Mine Water Environ (2011) 30:242–251
DOI 10.1007/s10230-011-0153-5

TECHNICAL ARTICLE

The Applications of Satellite Based Remote Sensing Techniques in the Hydrological Assessment of Mine Water Supply and Management Systems

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Received: 27 January 2011 / Accepted: 11 April 2011 / Published online: 20 May 2011

Abstract Mineral resources are often discovered in remote or mountainous areas where long-term hydrological records are either absent or limited. Satellite-based remote sensing techniques can provide indirect observations of phenomena of interest, such as rainfall depth, snow cover, evapotranspiration, and changes in groundwater levels. Quality and applicability of the data are limited by the spatial, spectral, and temporal resolution of images. Other limitations may arise from the algorithms used to interpret the data. Examples are provided on how new remote sensing has been used at sites owned by Barrick Gold Corporation. It should be stressed that, for the foreseeable future, remote sensing data can supplement, not replace, more traditional sources of information.

Keywords Evapotranspiration · Ground subsidence · Mine water management · Precipitation · Remote sensing · Snow melt · Spring peak flow

Introduction

An efficient water management system, which provides a sustainable water supply and minimizes potential social and environmental impact of mine operations, must be based on an accurate understanding of local water resources. This understanding is developed using existing meteorological, hydrological, and hydrogeological information supplemented by new information from site investigations. The outcome is expressed in the term of water balances for the mine site and for the larger hydrologic/hydrogeologic system in which it is set.

Many new mineral resources are discovered in remote or mountainous areas where long-term meteorological and hydrological data are absent or limited. A ground-based monitoring network takes time to establish and requires considerable effort and resources (Anagnostou et al. 2010; Milewski et al. 2009). In recent years, remote sensing has become a viable source of data to quantify the state and fluxes of water and energy between the land and the atmosphere (Anagnostou et al. 2010; Singh et al. 2004; Tang et al. 2009). Applications relate to many aspects of water cycles: rainfall (Anagnostou et al. 2010; Gebremichael et al. 2007; Huffman et al. 2007; Kummerow et al. 2007; Milewski et al. 2009), evapotranspiration (Bastiaanssen et al. 1998; Chen et al. 2005; Sun et al. 2009), soil moisture (Wigneron et al. 1998), watershed water balance (Singh et al. 2004) and groundwater elevation changes (Katzenstein 2008).

Different sensors are used to detect different hydrological and topographical parameters. Most satellite-based sensors are passive (Tang et al. 2009), detecting the natural radiation or reflection from an object. Passive sensors, such as the visible (VI) and infrared (IR) of the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board NASA's Terra and Aqua satellites observe ground snow cover. Passive sensors have been the dominant source of hydrological and hydro-meteorological observations (Michaelides et al. 2009). Other sensors are active, such as radar, which emits signals to be reflected from and absorbed by an object. The following sections describe applications of remote sensing techniques to study parameters

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that are frequently required in the design and operation of a mine water supply and management system.

Precipitation

Precipitation is, in most cases, the primary driver of the water cycle in a given watershed. In the context of mining operations, rainwater is desirable as a source of water supply, but problematic when excessive water enters mine workings and mine contact water holding facilities. The design of the mine site water supply and water management system must take into account the variability of precipitation and the risks associated with drought and flood events.

Regardless of its importance, precipitation is one of the most difficult atmospheric variables to measure due to large spatial and temporal variability. When using data from rain gauge networks for engineering design purposes, a general understanding of regional rainfall pattern and other hydrological characteristics must be included. Precipitation can be estimated using visible (VIS, 390–750 nm), infrared (IR, 0.75–1,000 μm), and passive microwave (PMW, 1–1,000 mm wavelengths) on geostationary (GEO) and low Earth orbiting (LEO) satellites (Michaelides et al. 2009). Although remote sensing has the clear advantage of wider coverage than traditional rain gauge networks, no single sensor type has demonstrated the capability to accurately measure precipitation. The trend in satellite-based precipitation measurement has been the development of hybrid systems that combine ground-based monitoring networks with multi-sensor and multi-satellite observations (Anagnostou et al. 2010; Michaelides et al. 2009; Tang et al. 2009). For example, a hybrid approach has been implemented in the Global Precipitation Climatology Project (GPCP) to provide monthly precipitation on a 2.5° global grid for the period between 1979 to present.

The Tropical Rainfall Measuring Mission (TRMM), a joint mission between NASA (USA) and the Japanese space agency, JAXA, is clearly a major advance in the observation of rainfall using combinations of sensors (Anagnostou et al. 2010; Michaelides et al. 2009; Simpson et al. 1988). The three primary precipitation sensors on board are TRMM Microwave Imager (TMI), the precipitation radar (PR), and the Visible and Infrared Radiometer System (VIRS). TRMM multi-satellite precipitation analysis (TMPA) combines precipitation estimates from various satellite systems, such as TRMM and the Defense Meteorological Satellite Program (DMSP), with land surface precipitation gauge measurements, where available. Generally, systematic and random errors are reduced when combining independent data sources. The TRMM_3B34 is a TMPA product that estimates monthly precipitation on a 0.25° global grid from 1998 to the present. A detailed description of TMPA is presented in Huffman et al. (2007).

Example Application: 1-Reko Diq Project, Balochistan, Pakistan

Precipitation estimated using TRMM is supporting the baseline study for the Reko Diq Project, which is being developed by Tethyan Copper Company Pty Ltd (TCC), an Australian company jointly owned by Barrick Gold Corporation (Barrick) and Antofagasta plc. The project is located near the western tip of Balochistan Province in southwestern Pakistan, bordering Iran and Afghanistan (Fig. 1). Geographically, it has the Chagâi Hills to the northeast and a highland area west of the Iranian border. The project area is in a region of transition between the summer monsoon system of the Indian subcontinent and the winter cyclone system of the Mediterranean climate. It is one of the driest areas in the world, with infrequent and highly variable precipitation.

The regional weather station network is sparse (Fig. 1). The nearest station, Nok Kundi, is about 72 km east of Reko Diq. It was necessary to determine whether the monthly precipitation record (1961–2006) at Nok Kundi station could be used to augment the short record (2005-present) at Reko Diq. In addition to direct comparison of the overlapping periods of record of the two stations, the TRMM-3B34 estimated monthly precipitation for the Reko Diq Project area and Nok Kundi station was also spot-checked. The TRMM dataset was extracted from the TRMM online visualization and analysis system (TOVAS) (NASA 2011).

The applicable domains for the Nok Kundi and Reko Diq weather stations were assumed to each span 0.25° of latitude and longitude. The domain of the Nok Kundi station is assumed to span latitudes 28.67°–28.92°N and longitude 62.67°–62.92°E. The domain of the Reko Diq station is assumed to span latitude 29.0°–29.25°N and longitude 62.0°–62.25°E. The location of the selected domains of the Reko Diq and Nok Kundi areas (rectangle boxes) are shown on Fig. 1. Comparisons between TRMM (for the Nok Kundi domain) and observed precipitation at Nok Kundi, and between the Nok Kundi and Reko Diq TRMM estimates, are presented in Fig. 2a, b, respectively.

Comparing the TRMM results to the weather station data at Nok Kundi (Fig. 2a), it is seen that the timing of wet and dry months matches well, but the TRMM estimates lower rainfall depths for some high-precipitation months. This agrees with observations that rainfall measured at a gauge is typically greater than average rainfall over the greater area surrounding the gauge, especially for high intensity rainfall events. Nevertheless, the TRMM results do provide a reasonable indication of the long-term rainfall patterns in the region. The comparison between TRMM results at Reko Diq and Nok Kundi (Fig. 2b) showed that the timing of rainfall matches well, although the magnitude showed considerable random variation, especially for January 2000 when a significant rainfall of 164 mm was reported for Reko Diq but only 10 mm for Nok Kundi. With the exception of this data point, the rainfall variations between the two locations appear to be randomly distributed without bias or trend. This indicates that the January 2000 high precipitation at Reko Diq could be treated as an isolated event. For the baseline study, it was concluded that the precipitation record from the Nok Kundi station could be used to represent conditions at Reko Diq. The annual average precipitation was therefore estimated at about 32 mm at the Reko Diq Project, equal to the long-term average annual precipitation at Nok Kundi (1961–2007). This conclusion is supported by the fact that the two locations have the same vegetation types and land use distributions.

Example Application 2: Cerro Casale Project, Maricunga District of Region III, Chile

The Cerro Casale project is located in Northern Chile, 145 km east-southeast of the City of Copiapó. The project is within a major mountainous area, at elevations ranging between 3,700 and 5,400 m above sea level (masl). Over mountains and other complex terrain, precipitation is often highly variable over short times and distances. This is due to rapid wind pattern changes and temperature decrease-induced condensation on the windward side of the slope; while precipitation increases with elevation, mountain ranges can create leeward-side “rain shadows”. This variation is poorly characterized worldwide due to lack of monitoring networks. Moreover, point measurements using can-type rain gauges often underestimate precipitation, due to high wind-induced under-catch in mountain areas (Sevruk 1997; Valéry and Andréassian 2008). In addition, snowfall at the project area, not measured, contributes a substantial portion of the annual precipitation, particularly at the highest elevations, which yield a large proportion of the basin water recharge. Consequently, the absence of snow measurement for weather stations at site and in the surrounding region lowers the level of confidence in the precipitation estimate.

To augment the general understanding of the site precipitation pattern, remote sensing-based precipitation data were obtained. As with traditional monitoring networks, TRMM-based precipitation data also suffer accuracy issues in snowy areas (Huffman 2007). This is mainly due to difficulty in distinguishing between snow cover on the mountain tops and precipitation clouds using the TRMM

Fig. 1 Topography of Pakistan, the locations of the Reko Diq Project and some regional weather stations (Modified after Map 5013839-73, Central Intelligence Agency, USA with new locations added)

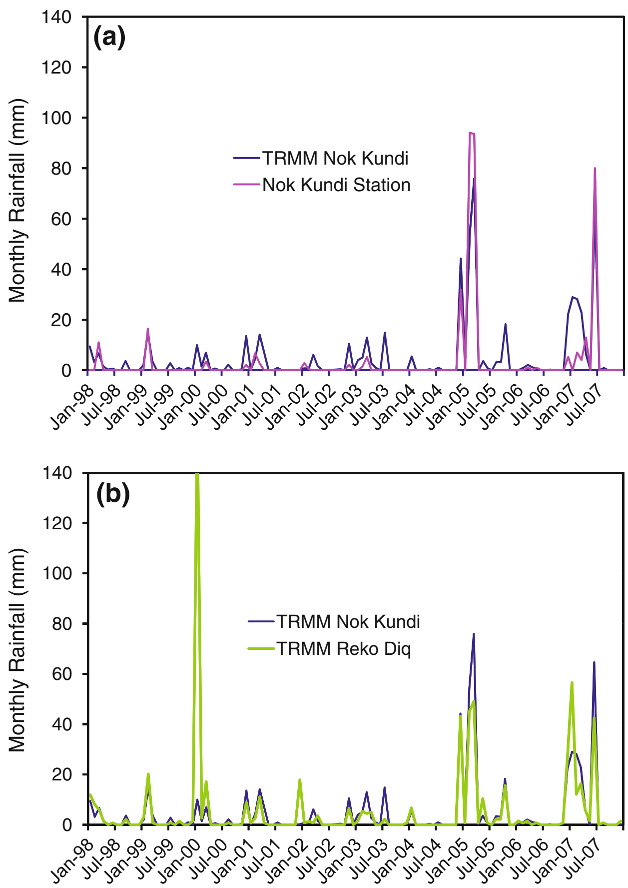

Fig. 2 **a** Comparison of Nok Kundi monthly rainfall between the TRMM and the records from the PMD (Pakistan Meteorological Department); **b** comparison of TRMM time series rainfall data and correlation (insert) at Reko Diq and Nok Kundi

microwave sensor, and the challenge that the infrared sensor has in capturing warm orographic rain (Dinku et al. 2007). Among all the TRMM datasets, the third level product, TRMM_3B34, appears to offer the best performance for the complex terrain, based on several validation studies (Casimiro et al. 2009; Chiu et al. 2006; Immerzeel et al. 2009). The study region of Casimiro et al. (2009) is in a Peruvian Amazon-Andes basin, the nearest and most comparable site to the Cerro Casale project.

The coverage area was selected as latitude: 27.59°–27.87°S, longitude: 69.13°–69.44°W. This area is outlined (pink) on the following SRTM world elevation data (Fig. 3). Monthly precipitation data representing site condition were extracted from an online source (NASA 2011).

The TRMM_3B34 based monthly precipitation for the period January 1998 through May 2009 is shown on Fig. 4. A summary of the dataset shows maximum, minimum, and average annual precipitation of 213, 103, and 151 mm/year, respectively, over the 10 year period. The TRMM dataset overlaps with the site summer (rainfall) measurement, also shown on Fig. 4. Comparison of the two data sets shows reasonable agreement in the timing of precipitation, but the TRMM data represent significantly higher precipitation than site observations. One possible reason for this is that the site rain gauge is located near the base of the valley, while the TRMM estimate represents a much larger area with both ridges and valleys. Since there are few rain gauges (and no snowfall measurements) in the study area, the ground-based monitoring network is inadequate for estimating the distribution of precipitation over the complex topography. Validation of the TRMM_3B34 dataset therefore requires further ground truthing. Based on some successful validation studies, especially in the region (Casimiro et al. 2009), the hydrological investigation for the project needs to take into account the possible higher precipitation indicated by the TRMM database, considering that the existing ground-based, rainfall-only monitoring network is expected to underestimate precipitation.

Peak Flow from Snowmelt

Snowmelt often accounts for a substantial portion of precipitation in mountainous and high latitude regions. Compared to rainfall, snow hydrology involves more physical processes and thus is more complicated to observe (Michaelides et al. 2009). Snowpack height and snow density are naturally highly variable over a basin, partially due to redistribution by wind and uneven exposure to sun. Snow density is expressed as snow water equivalent (SWE), the equivalent depth of water contained in the snow (US Army Corps of Engineers 1998). The water content of either newly fallen snow or of the accumulated snowpack has been traditionally measured by weighing a vertical core taken through the snowpack. The SWE and the snow cover extent (SCE) have been observed using airborne passive microwave radiometry (Derksen et al. 2005; Langlois et al. 2007).

As with the observation of rainfall, combinations of sensors and data sources have been the basis for the more reliable estimates of snowfall and snowpack (Durand et al. 2008). The National Operational Hydrologic Remote Sensing Center of the National Oceanic and Atmospheric Administration (NOAA) ingests daily ground-based, airborne, and satellite snow observations from all available electronic sources within the USA. These data are used along with estimates of snowpack characteristics generated by a physically-based snow model to support the daily NOAA National Snow Analyses (NSA). The NSA provide information on SWE, snow depth, surface and profile snowpack temperatures, snowmelt, surface and blowing snow sublimation, snow-surface energy exchanges, precipitation, and weather forecasts in multiple formats

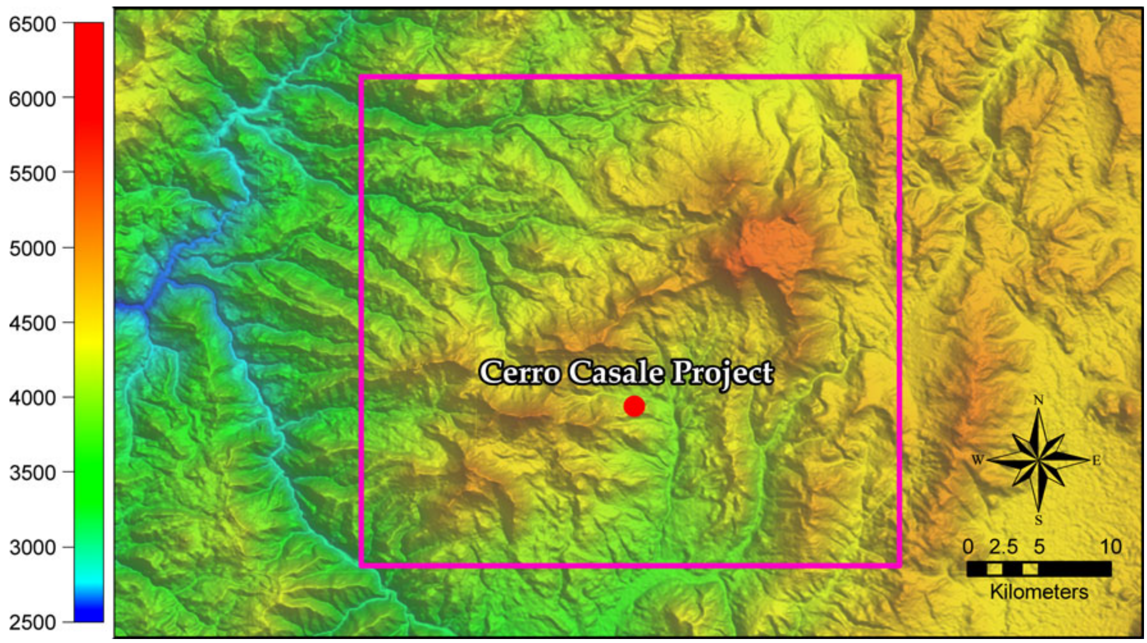

Fig. 3 Area (*pink outline*) selected for TRMM_3B34 data extraction

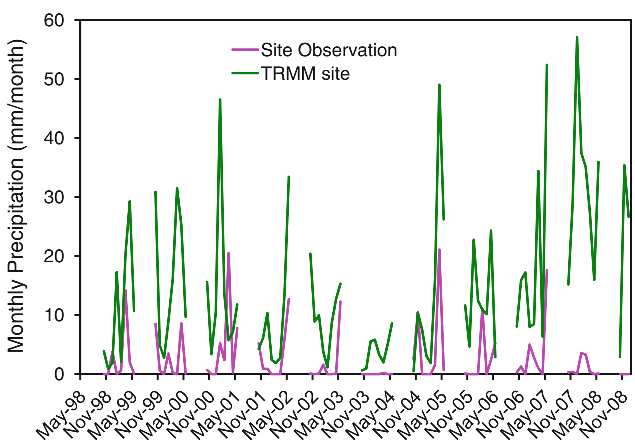

Fig. 4 Measured and TRMM-estimated monthly precipitation at Cerro Casale, excluding the winter months of June to September

(NOAA 2011a). The Advanced Hydrological Prediction Service (AHPS) of NOAA uses these various data, sophisticated computer models, and a communications system that is referred to as the Advanced Weather Interactive Processing System to provide hydrologic forecasts such as stream flow and stage for almost 4,000 locations across the United States.

Application Example 3: Homestake Mine, South Dakota, USA

The Homestake Mine, located in the Black Hills area of South Dakota, was a deep underground and open pit gold mine (Fig. 5). Since 2001, the mine has been under closure

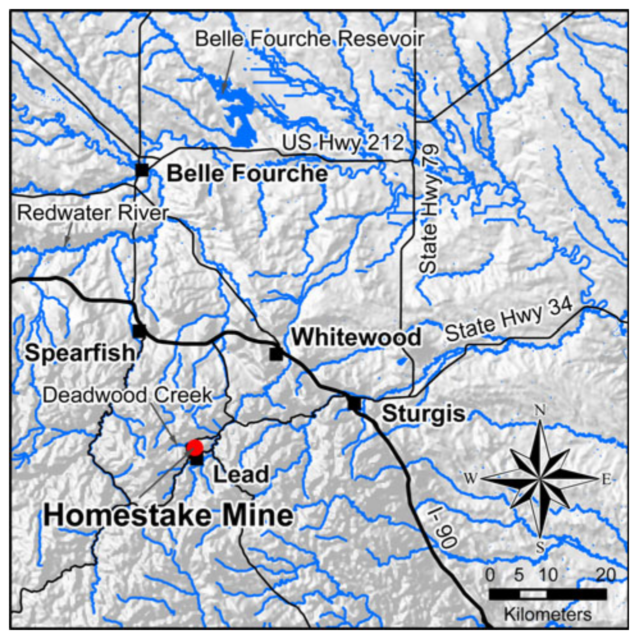

Fig. 5 Location of the Homestake Mine and the major drainage network (modified after USGS 2002: redrawn original figure and location added)

management, which includes the collection and treatment of runoff and seepage from its East and Sawpit waste rock facilities. Treated runoff and seepage is discharged to the adjacent Deadwood Creek and eventually reaches the Belle Fourche River (Fig. 5). The handling of runoff during the annual spring melt is one of the key components of effective site water management. This requires accurate

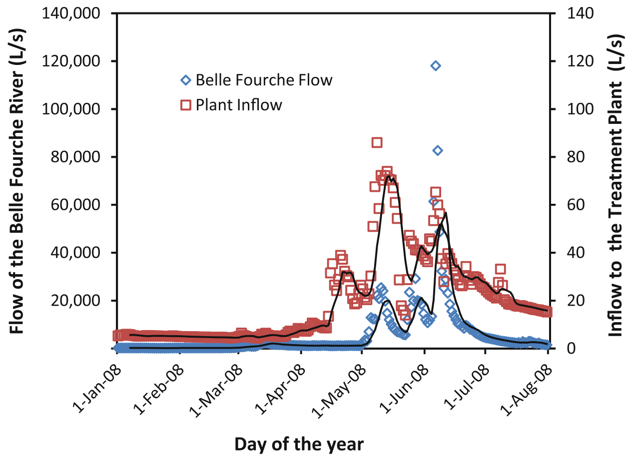

Fig. 6 Daily flow (*symbol markers*) and weekly moving average (*lines*) at the Homestake water treatment plant and the Belle Fourche River during the snowmelt of 2008

forecasting of the rate and timing of peak inflows and total volume of water to be treated.

A study was conducted to evaluate whether the AHPS-predicted annual peak flow at the Belle Fourche River could be used to guide prediction of the timing and the rate of the peak inflow to the water management system at the Homestake Mine. Historic Belle Fourche flow at the Wyoming—South Dakota state boundary was obtained online (USGS 2011).

Preliminary results show that the timing of peak flow in the Belle Fourche River and at the mine site match well for the 2008 (Fig. 6) and 2009 seasons (Fig. 7). Peak flow at the Homestake treatment plant occurred between 1 and 5 days later than at the Belle Fourche gauge. The apparent delay of snowmelt at Homestake was expected due to higher elevation and therefore lower ambient temperature.

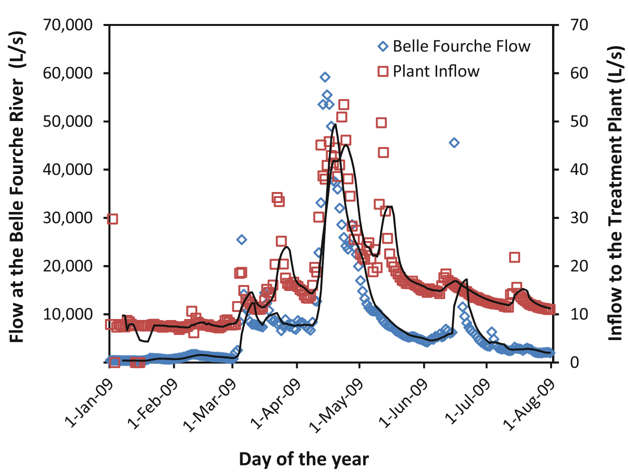

Fig. 7 Daily flow (*symbol markers*) and weekly moving average (*lines*) at the Homestake water treatment plant and the Belle Fourche River during the snowmelt of 2009

Due to the strong correlation between peak flow timing at Belle Fourche River and the Homestake treatment plant intake, the projected probability distribution of weekly maximum streamflow at Belle Fourche River can serve as an indicator for peak inflow timing at the Homestake Mine. The projected probability of weekly maximum streamflow at Belle Fourche River can be found online (NOAA 2011b).

The on-going work has determined that daily flow rates at the two locations are approximately directly proportional within a single melting season, but that the ratio changes from year to year. It is possible that a web-based tool may be developed to calculate future treatment plant inflows based directly on the weekly Belle Fourche River flow forecast by AHPS.

Water Resource Model Applications

Water resource models are generally required to support feasibility studies and environmental impact studies for mining projects. These models often have two objectives: to quantify the long-term average of local or regional precipitation, evapotranspiration (ET), recharge, and surface water discharge; and to project the possible impact on the current water resource by the additional water abstraction/re-injection associated with a proposed mining operation. A calibrated water resource model should be able to reproduce the current and historical status of the local or regional groundwater and surface water conditions. Remote sensing data are valuable to model calibration because of their wide coverage, especially in arid and semi-arid areas where ground observation points are sparse (Li et al. 2009). ET is a major component of most water balances and often is a parameter for model adjustment/calibration (Casper and Vohland 2008). Remote sensing techniques have been successfully used to estimate actual ET (as opposed to potential ET estimated from meteorological parameters) in recent decades (Bastiaanssen et al. 1998; Chen et al. 2005; Courault et al. 2005; Sun et al. 2009).

Application Example 4: Reko Diq Project, Balochistan, Pakistan

Under arid climate conditions, the loss of water through ET can account for nearly all discharge from a basin. Accurate estimation of this component is essential for the development of the water resource model for the Reko Diq Project. The Surface Energy Balance Algorithm for Land (SEBAL®) is a commercialized method that estimates ET as the residual of a surface energy balance, which is calculated using ground level meteorological data and satellite

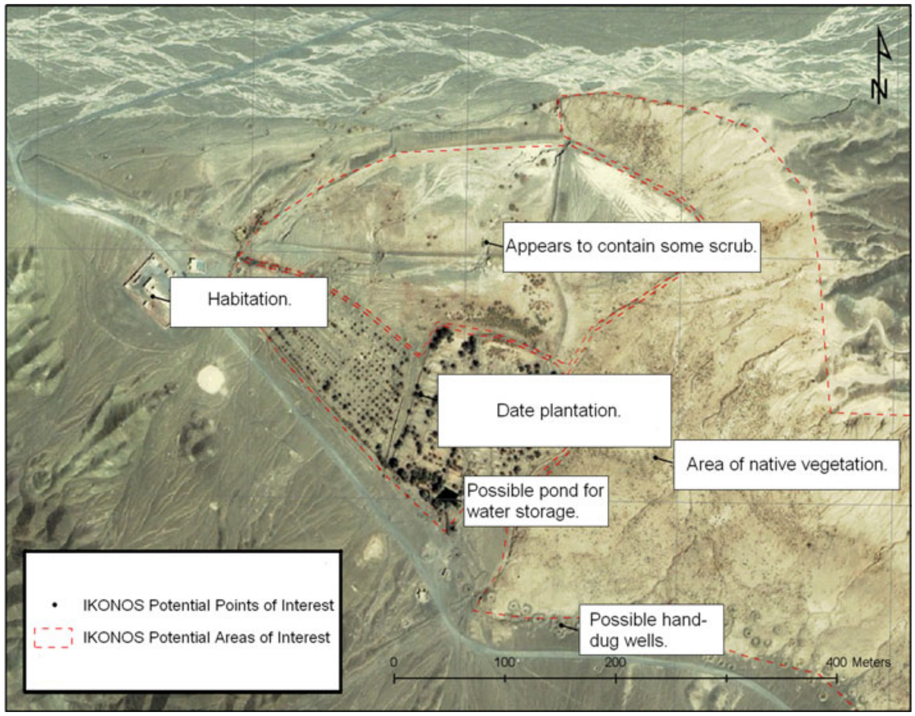

Fig. 8 Example of an apparent small scale agricultural area showing vegetation, plantation, and ponds (IKONOS imagary). Figure used with permission from Davids Engineering and SEBAL North America, California, USA

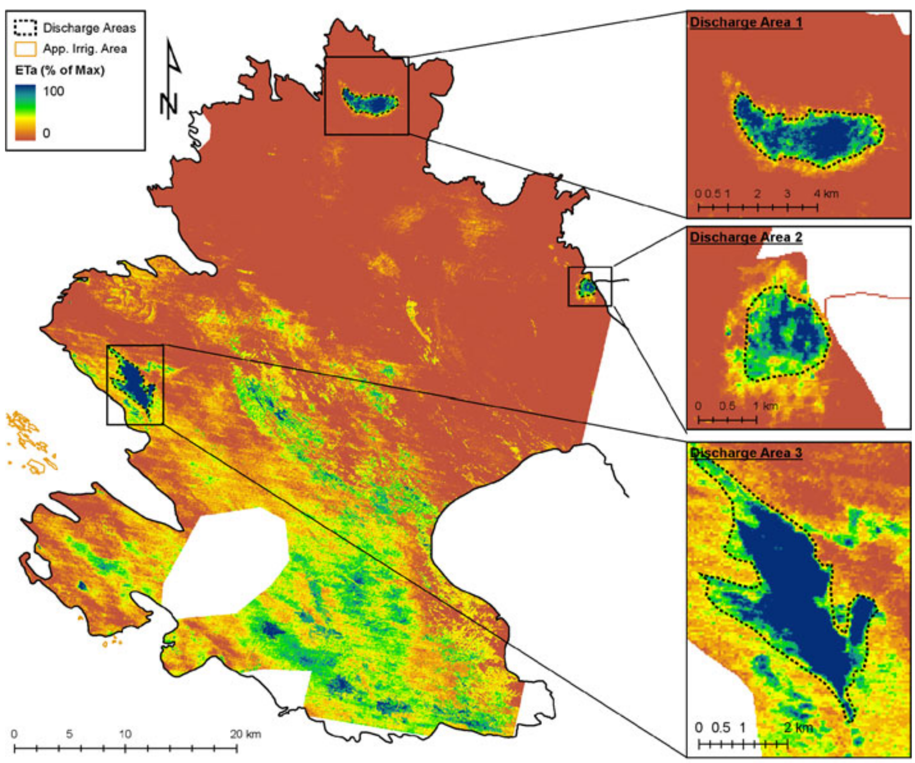

Fig. 9 Estimated annual ET as percent of potential evaporation from the Hamun -I-Mashkel using SEBAL method, Nov. 2003–Oct. 2004 (figure used with permission of Davids Engineering and SEBAL North America, California, USA)

observation data. Multi-spectral inputs of satellite images include visible, near-infrared, and thermal bands. Detailed description of this algorithm has been reported by Bastiaanssen et al. (1998). This process was selected to estimate ET from irrigated cultivation and natural ET by Davids Engineering and SEBAL North America, California.

A sample satellite image analysis, delineating vegetation, ponds, and irrigation canals, is presented as Fig. 8. With the satellite-based land and vegetation classification and other physical parameters such as surface temperature, solar radiation, and albedo, the SEBAL® method was used to estimate monthly ET for various land and vegetation classifications. ET discharge estimated for Hamun-I-Mashkel, a salt playa covering more than 2,288 km^2, is shown as Fig. 9. The estimated ET values were further checked against other indirect information, such as crop water requirements and estimates of local water well usage.

It is clear that ground-based monitoring could not cover the various landforms or the vast extent of the study area. The estimates of ET from the remote sensing investigation provide a semi-quantitative framework for understanding the baseline regional water resource.

Interferometric Synthetic Aperture Radar Technique

Interferometric synthetic aperture radar, or InSAR, has proven to be a valuable tool to measure ground motion or displacement; however, only recently has InSAR been used extensively to delineate the aquifer system response to groundwater pumping.

Application Example 5: GoldStrike Gold Mine, Nevada, USA

Groundwater has been pumped as part of gold mining operations along the Carlin Trend in northeastern Nevada, USA for about four decades. Pumping increased significantly beginning about 1989 as deeper gold deposits were mined. Accurately mapping the potential effects of the withdrawal of large quantities of groundwater on regional aquifers is of great interest to mining companies, local communities, and regulators. Mining companies in the Carlin Trend have implemented extensive surface water and groundwater monitoring programs that cover nearly 1,500 km^2. InSAR techniques using C-band radar (5.6 cm wavelength) data from remote sensing satellites ERS-1 and ERS-2 has also been used as to complement the ground monitoring network.

Radar satellites use active sensors that record the distance from the sensor to the ground surface. In the InSAR

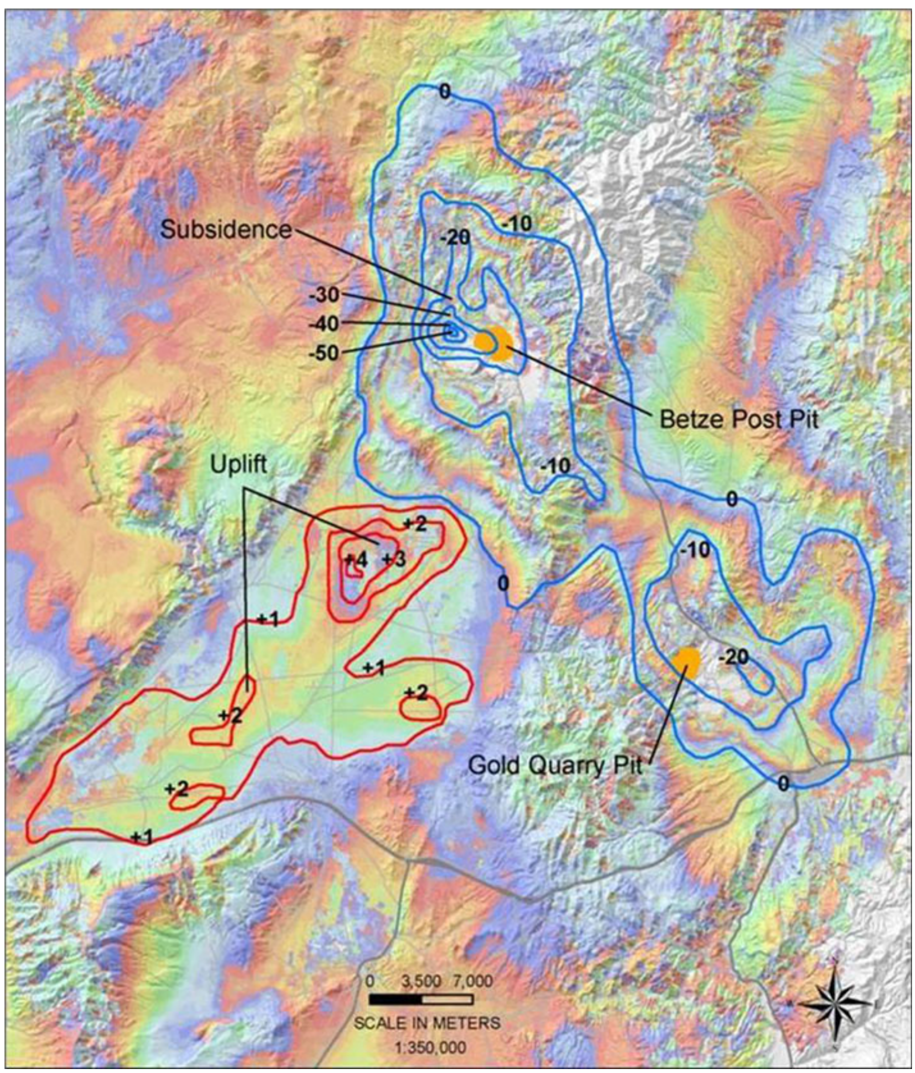

Fig. 10 Measured subsidence (−) and uplift (+) along Carlin Trend, northeastern Nevada (unit: cm) (period of 1992–2000; adapted from Katzenstein 2008, with permission of authors)

method, two images, taken at different times, are selected with acceptable baseline separation. The two images are then precisely overlain, or "interfered" over each other. Topography is then subtracted using a digital elevation model (DEM). The differences in phase between the two images are recorded and color-coded to create a map of surface deformation.

Figure 10, from the Carlin Trend InSAR study, indicates ground subsidence (blue contours) and uplift (pink contours) along the Carlin Trend. Subsidence is associated with groundwater withdrawal from the carbonate aquifer hosting the ore body. The uplift contour matches the observed elevated water levels in the alluvium and the highest uplift point coincides with the infiltration basin. Evidently, the mechanics of uplift in the lower Boulder Valley is related to the elastic properties of aquifer system due to injection and/or irrigation. This uplifting phenomenon has been observed by others in recent years. For example, Bell et al. (2008) concluded that uplift has occurred in much of the Las Vegas Valley, due to rising water levels in areas that had undergone subsidence previously. Similarly, Gourmelen et al. (2007) also observed that uplifting has occurred in Crescent Valley, Nevada due to mine water infiltration.

In general, the InSAR image confirms both field water level monitoring results and the projections of regional groundwater flow models.

Conclusions

Remote sensing techniques provide indirect observations of parameters of interest such as rainfall depth, snow cover, ET, and groundwater level changes. The advance of these techniques has reached the stage of commercialization and routine application. However, the quality and applicability of the observations are limited to the spatial, spectral, and temporal resolution of available images. Applicability may also be limited, due to site specific conditions, by the applicability of the algorithms used to interpret the remote sensing data. It should be stressed that, for the foreseeable future, remote sensing data can supplement, but not replace, ground-based methods of assessment. A rational approach to water resource investigation includes the use of common sense and as many independent sources of information as possible, including historical information, ground-based investigation, and remote sensing.

Acknowledgments The authors thank Davids Engineering and SEABAL North America for their contributions of SEABAL analytical results, Mr. Andrew Dean for the stream flow analysis for the Homestake mine study, and Professor John Bell from University of Nevada, Reno and Professor Kurt Katzenstein from the South Dakota School of Mines and Technology for the InSAR study. Special thanks to Tethyan Copper Company Pty Ltd (TCC), Cerro Casale JV, Antofagasta plc, and Barrick Gold Corporation for permission to publish technical material related to the Reko Diq and Cerro Casale projects.

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