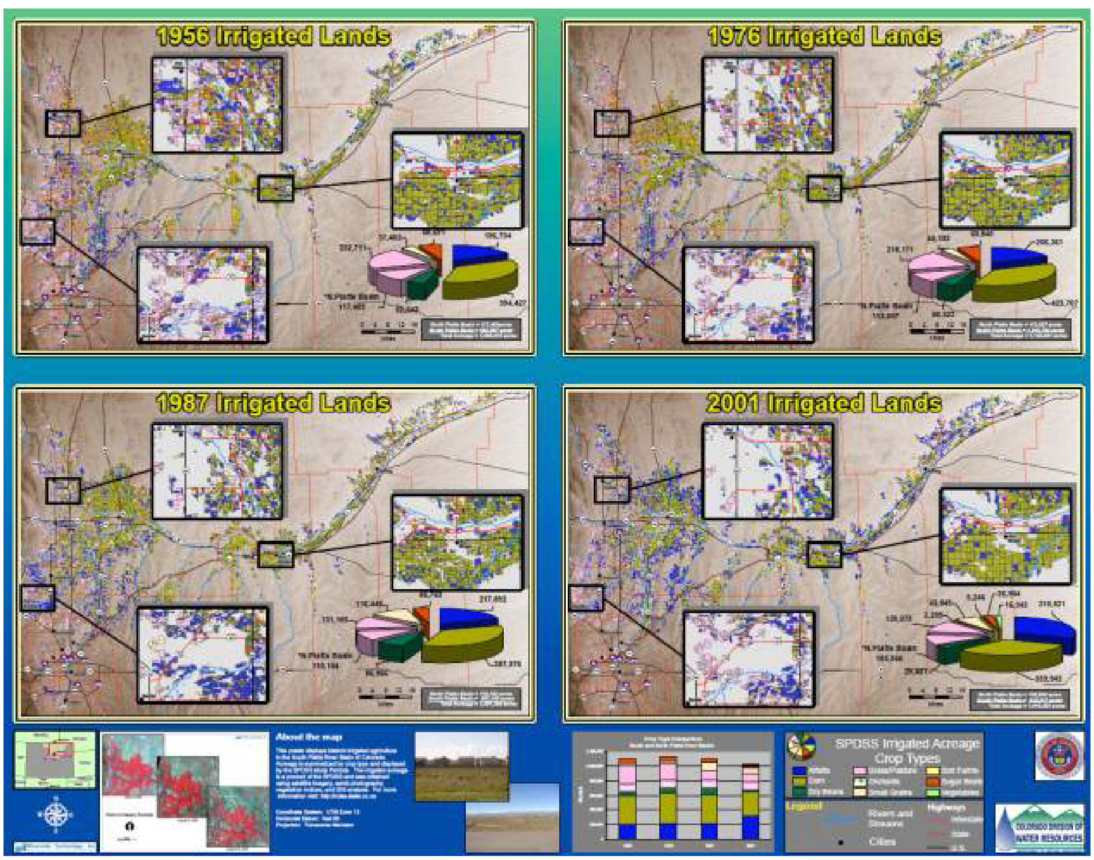


Figure 14. South Platte Decision Support System yearly crop production trends from 1976–2001 based on Landsat analysis. The 1956 crop production data is backcasted from 1976 while utilizing 1950's Farm Service Agency (FSA) aerial photos for field geometry. Courtesy of Riverside Technology, inc.

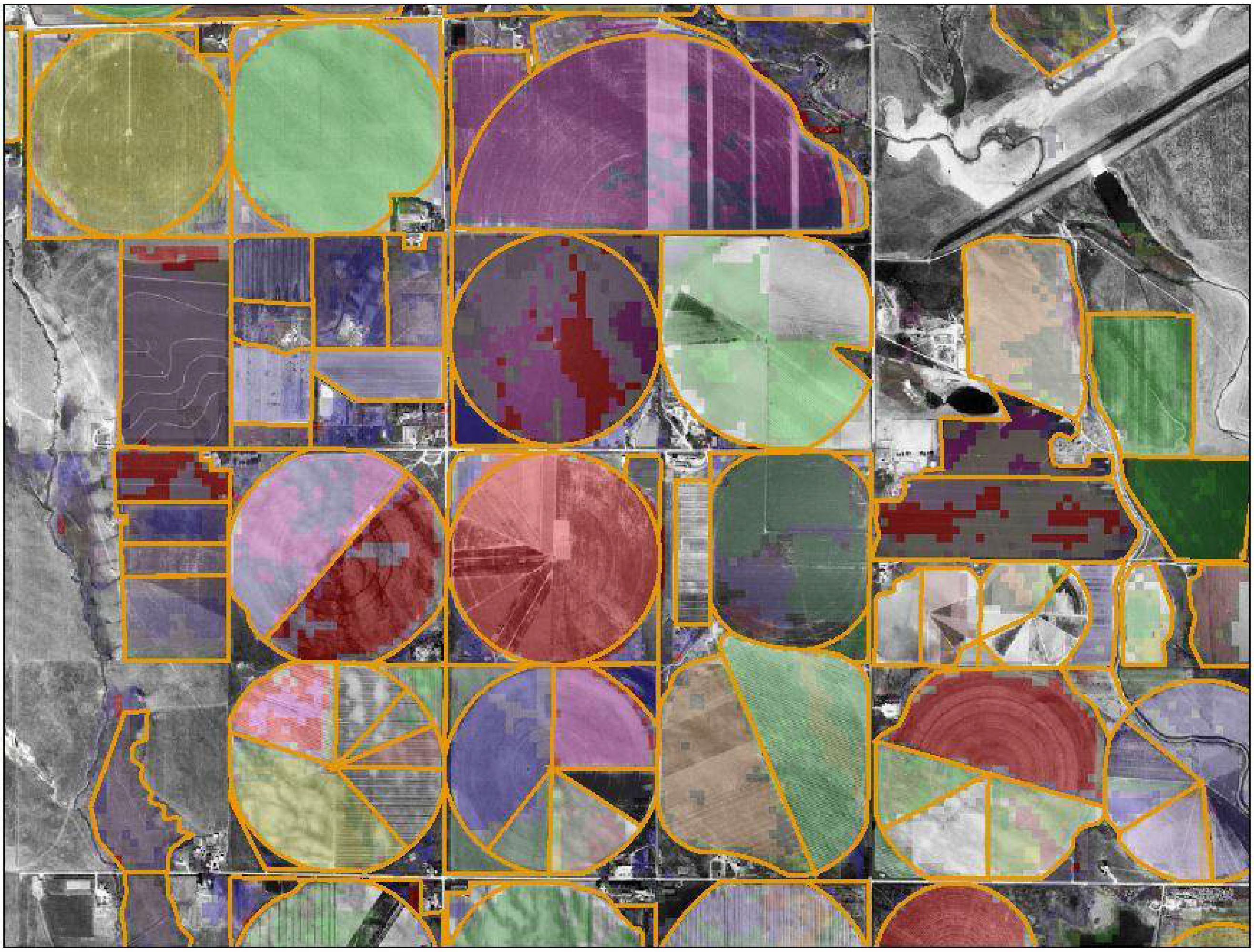


Figure 15. Multi-temporal Landsat NDVI (Normalized Difference Vegetation Index) product overlaid on aerial photographs used in the delineation of yearly individual irrigated agriculture crop parcels near the South Platte River, Colorado. Courtesy of Riverside Technology, inc.

Sonoma County Water Agency, California

The lands along the Russian River of California are home to over 61,000 acres of vineyards. The wineries, offering tours and tastings as well as producing wine, contribute greatly to the economic prosperity of the region. The valley's grapes produce some of the highest quality Chardonnay, Cabernet Sauvignon, and Pinot Noir wines. A thriving economy in the region depends on flourishing agricultural production while grape production relies on timely water availability for irrigation and frost control. The Sonoma County Water Agency (SCWA) manages flows in the Russian River during most of the growing season and controls releases from two reservoirs. The SCWA is responsible for managing the reservoir storage water collected in the winter to support habitat, recreation, and water-supply needs throughout the year.

To ensure the most efficient use of the limited water supplies in the reservoirs, the SCWA has an ongoing program to enhance water-management strategies. Recent studies have focused on developing a better understanding of total water demands on the Russian River. Given the large number of vineyards along the river and a lack of coordination of associated river diversions, the SCWA faces operational challenges in predicting demands on the river while maintaining a required minimum flow in the river. Better information on agricultural water use in the watershed is not only improving current operations, but is also important for long-term planning for the water resource.

To assess agricultural water demands, the SCWA contracted with Davids Engineering in Davis, California, to develop a methodology that uses Landsat imagery to determine crop coefficients based on data for a full growing season. Twelve Landsat scenes obtained for the 2008 growing season were used in the project. Davids Engineering, working with SEBAL North America, compiled the Landsat scenes and ancillary meteorological data sets to calculate consumptive water use using the physically-based SEBAL method for calculating actual evapotranspiration (fig. 16). Using crop field mapping, crop types were correlated with consumptive use to derive local crop coefficients that could be applied to estimate crop water use in different years under different meteorological conditions.

With crop water use established, Davids Engineering constructed a soil-moisture balance model to develop estimates of applied water use. Since the early growing season can coincide with the region's rainy season, a model was needed to predict when the growing crops would consume the stored water in the soil and require the supplement of irrigation water. Assessments at the field level were made possible due to Landsat's relatively high spatial resolution. The project developed an agricultural water-demand model that can be used to estimate river diversions for irrigation under various growing conditions. Historical Landsat imagery provided the base data to derive requirements for crop water use (Todd Schram, Sonoma County Water Agency, oral commun. and written commun., 2013).

The project provided the SCWA with a better understanding of how water is currently being used in the Russian River watershed. It developed the methodology, tools, and data to conduct long-term evaluations of the reliability of the available water resources in the face of projected increases in water demands and predicted changes due to climate change. The SCWA faced a few challenges when working with Landsat data. The primary challenge involved the scan-line gaps in Landsat 7 scenes, which were used to get better coverage for periods when Landsat 5 data were unavailable. The data gaps due to the satellite's scan-line corrector (SLC) failure resulted in limiting coverage of the consumptive use calculations at some fields for a few periods during the growing season. However, not only did the thermal band and relatively high resolution make Landsat the obvious choice, but the costs and benefits of using Landsat highly outweighed those of any other alternatives. In the case that Landsat data are not available, the California Department of Water Resources conducts land-use surveys approximately every 10 years and maps irrigated agricultural lands. From this, the Department develops irrigated land estimates of applied water use by crop over large watershed-planning areas, which does not capture the variability of the vineyard irrigation practices and micro-climates (Todd Schram, Sonoma County Water Agency, oral commun. and written commun., 2013).

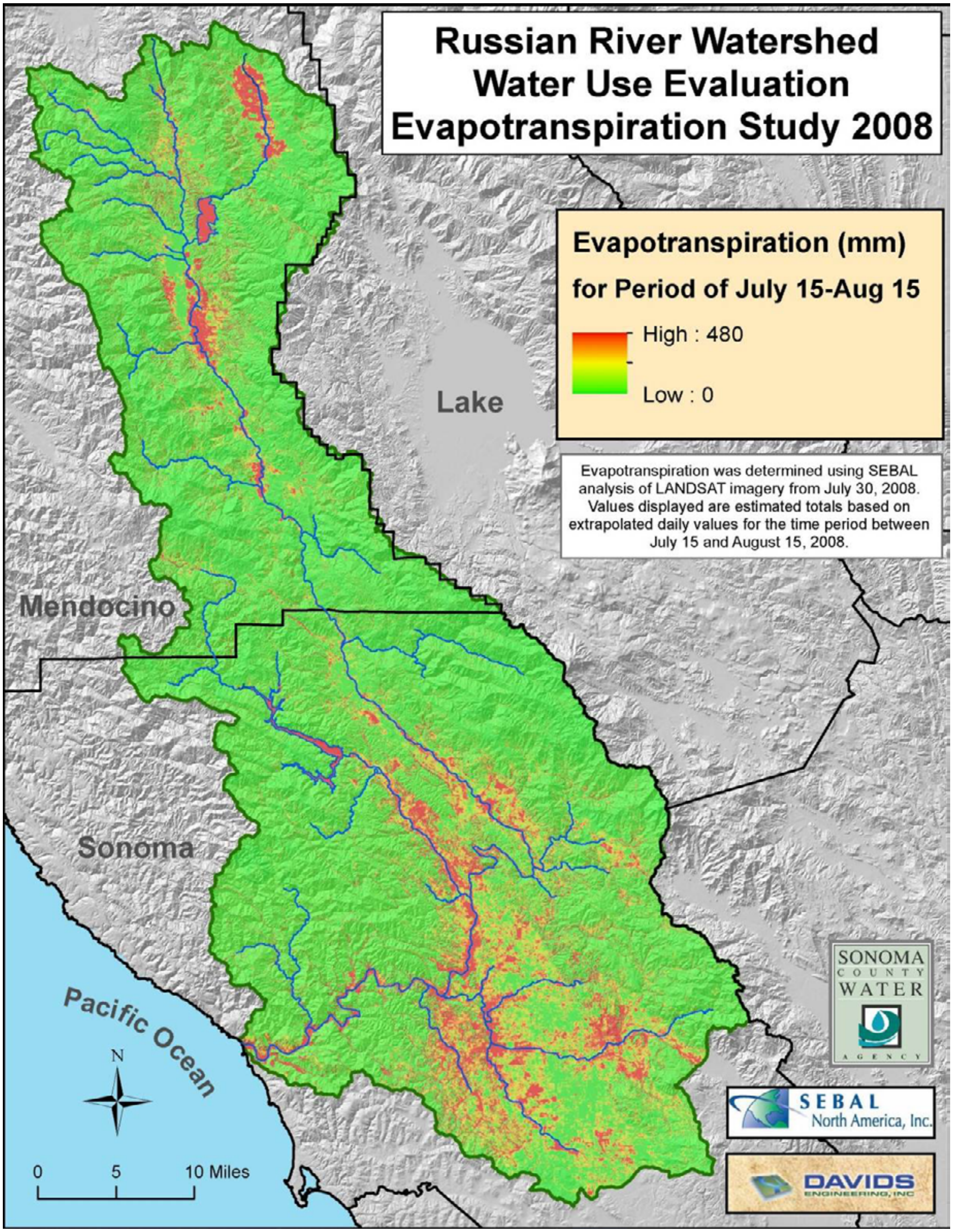


Figure 16. Evapotranspiration in the Russian River watershed determined using SEBAL analysis of Landsat imagery. Courtesy of Sonoma County Water Agency. (mm, millimeters)

Russian River NDVI (Normalized Difference Vegetation Index) Methodology and Use, California

In 2013, the SCWA updated the crop field GIS mapping in the watershed last completed in 2009. To facilitate the heads-up digitizing of crop fields, the SCWA developed a “screening tool” layer to identify changes in vegetation from the previous imagery to the most recent. The SCWA’s screening tool helped by highlighting changes using NDVI to track land use changes from 2006 to 2012. The SCWA calculated NDVI using the ArcMap NDVI function for two Landsat scenes from August 2006 and 2011 (fig. 17). Imagery for the month of August was chosen because of reduced cloud cover as well as being far into the growing season. These NDVI data sets were compared to aerial imagery from 2005 and 2012 to confirm that different vegetation was represented by different values. The “screening tool” layer that helped guide the staff to vegetative changes between the two years was calculated based on the difference between the 2006 and 2011 NDVI values. An iterative process was used to establish the criteria for identifying whether significant change was observed over the intermittent period (Todd Schram, Sonoma County Water Agency, oral commun. and written commun., 2013).

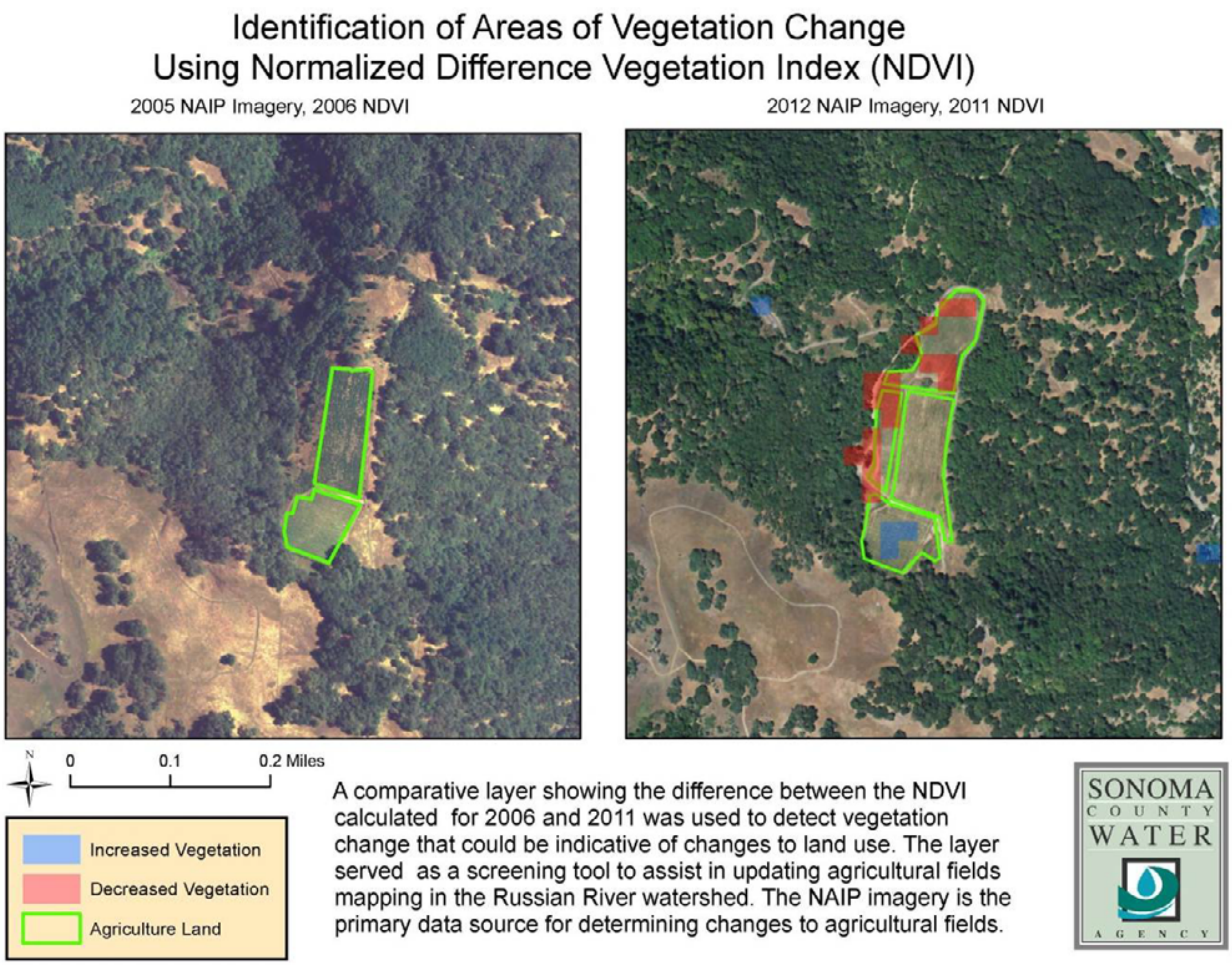


Figure 17. Change in NDVI over time derived from Landsat images of the Russian River watershed. Courtesy of Sonoma County Water Agency.

Agricultural Irrigation: Precision and Efficiency through Landsat

In addition to water demand and supply issues among states, municipalities, and industry, agricultural producers also face challenges with water shortages and water monitoring within their production practices. Agricultural production depends on an available water supply and the appropriate and timely application of that water to optimize crop production and sustain a profitable business. Remotely sensed data provided by the thermal band(s) of Landsat imagery allow producers to track consumptive water use, develop efficient seasonal irrigation schedules, and adjust the amount of water diverted and applied based on the consumptive use information. This leads to better management practices and more efficient crop production in wet and dry years.

E. & J. Gallo: Improving Irrigation Technology and Grape and Wine Quality

Landsat imagery is increasingly used in the private sector. E. & J. Gallo (Gallo), located in California, is the largest winery in the world and the first known company in the U.S. beverage industry to use Landsat data in viticulture practices. A pioneer of efficient water-management practices through Landsat, Gallo uses the imagery on approximately 20,000 acres of Gallo-owned vineyards from Southern California to Mendocino County. Evapotranspiration from vineyards is the primary interest, though other crops are also gaining attention, particularly when looking at land acquisition and water availability in various regions. Gallo's goals with using Landsat imagery include:

- Estimating the potential water use for vineyards by region and varietal,
- Estimating actual water use for irrigation and water stress index,
- Scanning every vineyard owned or purchased (approximately 150,000 acres) to develop area specific water budgets, and
- Supporting land acquisition based on water availability and quality.

Currently, Gallo downloads every available Landsat image during the grape growing season. Irrigation generally starts in March in the warmer areas and continues through the month of October. An adjusted form of METRIC is then used to map evapotranspiration of the vineyards (fig. 18). The METRIC model was originally designed to compute and map evapotranspiration based on Landsat images. Gallo developed an internal calibration of METRIC which is currently used by the company in vineyards. Operation of the METRIC model depends on Landsat's thermal data availability. Some of the benefits that Gallo observed in the last three years of using Landsat imagery include:

- Decrease in the amount of water applied by 20–30 percent, subject to region,
- Improved water management with the ability to run a seasonal water balance,
- Development of more efficient seasonal irrigation schedules,
- Improvement in grape quality which leads to improved wine quality,
- Upward movement in the wine program, due to higher grape quality, leading to an increase in bottle price and an increase in revenue,
- Reduced trimming of excess leaf canopies from over-irrigation,
- Decrease in the cost of irrigation from reduction of water and energy used,
- Using current year's data of water allocation to determine and plan next year's allocation.

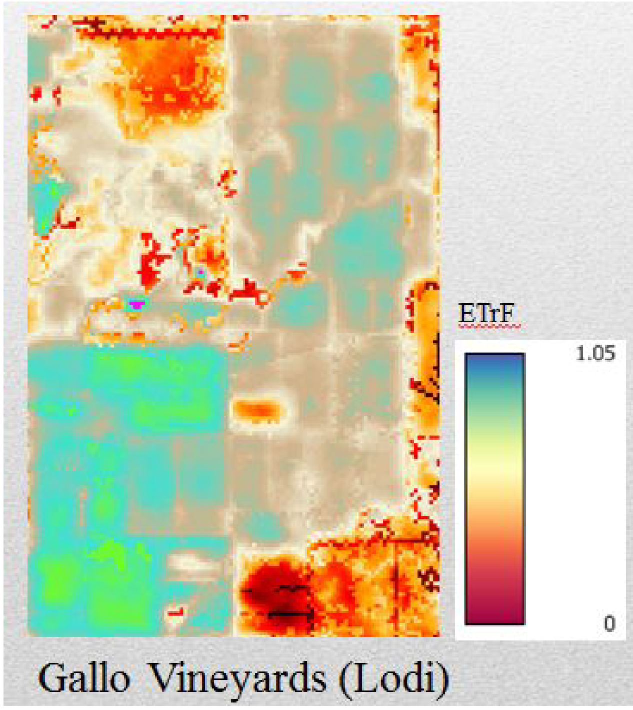


Figure 18. Evapotranspiration from Gallo vineyards in Lodi, California, measured using an adjusted form of METRIC. Lower evapotranspiration is shown in red and higher is in blue. Courtesy of E. & J. Gallo. (ETrF, reference evapotranspiration)

Not only is Gallo able to supply consumers with better quality products through the use of Landsat imagery, but they are also able to decrease their business' impact on the environment through a decrease in the amount of water applied during the irrigation season. The benefits from a reduction in application range from retention of in-stream flows to water-quality improvements due to decreased runoff.

Although other satellite imagery is available, the resolution is not as high as that of Landsat, and thus the data is not as useful for Gallo in this type of field application. However, Landsat itself also brings a variety of challenges. Cloud cover, for example, presents issues when obtaining data. Landsat 5 contributed significantly to the frequency of data availability as it shortened the lag between available images. One operational Landsat satellite is capable of providing an image every 16 days, and if an image contains cloud cover, it is not usable and is a loss of data. Timely and continued thermal data is particularly valuable in agriculture, as consumptive water use changes seasonally, even monthly. An increase in the frequency of imagery promotes efficiency of irrigation schedules. An increase in the number of operational Landsat satellites increases the benefits derived and improves assurance of data availability.

Gallo continues to use Landsat imagery with goals to expand its application through the Pacific Northwest and its international properties. Although significant benefits to Gallo and the environment (and, in turn, to society) are observed with the company's use of Landsat imagery, Gallo could not afford to purchase satellite imagery alternatives to Landsat, nor afford a privately operated satellite. Understanding the current and potential benefits of the imagery use, Gallo expresses great interest in supporting the Landsat mission (Martin Mendez, E. & J. Gallo, oral commun. and written commun., 2013).

Vineyards and Apple and Olive Orchards, Chile

Landsat has been instrumental in helping Chile estimate water demand. The country often faces drought conditions, and although some level of water supply is guaranteed from dams and reservoirs, seasonal supply is uncertain. Agricultural production is a large enterprise in Chile, and water shortages create uncertainty in agricultural production as well as economic growth and sustainability. Landsat imagery allows the country to estimate seasonal demand and match it against seasonal supply to achieve optimal irrigation practices for maximum production. Landsat data and the METRIC model are being used in Chile for the estimation of consumptive water use. Using this information, water budgets are created and a more accurate estimate of water demand is calculated. In conjunction with METRIC, Landsat data are being used to estimate evapotranspiration and the crop coefficient for olive and apple tree orchards as well as vineyards (figs. 19 and 20). The output is used to develop water-management strategies on farms and at the regional level.

Landsat data became available at no cost in 2008. This has had a significant effect on the extent of its applications, although its use in Chile by Dr. Samuel Ortega of the Universidad de Talca started a few years earlier, using only a few purchased scenes to launch the current research. Since 2005, over 500,000 acres of olive and apple orchards as well as vineyards have been surveyed using Landsat and METRIC to estimate regional and local consumptive use for water budgets. Landsat imagery allows adjusting the application of water on each vineyard based on water requirements for a specific production outcome. A Landsat-based recommendation of delaying the start of irrigation from September to November has saved up to two months of irrigation water in some regions for producers enacting the practice. While using Landsat imagery to help identify the most accurate crop water requirement on private agricultural lands at the farm level, the following benefits have been observed:

- A $80/acre cost savings in energy used for irrigation on over 3,700 acres of olive orchards per year,
- A 30 percent to 60 percent reduction in the amount of water applied on grapevines on 6,000 acres, and
- An increase in grape quality between 30–35 percent.

Water budgets allow for the control of water application and adjustment of the crop water coefficient. This enables strategic planning for water application and yields higher quality grapes. Although higher quality grapes correlate with lower production amounts, the profits are offset by higher wine quality and a higher price per bottle. An increase from $1.00 to $20.00 per bottle from water-application adjustment has been observed in some of the plots where Landsat imagery is used to adjust irrigation practices. Additionally, a decrease in irrigation energy cost, as a result of a smaller amount of water applied, contributes to the overall increase in profit.

As evident by the examples provided, Chile has been able to use Landsat imagery to improve agricultural production and use a scarce resource more efficiently. Government officials in Chile seek consumptive-use information from Landsat and METRIC to help drive informative policy decisions regarding water supply, storage, and allocation. The long term goal from using this technology would be to establish a water market. Although some challenges exist with current Landsat output, due to issues such as cloud cover and 16-day repeat coverage which limit the amount and quality of usable data, Landsat remains the main source of moderate resolution imagery with thermal data used for work in water resources ongoing in Chile (Samuel Ortega, Universidad de Talca, oral commun. and written commun., 2013).

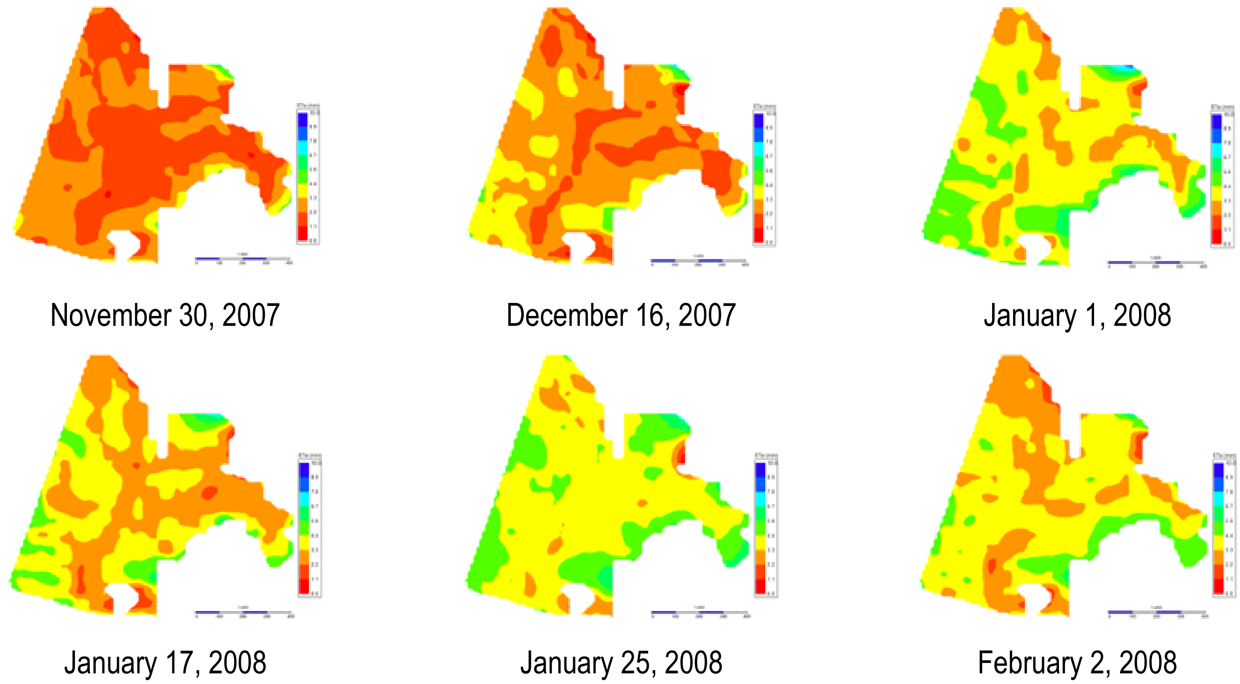


Figure 19. Evapotranspiration mapping of a drip-irrigated vineyard in Chile using images from Landsat 7 ETM+. Courtesy of Universidad de Talca.

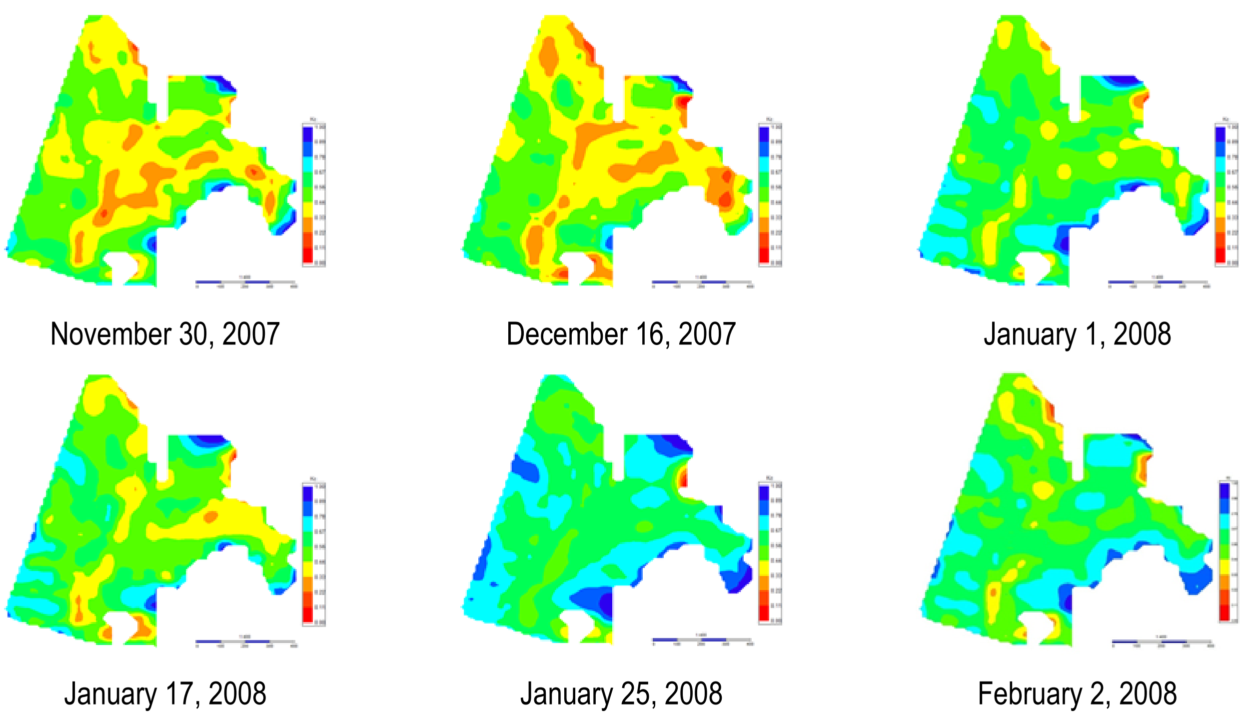


Figure 20. Crop coefficient mapping of a drip-irrigated vineyard in Chile using images from Landsat 7 ETM+. Courtesy of Universidad de Talca.

Irrigation Improvement for Yield Optimization, Australia

Australia's Murray-Darling Basin (MDB) produces the highest value and largest volume of irrigated products, including rice, cotton, dairy, horticulture, and viticulture, in Australia (Australian Natural Resource Atlas [ANRA], 2010). The MDB represents over 60 percent of all irrigated agricultural area in Australia. In the 2010–11 production years, MDB had nearly 3 million acres (1.2 million hectares) of irrigated land (Australian Bureau of Statistics, 2013). This large agricultural industry is responsible for 95 percent of all diversions of the Basin's water resources and represents 75 percent of all water used for irrigation in Australia and over half of all water use in Australia. The ANRA (2010) reports the estimated value of irrigated agricultural output to be between $3 and $4 billion per year.

Measuring and monitoring consumptive water use is an important task in a region where water is responsible for the economic prosperity of a large agricultural industry and the food supply of millions of people. Irrigation regions of varying size within the MDB, including the Shepparton Irrigation Region, Sunraysia Irrigation Region, Loxton in South Australia, Griffith in New South Wales, and Narrabri in New South Wales, as well as the McAlister Irrigation District in the Gippsland region of Victoria, have been surveyed using Landsat imagery. Land-use mapping is used to extract information relating to specific crops and vegetation, such as almonds, citrus, grape, irrigated pasture, and native riparian vegetation. The surveying primarily occurs on private lands, although some riparian vegetation on public lands is also included. Four to seven Landsat scenes are processed in a slightly modified version of METRIC to estimate seasonal consumptive use. Multiple passes are used where possible to improve image quality, which may be inhibited by cloud cover. Evapotranspiration information derived from Landsat data (fig. 21) is used to create water budgets for different agricultural areas and enterprises based on crop coefficients and regional characteristics such as soil and water quality. Crop- and region-specific water budgets allow for the most efficient delivery and timing of water application. Landsat-derived water budgets are expected to be applied to private and public operations over the coming years. Economic and financial benefits will be accrued post implementation. Since precision in irrigation improves crop productivity per unit of water used (O'Connell, 2011), an increase in financial return from a unit of water is expected. Optimization of irrigation and, as a result, production conditions will help growers and local industry.

This work is possible due to several unique characteristics of Landsat. The Landsat program offers continuity and no-cost imagery. The continuous archive of Landsat data enables evapotranspiration to be calculated retrospectively. This is important for basin-wide accounting of water. The availability of imagery at no cost increases the number of images that can be used and the scope of the work undertaken. Additionally, in order to derive evapotranspiration, both NDVI and land-surface temperatures are required. Consequently, the availability of a thermal band on Landsat makes it an ideal data set to use. The need for the thermal band also limits the availability of alternative sources of imagery. Where Landsat data is not available, the alternatives include MODIS and ASTER imagery. However, MODIS imagery has a spatial resolution too coarse for the purposes of measuring consumptive use. Imagery from ASTER is available on demand and costs $1,444 per scene, limiting the number of images an agency can acquire. Therefore, without Landsat, the work currently being completed in Australia would not be possible (Des Whitfield, Mohammad Abuzar, Kathryn Sheffield, Mark O'Connell and Andy McAllister, Department of Environment and Primary Industries, oral commun. and written commun., 2013).

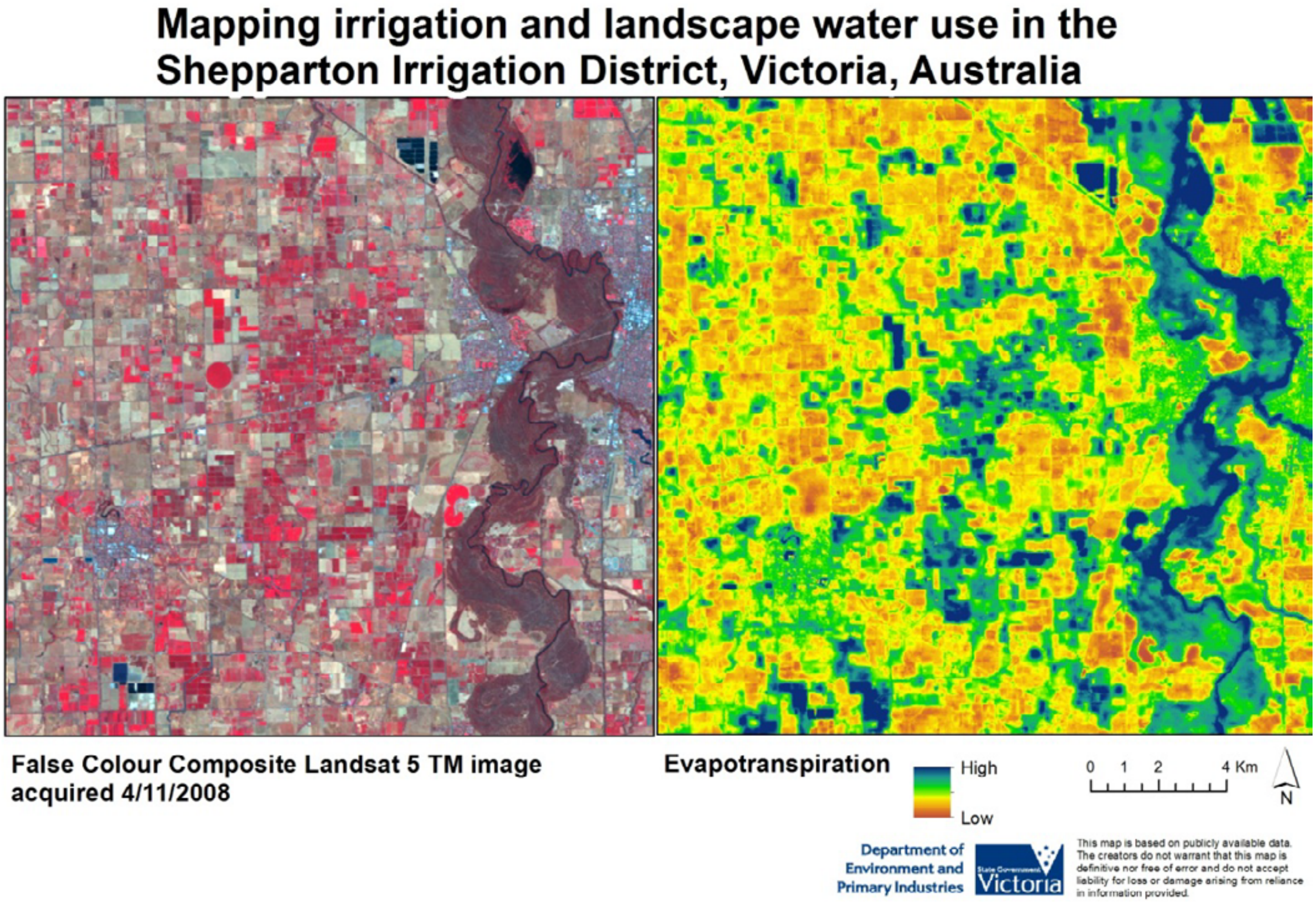


Figure 21. False color composite Landsat image and evapotranspiration map of the Shepparton Irrigation District, Victoria, Australia. Courtesy of the Victoria Department of Environment and Primary Industries.

Morocco Irrigation Efficiencies Improvements: Riverside Technology, inc.

Starting in 2011, Riverside worked with the World Bank to improve data collection for Morocco's irrigation systems and water-allocation methods. Eighty-five percent of the water in Morocco is consumed by irrigated agriculture. Increases in population and drought seasons have made it difficult for Morocco to use reservoirs and irrigation infrastructure. Groundwater has been relied on extensively by irrigators to meet their water demand. The increase in groundwater pumping leads to a rapid decrease of the water tables. With current irrigation demands depleting surface and groundwater supplies, immediate action in helping irrigators manage water supply is becoming necessary in Morocco.

Since measurements of groundwater extraction for irrigation use rarely exist, a new tool was developed by Riverside to calculate current estimates of groundwater use. Landsat imagery and the METRIC model were used to quantify irrigation consumptive use and to map water distribution (fig. 22). These maps and measurements, combined with records on surface water delivery, allowed modelers to estimate the amount of ground water used for irrigation (fig. 23). Landsat imagery was selected due to its spatial resolution and thermal band availability. During this process, results have shown the extensive use of groundwater, much of which is unregulated throughout the pilot agricultural study areas.

Information from the project has supported additional work performed by Riverside with USAID funding to develop improvements in irrigation scheduling based on specific crop water demands. New irrigation scheduling has the potential to motivate irrigation technology upgrades, from flood to sprinkler or drip irrigation. Efficiency and precision in irrigation improves crop productivity per unit of water used, which increases financial return from water (O'Connell, 2011). Optimizing production conditions has the potential to help growers, local industry, and the regional economy to prosper. The optimization of water usage decreases the amount of water pumped from the ground or diverted from surface based sources, leaving more water in the system for immediate uses (Jason Polly, Riverside Technology, inc., oral commun. and written commun., 2013).

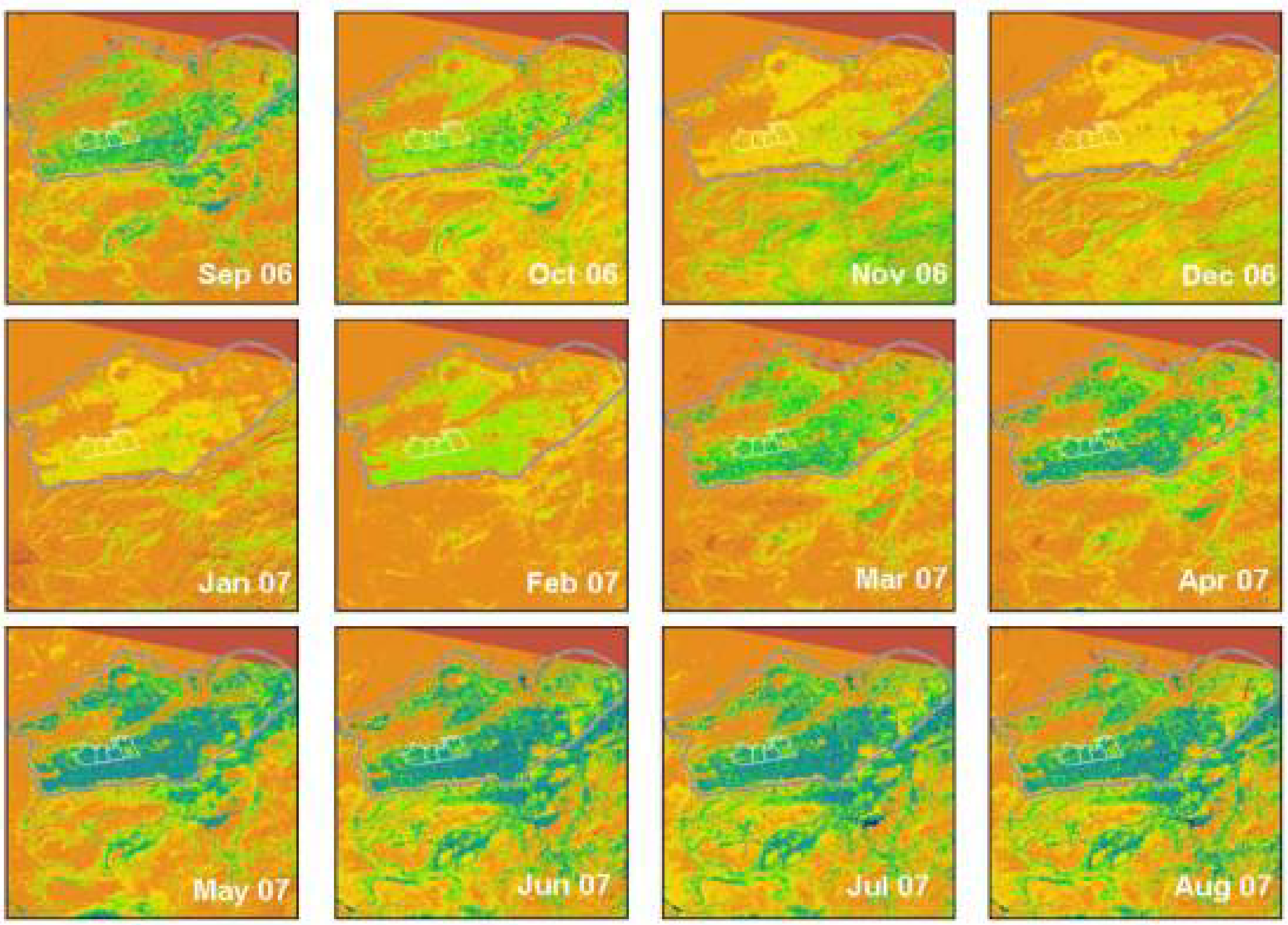


Figure 22. Monthly actual evapotranspiration (red is low evapotranspiration and blue is high evapotranspiration) from September, 2006, to August, 2007 for Tadla region, Morocco. Courtesy of Riverside Technology, inc.

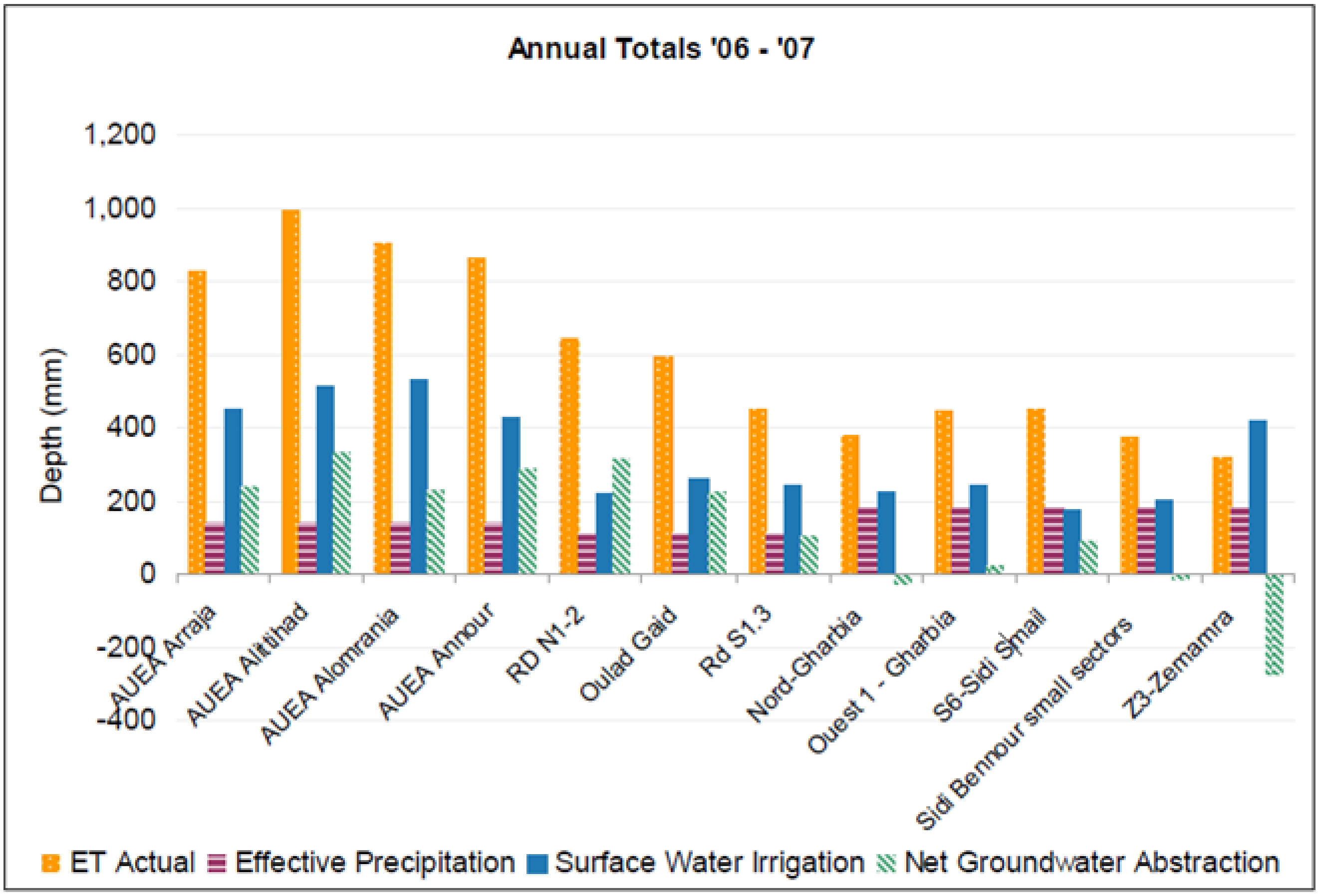


Figure 23. Water balance tool results using evapotranspiration results as input. Courtesy of Riverside Technology, inc. (ET, evapotranspiration)

Stream Flow Water Rights: Protecting the Environment with Landsat

In-stream flows contribute to the health of various habitats and related species. Use and non-use values are associated with in-stream flows. Some use values are experienced through recreation, aesthetics, water quality, hydropower, navigation, and fish and wildlife habitat. Non-use values are associated with simply knowing the river exists and that it will be preserved for future generation to experience (Platt, 2001). In-stream flows are yet another type of water use which requires a constant supply of quality water to sustain the environment. Landsat thermal data are used to measure consumptive water use in a variety of habitats to estimate the area of water shortage and to determine possible supply. This evapotranspiration data is used to make decisions regarding water allocation to in-stream flows and species management.

Salmon Basin, Idaho

Idaho water law, like much of the water law in the western United States, is based on the prior appropriation doctrine. The doctrine states that the water right is authorized for beneficial use based on the priority date: “first in time, first in right.” In cases where there is not enough water to satisfy all the water rights, junior water-rights holders must curtail their water use until the senior water-rights holders receive their allocated amount. In some cases this means that the junior holders receive no water. In the State of Idaho, most minimum stream-flow water rights are junior to the irrigation water rights. During drought years, when the flow in the river is low, there is typically not enough water to meet the needs of irrigators and fish. In some areas, irrigation can divert all of the flow in the stream (fig. 24).

Figure 24. Dry streambed of Big Timber Creek, Idaho, at a gaging station in April, 2004, illustrating the effects of diversion for irrigation. Courtesy of Idaho Department of Water Resources.

Idaho experienced drought conditions from 2000 to 2005. The long duration of the drought increased the probability of stream flows falling below desirable levels for fish populations listed under the Endangered Species Act (ESA). The State of Idaho took action to begin development of a conservation plan for the Lemhi River Basin with the National Marine Fisheries Service and U.S. Fish and Wildlife Service. One goal of the proposed plan was to identify stream flow targets for endangered fish in the long-term. In order to achieve this task, an accounting of the irrigation water use in the area was needed. Monthly METRIC- and Landsat-based evapotranspiration data was used to estimate basin-level consumptive use and to develop the area’s water budget (fig. 25). The data showed that irrigation in the year 2000 consumptively used 33,520 acre-feet (11 billion gallons) of water (Kramber and others, 2006).

The evapotranspiration data were then used to assess the consumptive use of water rights that may be leased under the Columbia Basin Water Transactions Program to improve stream flows. The Idaho Water Resource Board identified stream reaches that would benefit from flow enhancement and worked with willing irrigators through leases, agreements not to divert, and other transaction methods. The evapotranspiration data allowed negotiations with irrigators to be based on the consumptive use of the water rights instead of the maximum diversion allowed for the water rights (Kramber and others, 2012).

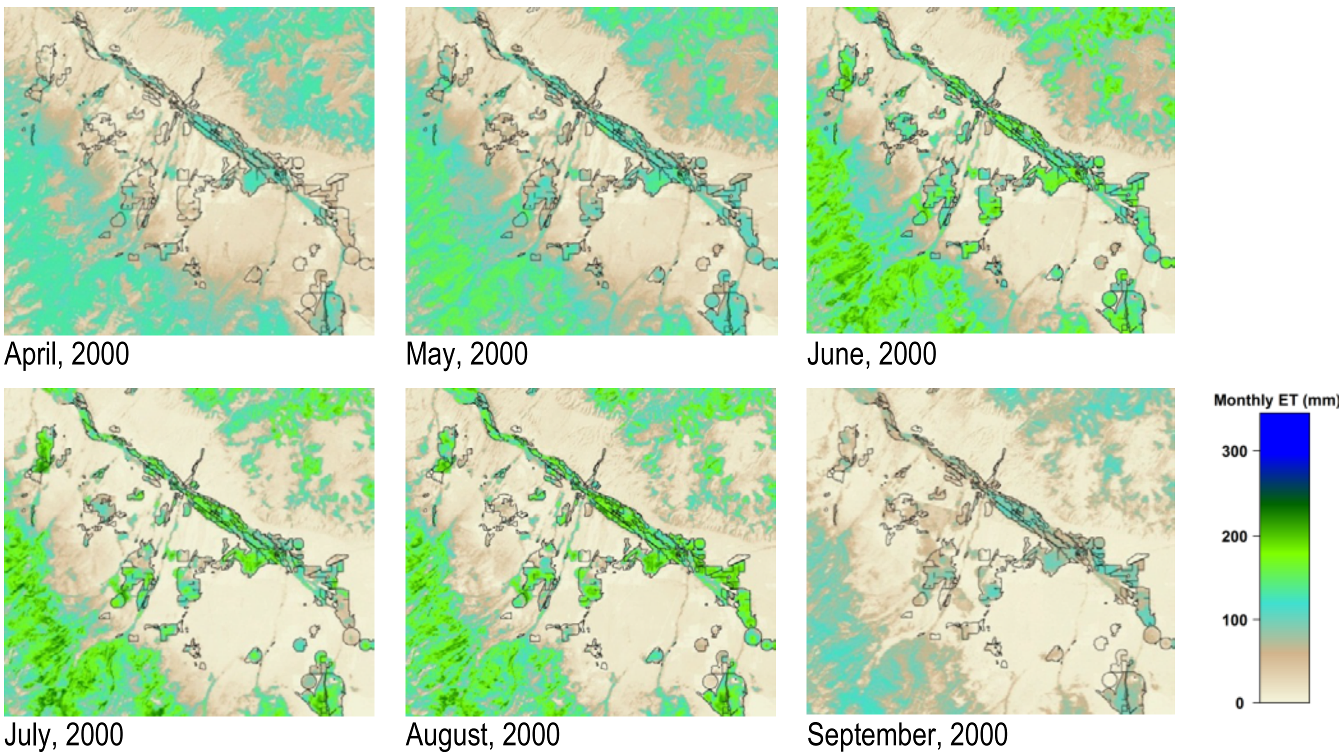


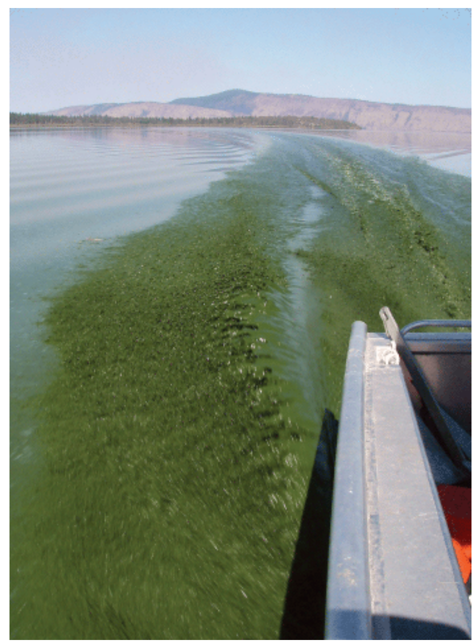
Figure 25. Evapotranspiration maps for the Lemhi Valley within the Upper Salmon River basin in 2000. Courtesy of Idaho Department of Water Resources. (ET, evapotranspiration)

Klamath Basin, Oregon

The Klamath Basin covers over 12,000 mi² in southern Oregon and northern California and contains natural resources and economic opportunities related to fisheries, farming, ranching, timber harvest, mining, and recreation (fig. 26*A*). These resources and opportunities economically sustain many communities throughout the basin, including six federally recognized Indian tribes who depend on many of these same natural resources to support their way of life and spiritual wellbeing, as they have for thousands of years (U.S. Department of the Interior, Department of Commerce, and National Marine Fishery Service, 2012).

Although rich in natural resources, communities throughout the Klamath Basin have faced repeated hardships because of water shortages, degraded water quality, diminished fisheries, and the need to protect three fish species under the Federal Endangered Species Act. These hardships have been most strongly felt by Indian tribes, commercial and recreational fishing communities, farmers, and ranchers, but they also affect the economy of the entire basin. Although hardships and conflicts have been prevalent for decades, they became particularly acute from 2001 to 2010. The conflicts included reduced water deliveries to the Bureau of Reclamation's Klamath Project, a major salmon fish die-off, and severe restrictions on commercial and sport salmon fishing along 700 miles of the Oregon and California coastline. These issues, among others, prompted development of the Klamath Hydroelectric Settlement Agreement (KHSA) and the Klamath Basin Restoration Agreement (KBRA), which were signed by a diverse group of over 40 local, Tribal, State, and Federal stakeholders in 2010. The KHSA provides for the study and evaluation of the potential removal of the four lower dams on the Klamath River that are owned by PacifiCorp. Although these dams provide locally important hydropower, they have also contributed to declines in fisheries and degraded water quality in the basin (fig. 26*B*). The KBRA contains many programs for resource restoration and re-balancing water sharing among multiple beneficial uses in the basin, including agriculture, fisheries, and National Wildlife Refuges (U.S. Department of the Interior, Department of Commerce, and National Marine Fishery Service, 2012).

A, Klamath River, Oregon.



B, Algae in Upper Klamath Lake, Oregon.

Figure 26. Klamath River and Upper Klamath Lake, Oregon. Courtesy of U.S. Fish and Wildlife Service.

The KBRA Water Use Retirement Program was developed to reduce agricultural water demand by 30,000 acre feet upstream of Reclamation's Klamath Project in order to provide more in-stream flow for fish and more reliable water deliveries to National Wildlife Refuges. This will be accomplished by acquiring water rights from willing sellers in the Upper Basin. Evaluation of water rights, and the actual water used on the land associated with those water rights, should be conducted in the area prior to acquiring a water right to ensure a water right retirement will achieve the expected goals. For example, purchasing a large water right could result in minimal in-stream benefits if that water right has not been used to its full extent or at all (Dan Snyder, U.S. Geological Survey, oral commun. and written commun., 2013). Thus a determination should be made about which water rights are being exercised to their fullest extent in order to retire water rights that would create the largest water savings. Landsat thermal imagery provides information for this type of assessment. It allows for the identification of crops and evapotranspiration mapping of the entire basin.

Historical Landsat data from 2004 and 2006 were crucial in determining the consumptive water use for the 2 years. Evapotranspiration data was mapped using Landsat imagery and METRIC software for most of the upper Klamath Basin (Snyder and others, 2012). This information provides the KBRA team and water-user groups with the opportunity to spend funds in the most efficient way possible in order to meet the goals of the restoration agreement. Identification of water right purchases with the highest consumptive use enables the team to get the most “bang for their buck” (Dan Snyder, oral commun. and written commun., 2013). More importantly, it provides for the optimal solution and maximum amount of water contributed to in-stream flow and achieves the objective of increasing inflow to Upper Klamath Lake. Using Landsat data also allowed the researchers to track monthly and seasonal evapotranspiration, due to the frequency of data supplied from the satellite.

In the case that Landsat imagery had not been available, aerial photography would have been used as a substitute. The use of aerial photography would greatly limit the availability and type of data available for use, as it is collected infrequently. While Landsat imagery covers the entire upper Klamath Basin, aerial photography would only make small sections available for processing at a time. This alternative is much more time and dollar intensive, and does not capture thermal data, thus the use of METRIC to map evapotranspiration would not be possible. Aerial scanning does capture the thermal data, and so it is another substitute to Landsat data. However, aerial scanning is very costly and requires much more processing time as the scenes are much smaller than those of Landsat. Another plausible substitute for Landsat satellite imagery is MODIS imagery; however, the 1,000-meter resolution is too coarse to allow the evapotranspiration identification of fields and landforms needed for analysis. Landsat remains the only viable option to use due to its resolution, thermal band and free availability (Marshall Gannett, U.S. Geological Survey, oral commun. and written commun., 2013).

Evaluation of potential voluntary water-rights purchases based on the water-rights documentation alone would not accurately reflect use. This alternative approach is not as efficient and is more time intensive than the use of Landsat data. More importantly, it may lead to water-right acquisitions that either do not contribute to in-stream flows, or contribute small amounts at high costs. In the case of the Upper Klamath Basin, Landsat thermal data allows the stakeholders within the basin to invest their funds effectively with a guarantee of an optimal return (Dan Snyder, U.S. Geological Survey, oral commun. and written commun., 2013).

Walker Basin, Nevada

Walker Basin is home to Walker Lake, a natural desert lake in Nevada at the terminus of the Walker River stream system of Nevada and California (fig. 27). Agricultural demand for water in the region has decreased the freshwater inflows to the lake. Since the early 1900’s, the lake’s elevation has been declining. Insufficient inflows of fresh water have contributed to an increase in salinity levels which threaten the ecological health of the lake. The lake is critical to recovery of the threatened Lahontan Cutthroat Trout. It is also an important stopover for migratory waterfowl such as Common Loons (Walker Basin Restoration Program, National Fish and Wildlife Foundation, 2012).

In October of 2009, the Walker Basin Restoration Program (WBRP) was established through Public Law 111-85. The primary purpose of the project is to restore and maintain Walker Lake.

Similarly to the Klamath River Basin, one of the initiatives within the WBRP is a Water Rights Acquisition Program. The program seeks voluntary water rights sales. A Decision Support Tool (DST) and Landsat imagery are used to help evaluate various scenarios associated with the WBRP. The DST consists of a supply side Precipitation Runoff Modeling System, MODFLOW groundwater model for the demand side, and the MODSIM river basin-management system. During these evaluations, METRIC evapotranspiration estimates based on Landsat imagery are compared to Nevada State Engineer Office evapotranspiration estimates used in the DST. The METRIC evapotranspiration estimates are related to consumptive use for individual fields. Landsat is also being used by the Nevada State Engineer's Office to look at voluntary water-rights acquisition independently of DST modeling. This information will be available as a second opinion for the project. Landsat imagery was selected for use in this project due to its spatial resolution, thermal band and historical data archive. The thermal band allows the scientists to estimate consumptive use levels within the basin. The relatively high resolution enables consumptive-use estimates to be conducted at the field level, while archived data captures the historical consumptive use on a given plot of land. Additionally, Landsat data is available for use at no cost. No other operating satellite encompasses all of these characteristics, making Landsat unique and most suitable for use in the WBRP (Justin Huntington, Dessert Research Institute, oral commun. and written commun., 2013).

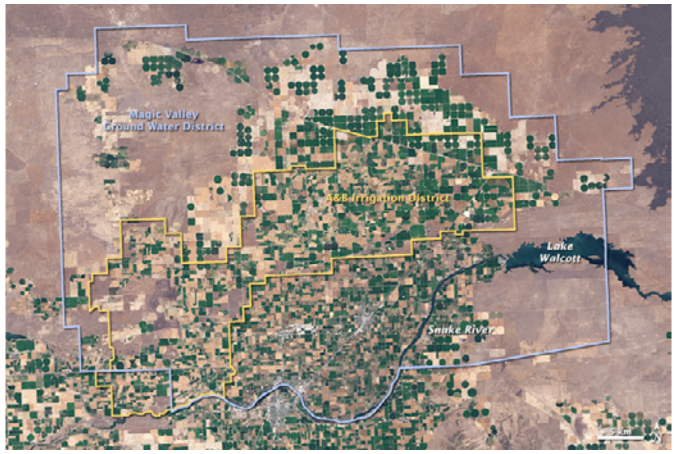
Figure 27. Walker Basin, Nevada. Photo by Mark Gamba, courtesy of National Fish and Wildlife Foundation.

Water Dispute Settlements: Justice and Transparency through Landsat

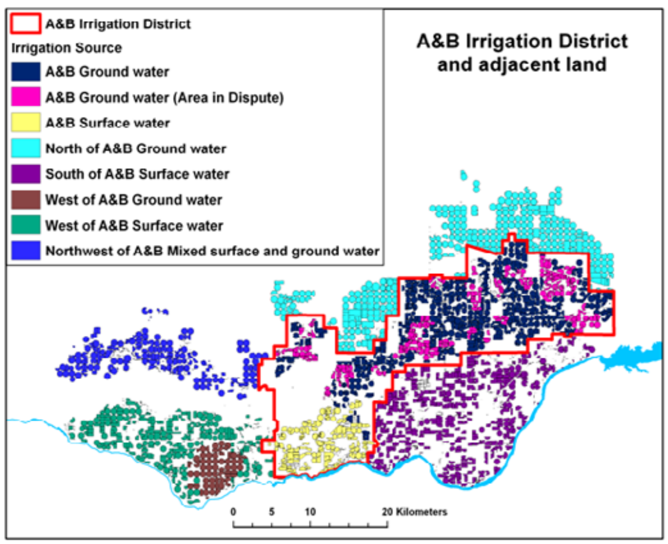
In water-short environments, water-allocation issues often find their way into water courts, where disputes regarding use, timing, and location are settled. Like much of the water law in the western United States, Idaho water law is based on the prior appropriation doctrine. The doctrine states that the water right is authorized for beneficial use based on the priority date: “first in time, first in right.” When a water shortage is experienced by a senior water-rights holder, a delivery call may be placed on the river or aquifer against junior water-rights holders. If the senior holder is found by the court to have experienced a shortage and requires additional water for beneficial use, a curtailment order is issued by the state. The order defines the means of how the junior holders must respond so that the senior holder receives the amount of water necessary for beneficial use. Landsat data has been a key contributor to evidence in several recent water court cases. The validity of the evidence provided by Landsat data has been upheld by the courts multiple times. Application of Landsat’s thermal data in METRIC energy balance model has the ability to map both current and historical consumptive water use. Two recent cases where Landsat imagery has been used as evidence regarding injury to senior water-rights holders are the A&B Irrigation District and the Clear Springs Foods, Inc. cases in Idaho. Additionally, Landsat thermal imagery allows for identification of irrigated and non-irrigated lands and has been used by the State of Nevada to confirm or deny irrigation of land plots.

A&B Irrigation District, Idaho: Call on the River

In 2006, A&B Irrigation District (A&B), a senior groundwater user, claimed it was materially injured due to junior groundwater pumping (fig. 28). Landsat data processed with the METRIC model served as key evidence for the case. One way of determining if there was a shortage of water in A&B was to analyze three archived Landsat scenes. Water use was compared through the evapotranspiration measurements conducted in METRIC for groundwater and surface-water users in A&B and the surrounding groundwater users (fig. 29). The mean daily evapotranspiration chart did not show water shortage in the area in dispute (fig. 30). Combined with an extensive examination of A&B’s water rights, history of diversions, and hydrogeology, the Director of IDWR determined A&B was not materially injured. On appeal, the A&B call was dismissed on procedural grounds.



A, Natural-color Landsat image of A&B Irrigation District (outlined in yellow), Idaho, on August 1, 2001.



B, Map of water sources in A&B Irrigation District (outlined in red) and adjacent land.

Figure 28. A&B Irrigation District. Courtesy of Idaho Department of Water Resources.

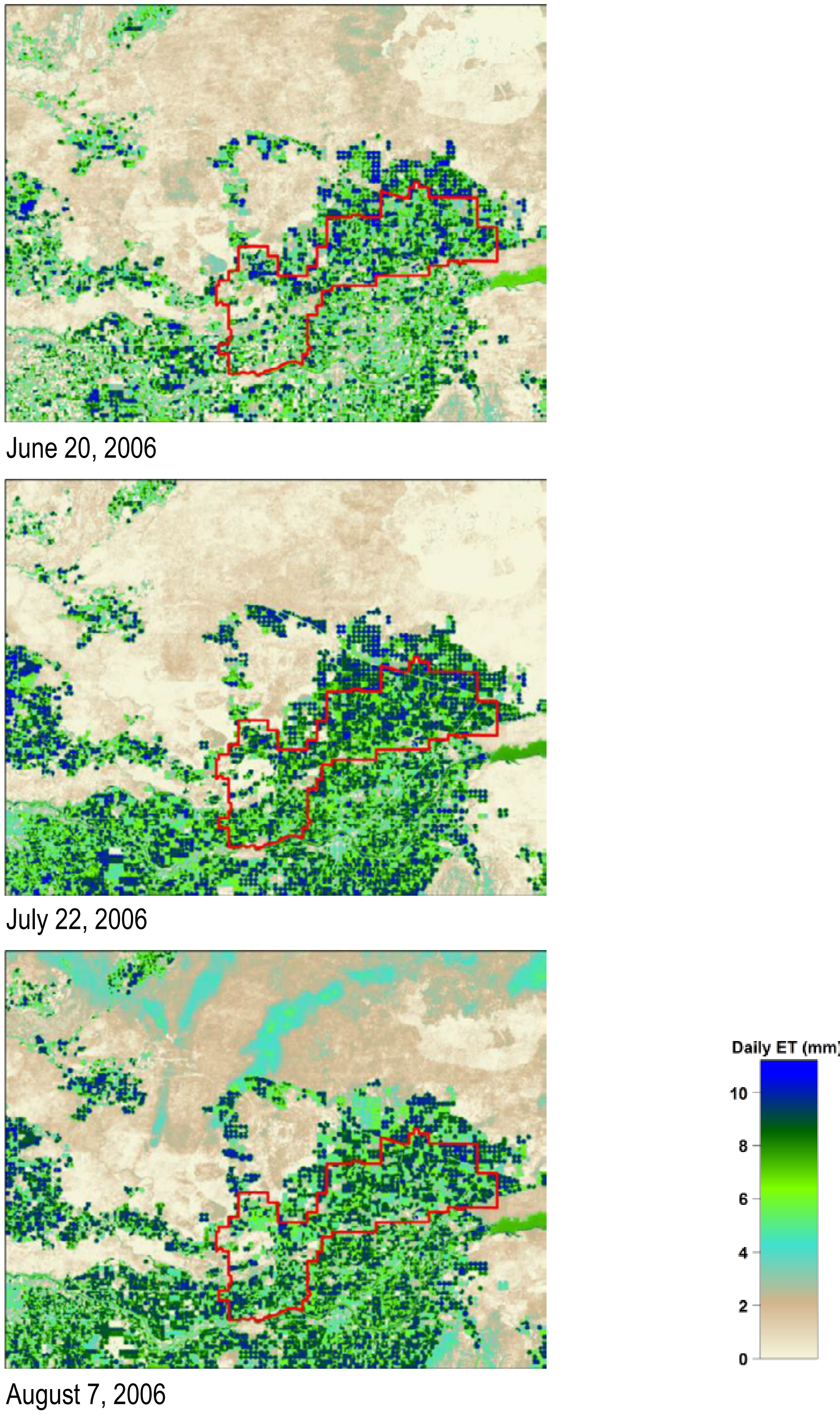


Figure 29. METRIC evapotranspiration images of A&B Irrigation District (outlined in red), Idaho. Courtesy of Idaho Department of Water Resources. (ET, evapotranspiration; mm, millimeters)

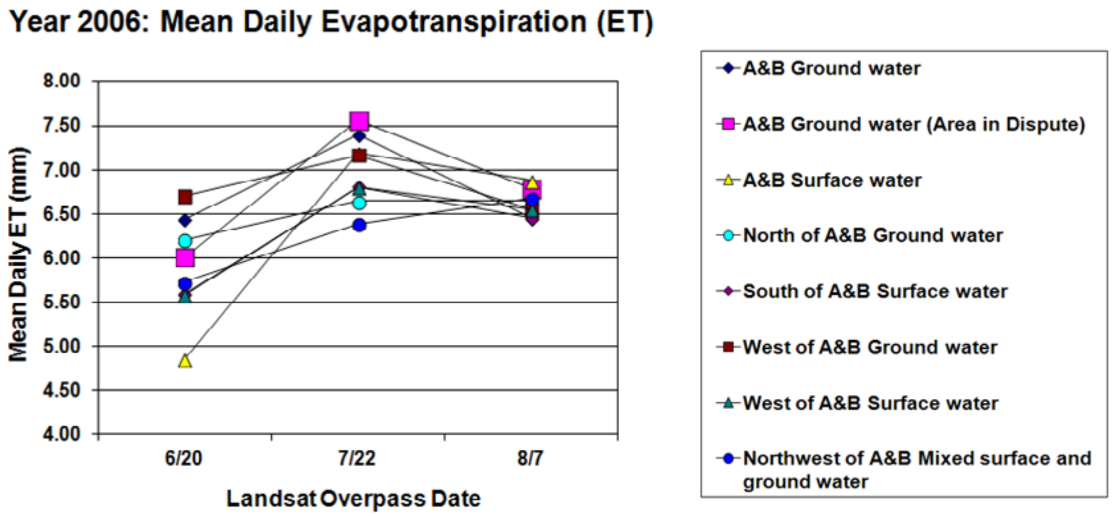


Figure 30. Mean daily evapotranspiration from various water sources in A&B Irrigation District and adjacent land. Courtesy of Idaho Department of Water Resources. (ET, evapotranspiration; mm, millimeters)

Clear Springs Foods Inc., Idaho: Curtailment Order

Similarly, in 2009, Snake River Farm, a trout farm owned by Clear Springs Foods, Inc., in Snake River Canyon (fig. 31) saw a decrease in surface water from springs (fig. 32) and sought curtailment of junior groundwater pumping. In this case, the Director of IDWR found that Clear Springs was materially injured by junior groundwater pumping and ordered curtailment. Landsat imagery processed with METRIC was used to establish water budgets to assess depletions versus recharge. For recharge estimates, both evapotranspiration and surface-water diversion return flows were used. In response to the finding of material injury, groundwater irrigators in the affected area (fig. 33) developed a mitigation plan, which was approved by IDWR, and they are no longer subject to curtailment.

Figure 31. Snake River Farm, Snake River Canyon, Idaho. Courtesy of Idaho Department of Water Resources.

Figure 32. Ground water outflows at Thousand Springs, Idaho, provide water to fish farms along the Snake River, Idaho. Courtesy of Idaho Department of Water Resources.

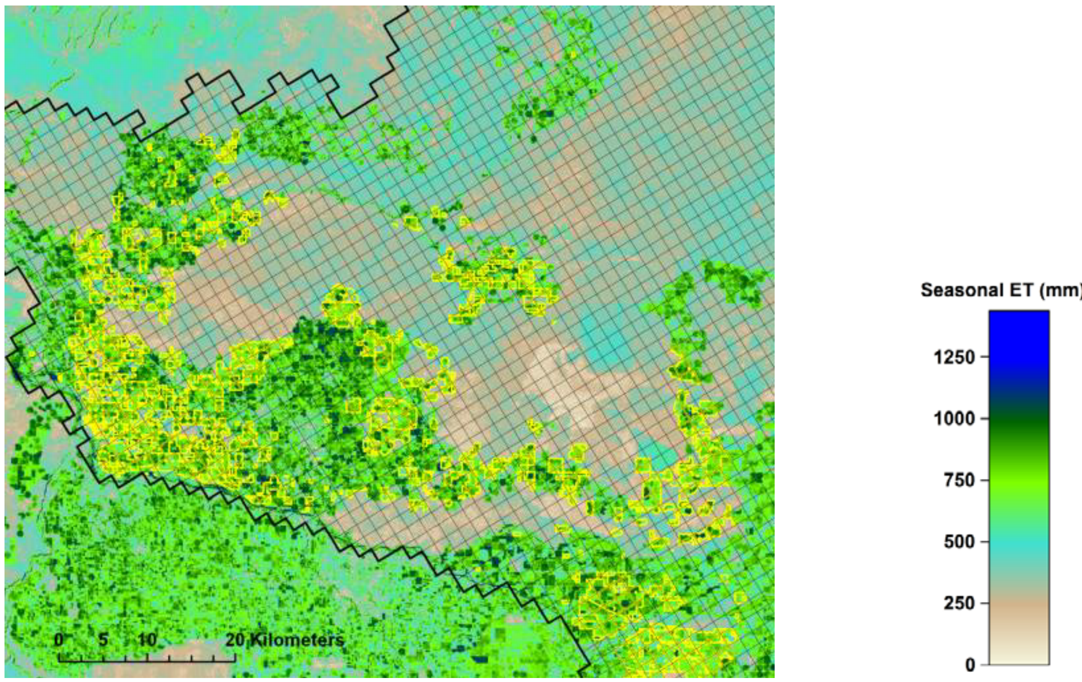


Figure 33. Seasonal METRIC evapotranspiration along the Snake River, Idaho. Junior water rights affected by curtailment are highlighted in yellow. Courtesy of Idaho Department of Water Resources. (ET, evapotranspiration; mm, millimeters)

Water Exploration: Providing Basic Needs with Landsat Imagery

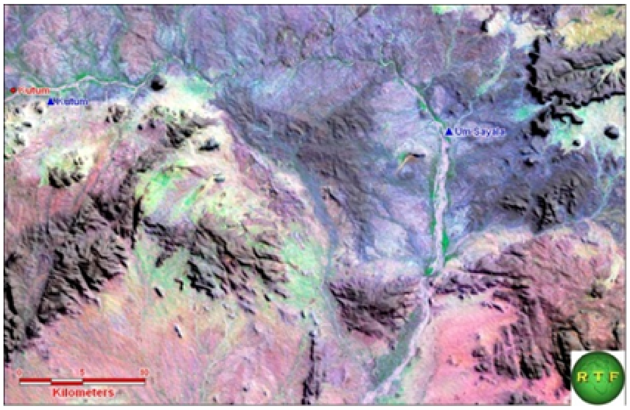
The arid climates throughout the world motivate exploration and mapping of water sources. Remotely sensed data, Landsat in particular, has been used since first becoming available 40 years ago by various firms to locate natural resources such as water, oil, and minerals. Substantial benefits are obtained from natural resource exploration, which would not be possible at the current level without Landsat data. Landsat has been a powerful source of continuous data. It has contributed tremendously to crisis prevention, mitigation, and improved management. Water explorations have been successfully conducted in the Darfur conflict region as well as Venezuela, while oil, gas, and mineral explorations have been done throughout the world.

Radar Technologies International: Water Explorations in Darfur

Amid the Darfur Crisis in 2004, more than 250,000 Sudanese refugees were forced to relocate to the desert landscape of eastern Chad. In a disaster situation, medical treatment and basic necessities become priorities for survival. Above all, the greatest need for survival was water. It is estimated by the United Nations High Commissioner for Refugees (UNHCR; 2008) that one person requires a minimum of 15 liters of water per day for basic survival. In the arid desert climate of eastern Chad, water is not readily available or easily accessible, leaving many refugees below the UNHCR standard for minimum daily water requirement (European Space Agency, 2013). Every passing day without an adequate supply of water meant the loss of 200 children's lives in the camps (Alain Gachet, Radar Technologies International, written commun., 2013) and water trucking cost the UNHCR millions of U.S. dollars per day. The need for water in refugee camps in the midst of a devastating human crisis was recognized as a major problem needing immediate attention.

In 2004, UNHCR requested that the United Nations Operational Satellite Applications Programme (UNOSAT) address the problem of water supply and help locate groundwater reserves to provide water for the refugees. With so many human lives at stake, the problem needed an immediate solution. UNOSAT reached out to Radar Technologies International (RTI), a French based company led by Dr. Alain Gachet (Radar Technologies International, written commun., 2013), to solve water supply issues. RTI, funded by USAID, partnered with USGS in designing a solution.

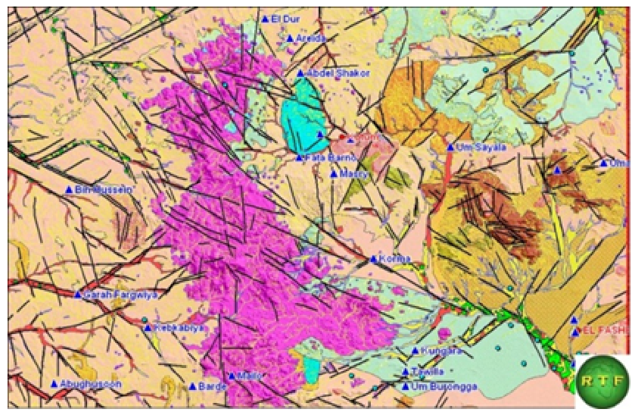
Due to the urgency of the matter, and the conflict in the area, the research team needed to use the most efficient technology available for the task. Landsat became an obvious choice, due to its relatively high spatial resolution, as a tool for landscape and terrain analysis. Twelve Landsat images were used in the identification of geological structures such as faults, dikes, and drainage channels, in combination with new Shuttle Radar Topography Mission (SRTM) data. This information was used with RTI's WATEX System which combines geology, slopes, fractures, watershed boundaries, regional precipitation and temperature data. The WATEX System allowed RTI to produce groundwater target maps using Landsat imagery as a basic input. Between 2004 and 2005, 250,000 square kilometers (km^2) were surveyed in the Darfur region. The maps identified where to drill and where not to drill in order to obtain water (fig. 34).



A, Landsat image of superficial land features north of El Fasher, Sudan.

B, Extraction of geological features from a Landsat image north of El Fasher, Sudan.

C, Map of potential water drilling sites north of El Fasher, Sudan, produced by WATEX.



D, Potential water drilling sites map for West Darfur, Sudan, produced by WATEX.

Figure 34. Maps based on Landsat images created by Radar Technologies International's WATEX System to identify potential sites to drill for water. Courtesy of Radar Technologies International.

In 2004, with the help of UNHCR, around 250,000 refugees in eastern Ouaddai in Chad were provided water from this project (fig. 35). In 2005 and 2006, with contributions from USGS and the U.S. Department of State, this project contributed to the survival of hundreds of thousands of people in the internally displaced persons camps in Darfur in Sudan (Alain Gachet, Radar Technologies International, written commun., 2013). The successful identification and drilling of 1,800 wells since 2005, with a drilling success rate of 98 percent, delivered water to the region. This work could not have been accomplished in the time frame needed without the existence of Landsat data. Landsat's resolution and its variety of spectral bands aided greatly in the success of water exploration.

A, 90-m deep water well in Lebotigue village, Eastern Ouaddai, Chad.

B, Successful water well in Wadi Gaga Campsite, Eastern Ouaddai, Chad.

Figure 35. Successful water wells drilled in Eastern Ouaddai, Chad, located based on information provided by Landsat images processed in the WATEX model. Courtesy of Radar Technologies International.

Dr. Gachet, who has led water explorations in Chad, Sudan, Ethiopia, Angola and Northern Kenya, says the following: “Landsat, with [the] Shuttle Radar Topography Mission (SRTM), are both a prodigious U.S. gift to humanity. Landsat with 7 frequencies offers a broad chemical-lithological vision of the surface of the earth, with a pixel size of 30 m which is far enough for resolving the major geological issues” (Alain Gachet, Radar Technologies International, written commun., 2013).

Additionally, in 2010, Landsat together with WATEX has been used to survey 50,000 km^2 in search of groundwater in Angola’s Kuenza sedimentary basin for reconstruction after the Angola Civil War. The old geologic data gathered by the Portuguese in the region had been destroyed during the Civil War. Landsat imagery became the only way to quickly acquire land and terrain maps.

In 2012 and 2013, Landsat and the WATEX System were also used to survey 36,000 km^2 in Turkana County in Northern Kenya and 16,000 km^2 in Northern Ogaden, Ethiopia. There has also been great interest from the new government of Kenya in a survey of all 590,000 km^2 of the country. The Iraqi Government and European Union (EU) have expressed their need to cover all of Iraq (436,000 km^2) with Landsat and the WATEX model, while USGS has expressed the will to cover the 400,000 km^2 Ogaden region of Ethiopia.

These applications of Landsat help save thousands of lives in extreme conditions and contribute to future economic development through agriculture. They have helped with identifying new possible camps for refugees near water and helped bring water to already established villages. Landsat has allowed for short response times and accurate data. No other data source comparable to Landsat’s capabilities is currently available, making it a unique and valuable asset.

Exploration Signatures: Water Exploration in Venezuela

In 1995, Exploration Signatures (then the Geologic & Hydrologic Division of Earth Satellite Corporation) used Landsat ETM+ imagery to complete water exploration work in Venezuela’s Falcón

State. The project was funded through a guarantee from the Export-Import Bank of the United States, administered by Harza Engineering Company, and performed for HidroFalcón C.A., the Venezuelan state water agency. At the time, the large cities depended primarily on reservoirs for their potable water supply, while the rural areas trucked their water in from the cities and stored it in small household water tanks. The reservoirs had begun silting-in at a high rate, causing water quality and supply issues for the rapidly growing cities, and trucking water to the rural areas was costly.

Exploration Signatures used Landsat imagery to locate water well locations in fractured rock for the entire state of Falcón. Due to the positional accuracy and relatively high resolution of the Landsat data, the team was able to establish drilling locations adjacent to communities with high water demand and low water supply. Use of the Landsat data analysis coupled with microgravimetric, magnetometric, and electromagnetic geophysical surveys ensured a high rate of success when drilling (figs. 36, 37 and 38). After drilling at all of the sites, it was estimated that 10 percent more of the in-town population and 30 percent more of the rural population would receive potable water from the new groundwater wells. Without the availability and accuracy of the Landsat data, this project would have required several years of fieldwork and many additional resources to accomplish the necessary hydrologic and geologic mapping prior to drilling. The Landsat data saved both time and money and provided the precision required for successful drilling and increasing the water supply in the areas of high demand (Ronald Staskowski and John Everett, Exploration Signatures, oral commun. and written commun., 2013).

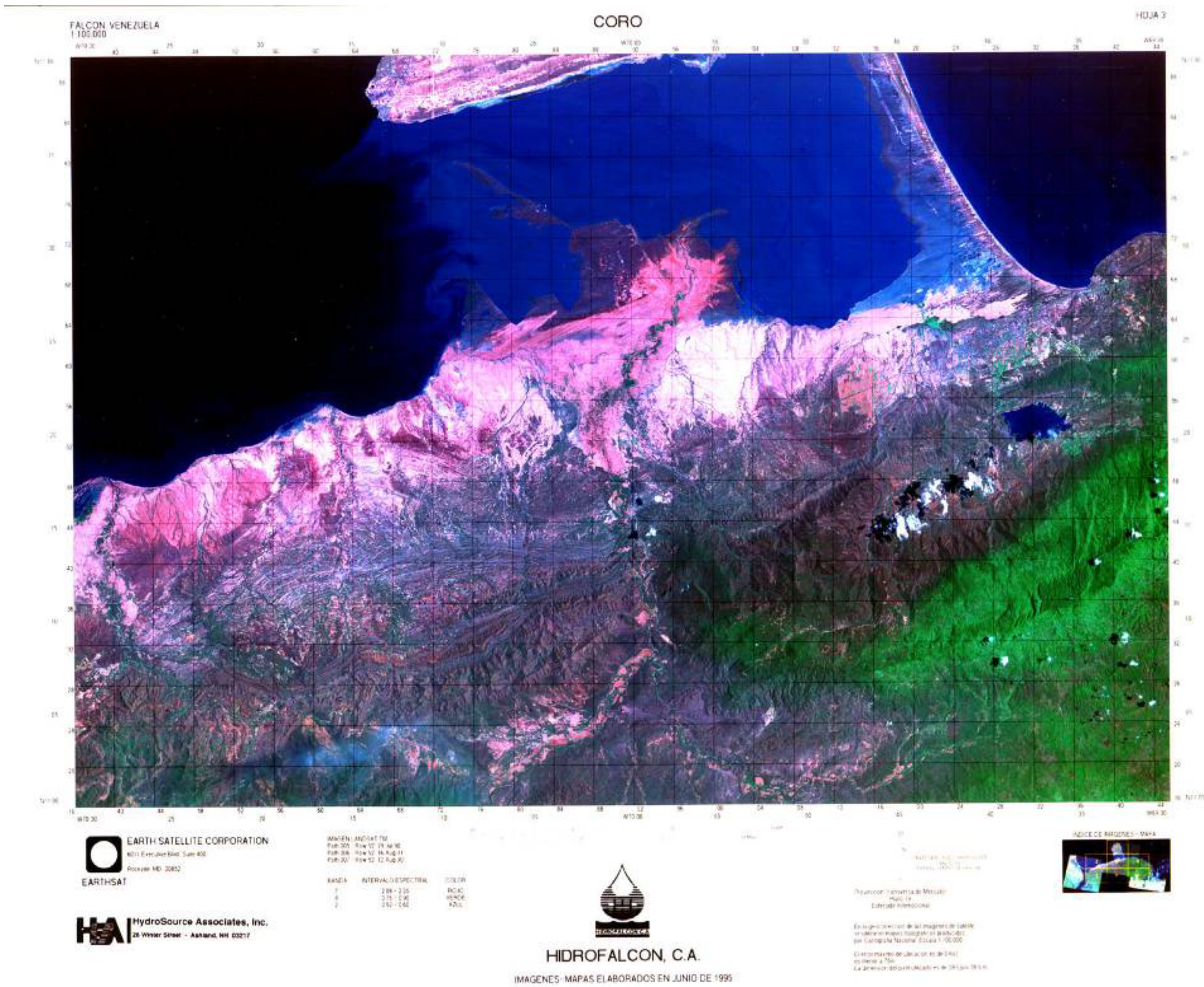


Figure 36. Landsat image of Coro, Falcon area, Venezuela. Courtesy of Exploration Signatures.

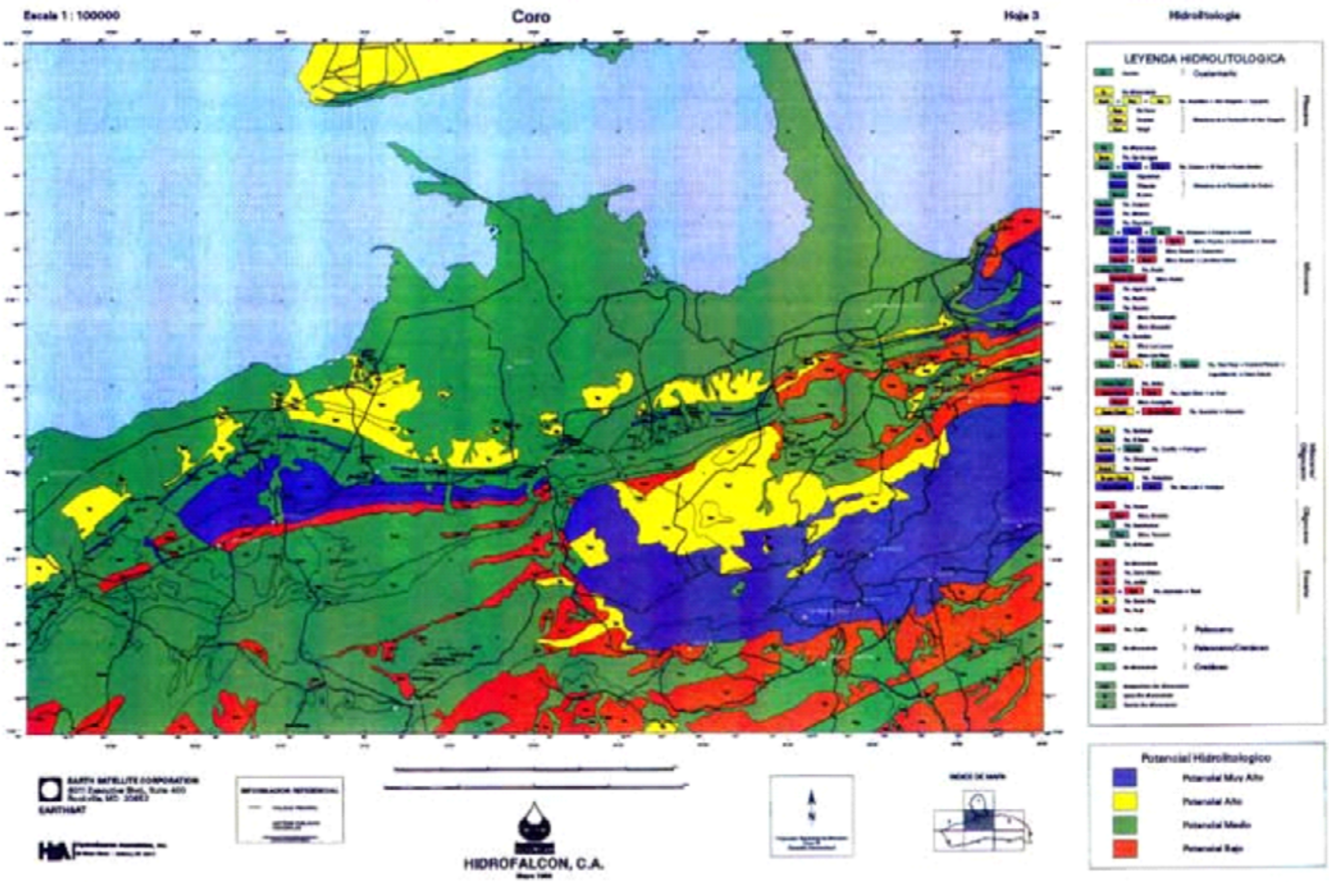


Figure 37. Hydrolithologic unit map of the Coro, Falcon area, Venezuela, based upon analysis of the Landsat data. Courtesy of Exploration Signatures.

Figure 38. Successful groundwater well at the Guaraba-Pedregal #2 drill site, Coro, Falcon area, Venezuela. Courtesy of Exploration Signatures.

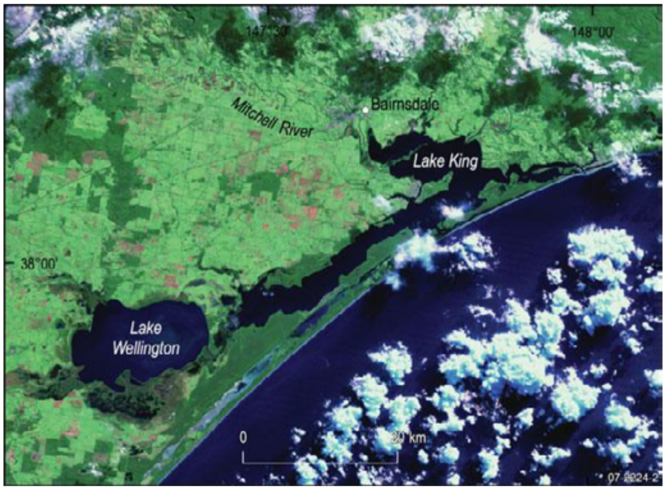
Flood Mapping and Monitoring

Flood Extent and Disaster Monitoring, Australia

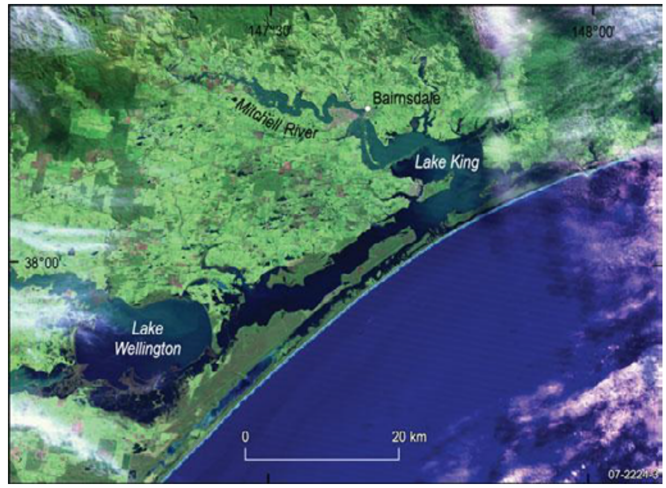
In Australia, between 1852 and 2011, at least 951 people were killed by floods, another 1,326 were injured, and the cost of damage reached nearly $5 billion dollars. More recently, the southeast Queensland floods during the 2010–11 season left much devastation, destroying 75 percent of the banana crop and, as a result, inflating banana prices (Carbone and Hanson, 2013). Floods have devastated communities and negatively impacted the regional and national economies in Australia. Landsat imagery, in conjunction with MODIS and several other commercially acquired satellites, has been used to map flood extent to provide situational-awareness information to emergency services in order to save lives and mitigate economic impact.

During June 2007, the Gippsland region in southeastern Victoria experienced heavy rainfall and widespread flooding. Geoscience Australia used Landsat 5 satellite images of the area around Bairnsdale and Sale, acquired two weeks before the heavy rains and then around the flood peak, to determine the extent of flooding (Thankappan, 2007). Visual comparison of a Landsat image acquired on June 13, before the flood, with an image taken on June 29, showed the inundated areas clearly (fig. 39*A* and *B*). In the first image, the Mitchell River is a thin, meandering black line flowing into Lake King, while the second image shows the inundation of areas around Bairnsdale, as well as the Mitchell River breaching its banks (Thankappan, 2007). Geoscience Australia provided the map of surface water extent derived from satellite images (fig. 39*C*) to the State Emergency Services in Victoria for their assessment and use. Feedback indicated that the satellite-derived information complemented local information available to emergency managers during the disaster. Information on flood extents is invaluable for emergency authorities involved in flood recovery and damage assessment. Prompt delivery of such information to emergency managers helps them prioritize their response activities. This enables flood managers to save more lives while spending less money and time on identifying flood extent (Thankappan, 2007).

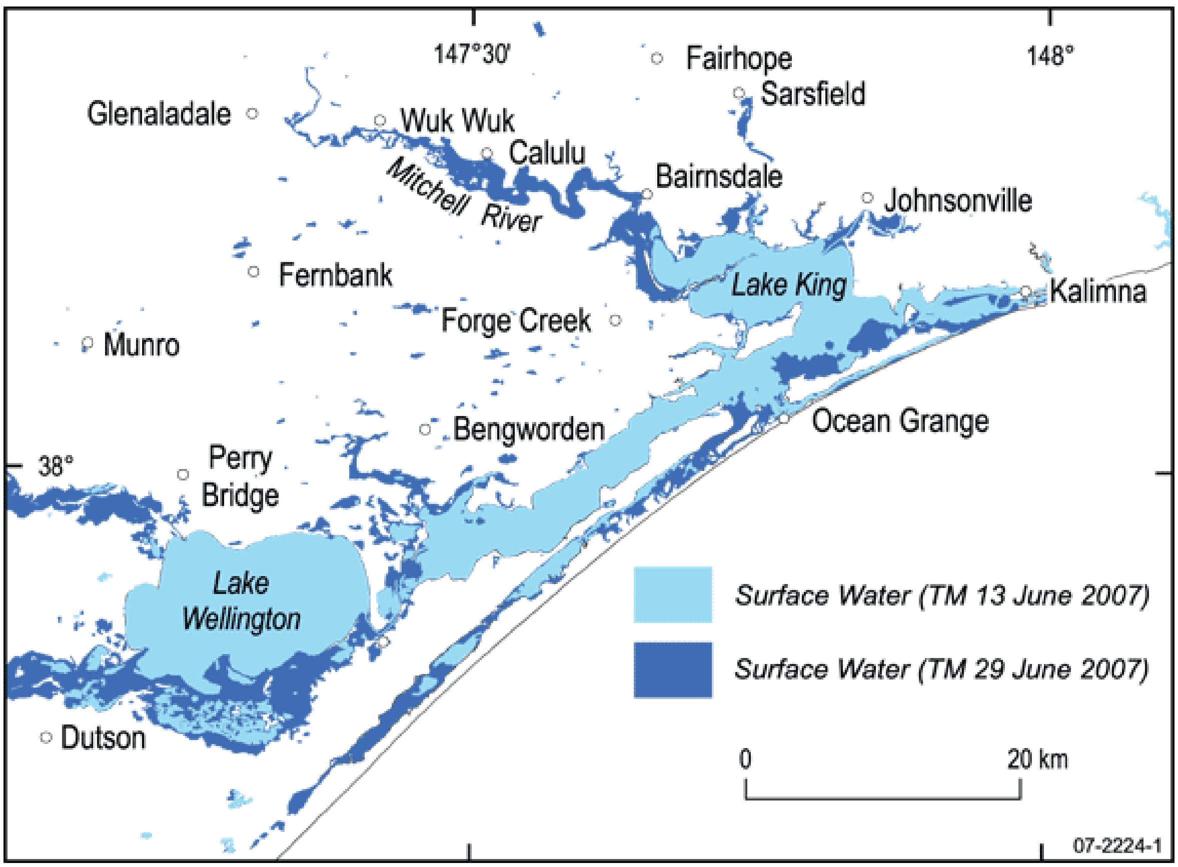
During the 2010–11 flooding of Queensland and New South Wales, Geoscience Australia provided over 100 Landsat images to and derived flood extent products for the Queensland Department of Community Safety and related emergency services. Landsat data was used to help plan access to flooded regions, sites for food and medical supply stations, and to help assess the progress of floods as they moved across inland floodplains. The resulting data were used to determine the extents of several flood plains and the locations of water diversion structures (Norman Mueller, Geoscience Australia, written commun., 2013).



A, Landsat image acquired on June 13, 2007, before the flood.



B, Landsat image acquired on June 29, 2007, during the flood.



C, Map showing extent of surface water derived from Landsat images acquired before and during the flood.

Figure 39. Images showing flooding in Victoria, Australia, in 2007. Courtesy of Geoscience Australia. (km, kilometers)

Flood Extent Monitoring in Riparian Forests, Australia

Landsat imagery is also used by the Department of Environment and Primary Industries in Victoria, Australia, to map flood extent in some of the major riparian forests along the Murray River (New South Wales and Victorian border). The results of flood mapping are used as an input to hydrological models in some instances, and in other cases as an independent source used for the calibration of model outcomes. Hydrological models are actively used as management tools. The cost of satellite images has a direct bearing on how often flood mapping is carried out to support forest management. In the absence of Landsat data, alternative sources (for example, SPOT-5) cost about $3,853 ($4,000 in Australian dollars) for the Barmah-Millewa forests (fig. 40), and the same amount for the Gunbower and Koondrook-Perricoota forests within the Murray Valley riparian systems. The current frequency of monitoring and flood mapping would not be possible without Landsat imagery availability (Kathryn Sheffield and Mohammad Abuzar, Department of Environment and Primary Industries , written commun., 2013).

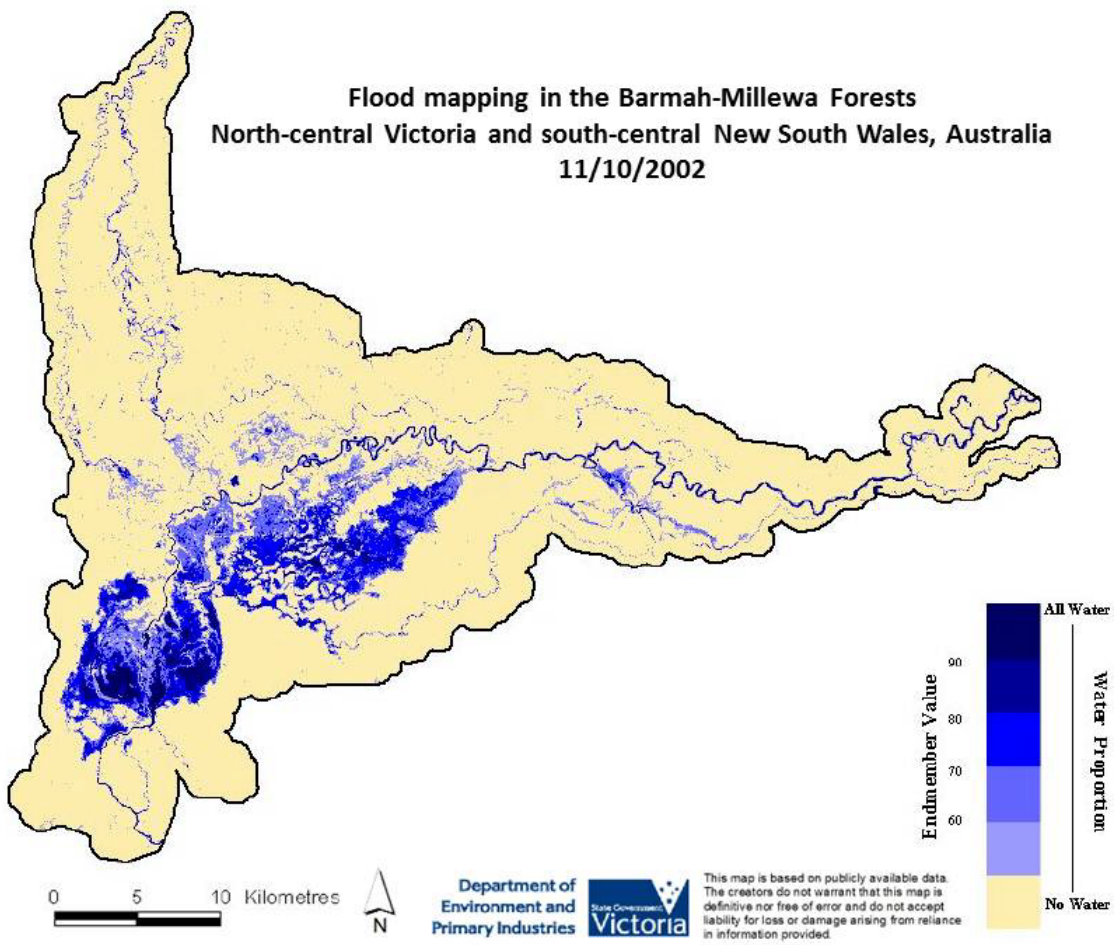


Figure 40. Flood mapping in 2002 in the Barmah-Millewa forests, north-central Victoria and south-central New South Wales, Australia. Courtesy of the Victoria Department of Environment and Primary Industries.

National Flood Risk Information Program, Australia

On July 1, 2012, Australia commenced the National Flood Risk Information Program (NFRIP), which includes mapping of flood extents from the entire historical archive of Landsat data over Australia (National Flood Information Portal, 2013). The Australian Government's Natural Disaster Insurance Review highlighted the lack of consistency across the country in the way flood-risk information was collected and made available to users. It also recognized the need for consumers to be aware of the natural disaster risks they may face, as well as the benefits of making flood-risk information more readily accessible. The aim of the NFRIP is to improve the quality, availability and accessibility of flood-risk information across Australia, and raise community awareness of flood risks (Medhavy Thankappan, Geoscience Australia, written commun., 2013).

Additionally, Australia's Department of Human Services is considering using satellite imagery to determine whether a financial assistance claim for hardship due to flooding is valid. This would be done by comparing the location of a claimant's home against a flood extent mapped with satellite imagery. The outcome of this data use would minimize the probability of unjustified claims and expedite the payment process to those who are experiencing hardship.

Landsat is a very valuable tool in these endeavors; however, several challenges exist in using the data. For example, the accuracy of surface-water extent is determined by the spatial and spectral characteristics of the satellite data from which it is derived. Since the spatial resolution of Landsat is 30 m, water bodies smaller than the spatial resolution may be difficult to identify. The quality of the image could also be affected by clouds or cloud shadows. The accuracy of final flood-extent maps is therefore influenced by these factors (Thankappan, 2007). In addition to the aforementioned issues, during the 2011–12 flooding of Queensland, data from Landsat 5 was not available, and Landsat 7 data was affected by the scan-line corrector issue. This forced Geoscience Australia to use Disaster Monitoring Constellation International Imaging (DMCii) and other commercial satellites to track the progress of flooding along several major rivers in New South Wales over a period of three months. The cost of commercial data acquisition for the 2012 floods was close to $100,000. The commercial data, especially DMCii, provided broader and more frequent coverage than Landsat, at the expense of spectral information. This lack of spectral information made the data harder to analyze (Norman Mueller, Geoscience Australia, written commun., 2013).

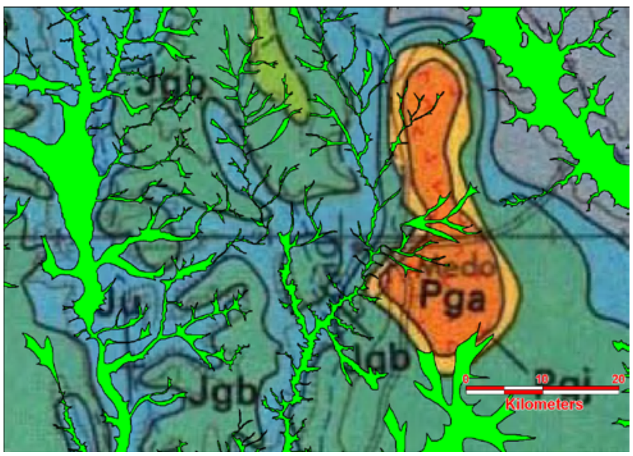
Land Cover Mapping

Africa

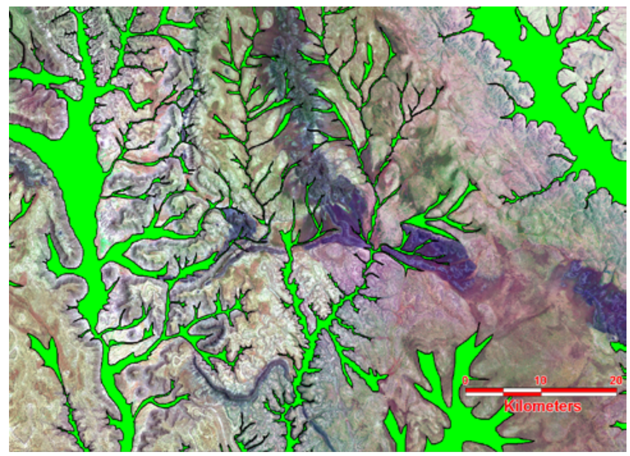
While working in Africa, Dr. Alain Gachet of RTI saw a need for new maps of the continent, particularly inland maps (written commun., 2013). Almost all geological maps of Africa were created during the 1960s before some African countries became independent. The coastal maps are fairly accurate, as they were required to meet the standards of the French, English, and U.S. Navies. Inland maps beyond 50 km from the shore, however, diverge significantly, with geolocation errors of several kilometers. This is due to the nature of the tools used at the time, such as the astronomic compass (sextant) and the clock. Most topographical maps drawn during this period contain errors up to 22 km on 1:50,000 scale. Such inaccuracies make it very difficult to conduct inland work relating to oil, gas, mineral and water exploration.

Radar Technologies International was able to use Landsat to redraw the geological maps of Africa, the Middle East and Australasia. Landsat imagery, combined with SRTM data, provides an excellent overview of the topography, including drainage and watershed boundaries, with a geolocation accuracy of 10 m. Redrawing new maps with Landsat data enabled RTI, as well as other companies, to use the maps for mineral and oil exploration within those regions.

Figure 41 illustrates the discrepancy between a geologic map drawn in 1972 over a topographic map from 1968 and a Landsat image wrapped on SRTM. The topographic base of the older map is from the U.S. Army Map Service series 2201 Edition 1968. The alluvial layer has been extracted from Landsat and georeferenced on SRTM data from 2004. The basaltic formations are coded in orange in the first map and appear in dark purple in the second. It is hardly possible to recognize the geologic contours drawn in the older map. There is a shift of almost 15 km between the basaltic formations of these two images. Such accuracy is crucial in natural resources exploration: it draws the boundary between the success and failure of an exploration program. Increased accuracy of this type of information also minimizes costs as well as risks, which provide a higher probability of exploration success.



A, Geological map of Ethiopia drawn by V. Kazmin (United Nations) in 1972. Topographic base is from the U.S. Army Map Service series 2201 Edition 1968. The basaltic formations are orange.



B, Landsat imagery of Ethiopia georeferenced on SRTM data from 2004 with the alluvial layer extracted. The basaltic formations are dark purple. There is a shift of almost 15 km between the basaltic formations of these two images.

Figure 41. Comparison between geologic maps of Ethiopia, the first drawn in 1972 over a topographic map from 1968 and the second consisting of a 2004 Landsat image georeferenced on SRTM. Courtesy of Radar Technologies International.

Australia

Australia's agricultural industry has evolved significantly within the last decade. Change in agriculture, whether it is an increase in land used for production or the types of crops being produced, has an impact on land-cover soil properties and water availability. Landsat imagery is used in monitoring irrigation areas and dry land agricultural areas to detect changes in agricultural practices over time. Additionally, land cover is also used in benchmarking of water-use efficiency which supports irrigation water management at the catchment level. Victoria's Department of Environment and Primary Industries has been using a historical land cover data set from Landsat in a major cropping region in central Victoria. The NDVI and land-cover classifications from the Landsat images are used to conduct the analyses. Figure 42 shows largely a dry land cropping area in the Wimmera Region. Historical soil and land-use information from government surveys will be used to compare against the Landsat data. The goal is to examine the linkages between the historical soil information and imagery to investigate influences of long-term farming trends on soil properties. This project would not be undertaken if the archive of Landsat imagery was not available. The historical continuity of Landsat data allows for the observation of changes in land cover over time since the 1980's, which is not possible with other satellite imagery.

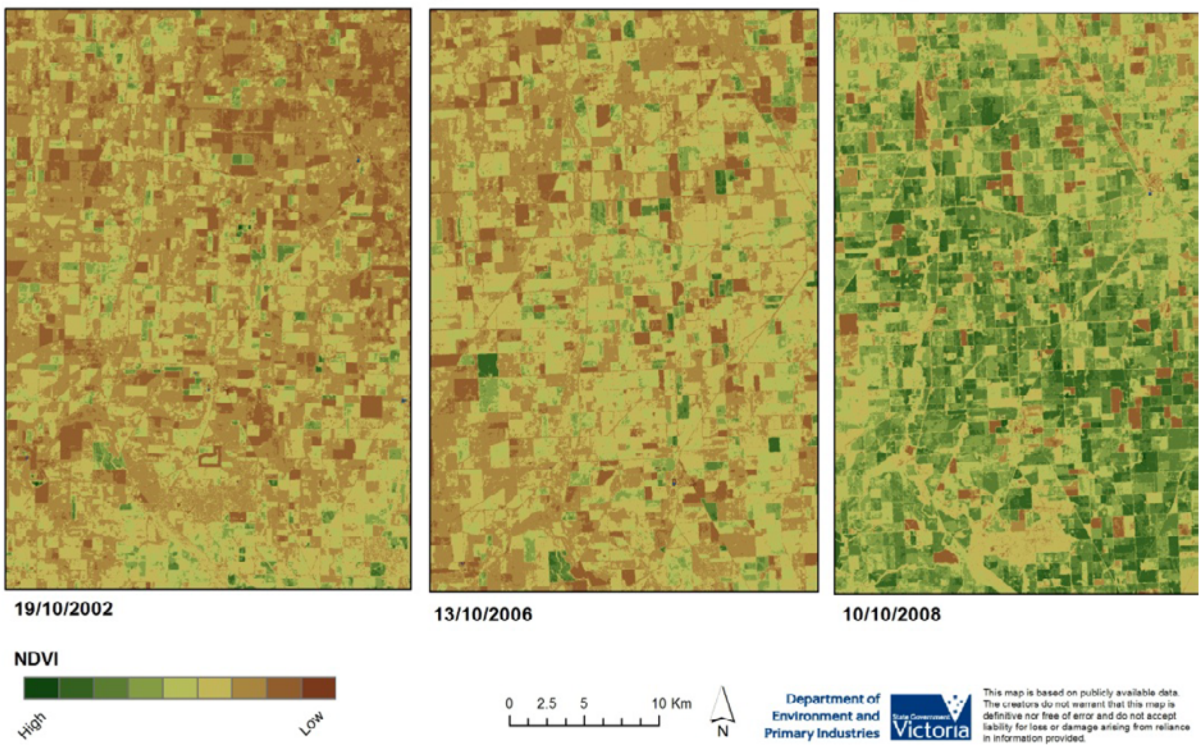


Figure 42. NDVI (Normalized Difference Vegetation Index) maps derived from Landsat 5 imagery in the Wimmera Region, north-central Victoria, Australia. Courtesy of the Victoria Department of Environment and Primary Industries.

Landsat imagery is also used to create an annual land cover map for a section of the Goulburn-Murray Irrigation Region. This map identifies the type of pastures grown in the area (seasonal/annual/perennial) and is then used in other projects. The production of this information relies on NDVI and thermal information and would be restricted without the availability of the Landsat data. If Landsat were not available, suitable alternatives would incur costs which would limit the amount of work able to be done. In the absence of Landsat data, the alternative source of imagery which could be used is ASTER. For one season of land cover of the Goulburn-Murray Region, ASTER images would cost about $14,462 ($15,000 in Australian dollars) at present. The ASTER sensor is onboard the aging Terra satellite with no continuity plan in place. In the near future, Landsat 8 will be the only available satellite with moderate spatial resolution and the thermal band. Future land-cover monitoring for this region will depend solely on Landsat data (Mohammad Abuzar, Elizabeth Morse-McNabb and Kathryn Sheffield, oral commun. and written commun., 2013).

Conclusion

This set of case studies in water resources and other application areas illustrates that Landsat's characteristics make it unique and necessary for the accomplishment of a variety of water and land monitoring as well as resource-exploration tasks. Although substitutes for Landsat exist, none are as suitable as Landsat for a variety of reasons (see table 1 for a comparison of satellite imagery attributes). Given the number of possible, though typically less favorable, alternatives presented in the case studies, this summary provides comparisons of those alternatives.

Table 1. Comparison of operational satellite imagery attributes. (m, meters) (km, kilometers)

Characteristic	Landsat	MODIS	ASTER	SPOT	DMC
Spatial resolution	15–30 m	250–1000 m	15–30 m	2.5–20 m	22–32 m
Thermal band	Yes	Yes	Yes	No	No
Thermal band resolution	100 m	1000 m	90 m	NA	NA
Market cost (US$)/ scene	Free	Free	Free to U.S. users	$2500-$11600	NA
Cost (US$)/ acre	Free	Free	Free to U.S. users	$0.002-$0.004	$.0008- $.0014
Frequency of repeat coverage	8 days	1–2 days	Potential 8 days	4–5 days	1–3 days
Geographic extent of coverage	World-wide	World-wide	On-demand	World-wide	On-demand
Continuous historical archive	Yes (since 1972)	Yes (since 1999)	No (archive of previously requested data)	Yes (since 1986)	No (on-demand data collection)
Swath	170 km by 185 km	2330 km by 10 km	60 km by 60 km	60 km by 60 km	650 km by 650 km

The continuity and frequency of Landsat data allows for biweekly, monthly, and seasonal comparisons to take place, whether they are of flood extent or evapotranspiration on agricultural fields. Although ASTER imagery has some comparable features to Landsat, it is only available on-demand, and data acquisition is never guaranteed in the area requested. This limits data availability to one use at a time and does not ensure continuity. Thus, ASTER does not deliver the continuity and frequency of global data coverage that Landsat does, and so does not allow for easy multi-temporal analysis. Imagery from SPOT offers frequent data with higher spatial resolution to that of Landsat. However, SPOT data is not free, and the SPOT sensor does not carry the thermal band, making it a costly and imperfect substitute for Landsat imagery.

The moderate spatial resolution of Landsat enables users to track changes in agricultural production, water consumption, and land cover at the field level. The resolution is just high enough to detect the location and impact of many natural and anthropogenic changes but also moderate enough so that large areas can be analyzed easily. Sensors with lower resolution, such as MODIS, prevent field-level understanding or accuracy when mapping land-cover changes (fig. 43). Although many other uses exist for MODIS data, water measuring and monitoring is not one that is easily accomplished with MODIS. Higher resolution satellites such as DMC provide data that is often beyond the information necessary for the work described in the case studies. Due to higher resolution, some sort of data aggregation would need to take place before information could be used for large area analysis. The DMC data is also available on demand for a specific section of the earth. The costs and sporadic special availability of the imagery would not make it possible for local or industry level water monitoring to be accomplished.

Figure 43. 30-meter resolution Landsat (left) and 500-meter resolution MODIS (right) images of agricultural fields south of Albuquerque, New Mexico, acquired on August 26, 2002. Courtesy of University of Idaho.

The thermal band is another key component of the Landsat satellite, particularly for water-related applications. In fact, a large portion of the work reported in these case studies could not be accomplished without the thermal band. When looking for satellites that are comparable to Landsat and have a thermal band, ASTER is an option. However, as described above, ASTER's data acquisition dependability and continuity issues would not meet water resources project needs consistently. While aerial scanning also has thermal data as an option, it is very costly and presents similar processing issues as a high-resolution satellite for the uses captured in the case studies. Thus, additional time and dollar costs make it less favorable than Landsat. Aerial scanning, similar to the acquisition process of ASTER imagery, must also be acquired on-demand for a specific plot of land. This minimizes the amount of users able to use data due to the relatively small areas that are scanned and likely due to private ownership of the requested imagery. The resolution of MODIS imagery is not high enough for use at a farm field scale, even though the thermal band is available on the MODIS sensor.

Landsat satellites consistently scan the entire earth and provide data to all national and international users for use at no cost. Lack of acquisition cost, combined with frequency, continuity, moderate spatial resolution, and a thermal band, make Landsat a valuable satellite for use in water-resource management, as many of the case studies in this report illustrate.

The benefits from Landsat data use are abundant; nonetheless, uncertainty about the future of the Landsat program exists among users (Powell and others, 2007). Many agencies are faced with choosing between old models and approaches and new, more efficient, accurate, and cost effective methods that involve the use of Landsat imagery. It may seem like the choice is obvious; however, it is not so simple. Even though current and traditional methods are not as accurate or cost effective, there is already a structure in place for them. Transferring to Landsat could require anything from additional time and training, to hiring new staff and restructuring of the program. Most of the users in these case studies are willing to undertake the transition because the potential and realized benefits are much greater than the cost of restructuring. Many users are switching from traditional models and methods to using Landsat and Landsat-derived applications such as METRIC. What makes the transition difficult, however, is the uncertainty that the data the users need, currently provided by Landsat, will be available in the future without interruptions. This leaves many users unable to plan for a future which relies heavily on Landsat, requiring them to maintain old methods and strategies, and in some cases implement both Landsat and older methods concurrently to some degree.

Some features of the Landsat program that would provide more reliability and usability are outlined by the Western States Water Council in 2012, as they pertain to the uses of Landsat in the area of water resource management in the western states. Some of the needs listed include an operational land-observation program that would maintain continuous scene acquisition around the globe without any data gaps, moderate resolution to observe land and water at the field scale (30- to 60-meter pixels) and the near infrared, short-wave infrared and thermal bands on all future satellites.

At the time that these case studies were conducted, Landsat data had only been available free of charge for about 4 years. The majority of the people interviewed for the case studies anticipate continuous and increasing returns on their use of Landsat in the coming years. These and other benefits could be captured by additional case studies of Landsat uses and benefits.

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