THE POTENTIAL TO INVESTIGATE THE INTERACTION OF SURFACE WATER AND GROUNDWATER IN NEW ZEALAND USING REMOTE SENSING TECHNIQUE

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ABSTRACT

Surface water bodies are normally linked to groundwater. Rivers, lakes, wetlands and estuaries may act as recharge sources for an aquifer or vice versa (Braaten and Gates, 2001). Understanding the basic principles of groundwater/surface water (GW–SW) interactions is essential to effectively manage water resources. The necessity for sustainable use of groundwater and surface water in New Zealand will continue to increase in the future due to global warming, contamination of water resources and increasing demand for water. A good understanding of groundwater-surface water interactions is important for decision makers and water resources managers.

Remote sensing is a powerful tool to identify the spatial distribution of groundwater discharge and improve our knowledge of the interactions between groundwater and surface water. Discharged groundwater in the surface water features have some signatures such as thermal or chemical which is different from that of surface water and can be sensed remotely. Assessing the thermal infrared imagery from satellite or airborne is an effective method to quickly assess large areas and obtain information about specific locations of the interactions and regional groundwater flow pattern at larger spatial scales. This technique can help in designing groundwater monitoring networks, sampling sites in groundwater and surface water, establishing a baseline for the future of ground level monitoring systems and also for estimating the environmental effects of contaminant migration. The observations during analysis of the thermal images can be considered as a starting point for more rigorous spatial analysis and fieldwork. The exact locations, boundaries and magnitude of the interaction can be verified using field measurements. Remotely sensed data are most accurate when they are combined with numerical modeling, geographic information systems, and field base information (Becker, 2006). This paper reviews the state of knowledge regarding the remote sensing of groundwater/surface water interactions worldwide and describes the existing potential to apply this technique to New Zealand's water resources. This method can be applied on springs, rivers, lakes, wetlands and estuaries to define the spatial pattern of groundwater/surface water interactions and establish a base line for more detail investigation. Delineating the area of interaction before conducting the experimental tests can save time and reduce cost during the research.

KEYWORDS

Remote sensing, Groundwater, Surface water, Interaction

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1 INTRODUCTION

In New Zealand water was not a major concern in the past due to relatively high and consistent quantity of rainfall (NIWA., 2001) and river flow during the year. Water demand has risen as a result of intense agricultural activities (Woods and Howard-Williams, 2004) and irrigated lands have been increased by 55% in every decade since 1960s (Lincoln Environmental., 2000). In addition to stresses on water resources, deterioration of water quality by polluted runoff of agricultural lands, fertilizer and dairy factories has caused nearly 50% of New Zealand's lake (Verburg et al., 2010) and about 60% of lowland rivers (Unwin et al., 2010) to be classified as polluted. This trend will continue in the future unless water planners pay significant attention to the surface and groundwater resources issues. Integrated management of surface and subsurface water supply is crucial for the sustainability of water resources and reducing contamination level.

Groundwater/surface water (GW/SW) interaction assessment has recently received further consideration in the world due to its importance for the ecological health of streams and rivers (Winter, 2001, Woessner, 2000, Findlay, 1995) and groundwater ecosystems (Hancock et al., 2005, Humphreys, 2009). There are several approaches that can be undertaken to investigate this phenomenon according to the scale of study. During the last decade, heat has become a widespread tracer in GW/SW connectivity studies (Schuetz and Weiler, 2011). While temperatures of surface water change diurnally and seasonally, groundwater temperature is relatively constant (Kalbus et al., 2006) and is nearly the same as the average annual air temperature (Deitchman and Loheide, 2009). Therefore, a substantial temperature difference exists between surface and subsurface water in summer and winter and this contrast leads to the study of thermal remote sensing of groundwater/surface water interaction (Tcherepanov et al., 2005).

Locating the area and extent of groundwater discharge in the body of surface water is complex and challenging. Among various methods that can handle this issue, remote sensing can be a useful technique for quantifying the spatial distribution of groundwater discharge to rivers, lakes, estuaries and oceans (Becker, 2006). Assessing the thermal infrared imagery from satellites is an effective method to quickly assess large areas and acquire information about specific locations of the interactions and regional groundwater flow pattern at larger spatial scales, although quantifying the amount of exchange is still the subject of active research. The main aim of this paper is to summarize the state of knowledge regarding the remote sensing of groundwater/surface water interactions internationally and the enormous potential to apply this technique in New Zealand water resources.

1.1 THE IMPORTANCE OF SURFACE WATER/GROUNDWATER INTERACTIONS

In many catchments, surface and subsurface water are hydraulically linked and the quality of groundwater and the direction and intensity of exchanges with lakes and wetlands noticeably affect the contribution of dissolved chemicals in these entities (Winter et al., 1998) and the quality of life for fish or drinking water for humans (Gardner, 1999). Inflow of groundwater into a river can be vital in sustaining flows during dry seasons. This is indispensable in providing the needs of surface water users and aquatic ecosystems. The quantity of baseflow to the river can significantly change if pumping occurs from an aquifer adjacent to a river. However, if the groundwater is contaminated, enhanced groundwater discharge can have a damaging impact on river water quality (Brodie et al., 2007).

In recent years submarine groundwater discharge (SGD), which is a widespread phenomenon in many coastal regions of the world (Shaban et al., 2005) has received growing attention owing to its potential in the transport of chemicals to the sea (Gallardo and Marui, 2006). It has been approximated that groundwater contributes 10%, and possibly much more, of the total fresh water flux to the coastal environment (Zektser and Loaiciga, 1993, Moore, 1996). It is clear that quantity and quality of surface water and groundwater are influenced by each other, yet little is known about the mechanism and process by which these two resources interact (Gardner, 1999). Delineation of the spatial and temporal pattern of interaction and its specification is still an immense challenge for hydrologists.

2 REMOTE SENSING TECHNIQUE IN THE STUDY OF SURFACE WATER- GROUNDWATER INTERACTION

Contrast between the temperature of surface water and groundwater leads to the study of thermal remote sensing of groundwater/surface water interaction. Surface water is warmer than groundwater during summer and colder during winter. As a result, influx of cooler groundwater into warmer surface water during summer results in plumes of water which have lower temperatures at the surface in the areas of groundwater discharge. During cold periods, the inflow of groundwater can cause warmer patterns in the discharge zones (Tcherepanov et al., 2005).

Heat energy and dissolved chemicals are the signatures for the discharged water in the surface. All of these indicators of groundwater flow can be monitored remotely (Becker, 2006). Surface water gains from groundwater via (1) springs; (2) rivers; (3) lakes and wetlands and (4) estuaries. In the following sections of this paper, we discuss the application of remote sensing in each surface water feature separately.

2.1 SPRINGS

Inflow of groundwater to the surface via springs has been a main source of water in New Zealand for a long time (Rosen and White, 2001) and this has various uses. For instance, Rotorua, Pukekohe and Whangarei water supplies have been provided by springs (Thorpe, 1992). Furthermore, some streams get their baseflow from springs as in the case of the spring-fed Avon and Heathcote Rivers in Christchurch (White, 2009). Further use of spring water is as bottled water and tourist attractions (e.g. Paradise Valley springs, Rainbow Springs near Rotorua). In addition to cold water springs, hot springs are another feature of water in New Zealand, which is a major tourist attraction.

Generally, remote sensing can monitor the location of a spring, which is discharged to the surface. As Moore (1982) suggested, thermal infrared investigation is the best method for identifying springs remotely. However, When the difference in temperatures of surface and groundwater is maximam, the results are most accurate. Another sign which displays the location of a spring is chemical changes of the land surface that has been used to identify geothermal systems based on the mineral deposition as a result of hydrothermal alteration (Crowley and Hook, 1996, Littlefield and Calvin, 2009, Calvin et al., 2005). Changes in vegetation species can also be sensed remotely as a result of mineral discharge to the land surface, surface water, or the root zone. The difficulty in all thermal, vegetation and chemical indicators is that the sensor must have a high resolution (meters) to accurately show the location of a spring (Becker, 2006).

As springs are a very precious water supply in New Zealand, remote sensing can be a useful tool to enhance our ability to specify spring location as well as finding spring-fed rivers and mapping hydrothermal alteration and identify hidden geothermal systems. Identifying hydrothermal alteration can be difficult in the field, but related minerals are spectrally discrete and can be recognized through remote sensing techniques (Littlefield and Calvin, 2009).

2.2 RIVERS

River/groundwater interactions are very common in New Zealand water resources. For example in the study by Dravid and Brown (1997) in Hawkes Bay, the interaction between Ngaruroro River with the underlying aquifer system was investigated. Likewise, a dynamic interaction between rivers and the aquifer system in the upper part of Motueka river catchment, Nelson was reported by Hong et al. (2010). The exchanges between river water and groundwater are crucial to maintaining good habitat for fish and other aquatic creatures in streams by decreasing stream temperature as well as reducing the daily stream temperature variations in the summer seasons (Loheide and Gorelick, 2006). By contrast, increased groundwater withdrawals in a catchment can considerably reduce the baseflow to rivers which can cause stream depletion. Thus, baseflow is essential to preserve the streams from drying up in the summer. In a recent study in New Zealand by Wilson and Davidson (2011), they predicted that Wairau River flow will be reduced as a result of pumping from the Wairau Aquifer.

In applying remote sensing to the study of river/groundwater interactions, Salama et al. (1994) used this technique to understand the connection between rivers and groundwater in southern Australia to control salinity in rivers resulting from saline groundwater outflow. As these interactions are controlled by basin geomorphology, geology and structural pattern of the region, aerial photographs (AP) and Landsat Thematic Mapper (TM) data were used to establish a relationship between these units and the groundwater in the Salt River system. Permeable areas around the circular granitic plutons and also highly permeable areas of the sand plains were the major sources of recharge in the region while discharge zone was found to be mostly along the drainage lines, on the edge of the circular sand plains, in depressions and in lakes.

Airborne Thermal Infrared Multispectral Scanner (TIMS) was used by Banks et al. (1996) to locate concentrated and diffused groundwater discharge in the creeks and ponds and also in the shoreline in Aberdeen Proving Ground, Maryland. Airborne thermal infrared imaging proved to be a successful technique to quickly consider large areas and acquire information about the location of groundwater discharge. Forward looking infrared (FLIR) images and in situ temperature data were used by Loheide and Gorelick (2006) to quantify the spatial pattern of groundwater discharge in a 1.7 km reach of Cottonwood Creek in Plumas National Forest, CA. Estimation of temperature using the remote sensing technique correlated well with in situ data. Streamflow measurements proved that groundwater discharge (baseflow) rates estimated using FLIR thermography were accurate within 10% in this application.

In general, quantifying stream flow from space is very challenging and according to Becker (2006), the best achievement in the remote sensing of groundwater-stream interactions is detecting the spatial distribution of groundwater inflow in a river. Recently, ground-based thermographic systems have been used by Schuetz and Weiler (2011) to directly localize and quantify groundwater discharge into small streams. Consequently, effective understanding of the interaction between the river and groundwater will contribute to improve management of our water resources and remote sensing is a beneficial method in this respect.

2.3 LAKES AND WETLANDS

Lakes and wetlands are invaluable water resources in New Zealand. Attention to New Zealand's wetlands has increased recently due to their significance as habitants for endangered species and also their roles in flood control and water storage (Wellington RegionalCouncil, 2005). Groundwater discharge to lakes and wetlands is vital in sustaining water during dry seasons through buffering water level changes (Tweed et al., 2009) in order to maintain the ecological character of these water resources. Nevertheless, contaminated groundwater movement is a potential pathway to transfer pollution to the lakes and wetlands. An example of this phenomenon has been reported by Morgenstern (2008) in Lake Taupo where the nitrogen transferred from farms to the lake was mostly via seepage of groundwater-fed streams through the lake bed.

Although different hydrological techniques such as installing wells and piezometers have been used previously in the study of lakes/groundwater interactions, application of these methods in large scale would be very costly and time consuming and even impossible in some areas due to difficulty of site access (Tcherepanov et al., 2005). However, remote sensing technology can be used as a cost effective method for locating regions of groundwater discharge in the body of lakes and wetlands at regional scale.

Due to the difficulty in estimating the water balance parameters such as all surface water inputs and outputs, as well as direct precipitation and evaporation in standing bodies of water, determining the amount of discharge to lakes is very difficult (Winter et al., 1989, Winter et al., 1998). Although, space-borne and airborne thermal imaging sensors have shown a good potential to reveal the areas of groundwater-surface water interactions, quantifying the amount of groundwater inflow into lakes has not yet been undertaken directly by remote sensing.

In an early attempt to apply thermal infrared remote sensing methods, Rundquist et al. (1985) detected groundwater flow through lakes in the Nebraska Sandhills using Thermal Infrared Multispectral Scanner (TIMS). The same airborne techniques were used to delineate groundwater inflow to the Great Salt Lake, Utah by Baskin (1990). In another case, radar images revealed 3 zones of groundwater discharge in wetlands of northwestern Yucatan Peninsula, Mexico (Pope et al., 2001). In one more investigation in the Nebraska Sandhills, Landsat thermal infrared imagery and in situ temperature data were used to study the groundwater inflow to the lakes in large scale, by Tcherepanov et al. (2005). In situ temperature measurements during summer 2002 showed cool zones of water. Similarly, analysis of 20 Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM $^{+}$) scenes from 1989 to 2002 identified two main seasonal patterns in the lake surface. GIS based analysis of remote sensing data along with in situ measurements, showed some areas in lakes with cold temperatures which were identified as potential areas of groundwater outflow.

Geospatial analysis (remote sensing and geographical information systems) in combination with groundwater modeling can reveal the spatial distribution and intensity of groundwater/surface water exchanges in the large scale. A study was done by Leblanc et al. (2007) in a Quaternary unconfined aquifer in the central part of the Lake Chad Basin in north-central Africa using geospatial, hydrological and numerical analysis to identify the spatial distribution and amount of recharge and discharge in the regional scale. Different sensors such as thermal (Meteosat, AVHRR), elevation (SRTM), optical (MODIS, Landsat TM, AVHRR) and vegetation index (MODIS) with a variety of spatial, temporal and spectral resolutions were used. The spatial distribution of recharge and discharge was revealed using the combination of hydrological and satellite data. The annual rates of discharge/recharge were calculated by importing the provided map into the finite difference groundwater model MODFLOW96.

As Becker (2006) suggested that the most accurate result in remote sensing can be achieved when they are combined with geographic information systems (GIS), numerical modelling and in situ investigation.

2.4 ESTUARIES

Attention to the study of submarine groundwater discharge (SGD) for the coastal environment has enhanced since it was recognized in the South Bay, New York that about 60% of the influx to the ocean was via SGD (Capone and Bautista, 1985). Before that rivers were considered as the only way to transport contamination to the oceans. Taniguchi et al. (2002) described SGD as all direct discharge of subsurface waters through the land-ocean boundary. SGD mostly happens in areas where an aquifer is connected to the sea and sea level is lower than the head of groundwater (Kim et al., 2011).

Although, the SGD has gained prominence in the coastal regions of the world in the last decade, the literature in New Zealand is very rare and mostly dedicated to sea water intrusion risk. Occurrence of this phenomenon in New Zealand has been reported by Ridgway and Stanton (1969) in Hawkes Bay and by Williams (1977) in Golden Bay. Groundwater discharge to the coastal zones, together with evapotranspiration and surface runoff, are the three main discharge paths of water from the Australian continent (Varma et al., 2010).

Determination the extent and quantity of substantial inputs to seas and oceans is a fundamental issue in the management of coastal areas particularly in New Zealand with current levels of pollution in the lakes and rivers which can infiltrate to groundwater and transfer to the seashores. Although seepage meters and geochemical tracers can estimate the amount of flow to these areas, identifying the locations of discharged groundwater in large scale is difficult due to the point measurements. However, remote sensing technology is a powerful tool to reveal groundwater discharge locations in coastal water bodies as well. Following that, detailed in situ investigation can be undertaken.

Among all applications of remote sensing to the study of surface water/groundwater resources, this technique has been mostly used in the estuaries to disclose the spatial distribution of submarine groundwater discharge as this phenomenon has considerable potential to carry nutrients and pollutants to the seas. Davies (1973) and Brereton and Downing (1975) located submarine springs in the foreshore using airborne thermal infrared line scanners. Roxburgh (1985) identified the hydraulic connectivity between the fresh groundwater from the Plymouth limestone in the form of submarine spring to the marine waters of Plymouth Sound, UK, using an aircraft-mounted thermal infrared line scanner.

Generally, residential development increases the pollution levels in the coastal regions. To define the contaminated groundwater flow paths into the Nauset Marsh estuary, Massachusetts, Portnoy et al. (1998) used thermal infrared imagery in combination with salinity surveys and hydraulic studies. Results revealed that most of the groundwater inflow occurred in the sandy sediment during low tide periods. In another attempt, results of thermal infrared surveys in the approximately 50 miles of the Great Bay Estuary in coastal New Hampshire have been combined with the piezometric analysis and water quality samples by Roseen (2001); the results show significant agreement between the methods. As the combination of remote sensing and quality data improved the understanding of SGD in previous studies, Shaban et al. (2005) used airborne thermal infrared survey with radiometers and quality investigation along the Lebanese shoreline. Twenty seven major SGDs were recognized. Chemical analysis confirmed the presence of some water with lower salinity and temperature compared to the nearby seawater. Moreover, geologic studies using Landsat 7ETM$^+$ images identified karstic galleries, faults, and tilted rock strata as the main structural controls in the transport of groundwater to the coastal region.

The knowledge about SGDs has also been enhanced in the synergic study of numerical models and remote sensing techniques. A combined approach including analysis of airborne thermal infrared imaging, direct discharge measurements in streams and shoreline springs, and numerical simulation of groundwater flow have been used for two estuaries in Prince Edward Island in Canada by Danielescu et al. (2009). The thermal infrared survey indicated that groundwater discharge occurred via springs in both sites and the spatial distribution was in good agreement with field measurements and the contribution of stream and groundwater in two estuaries has been determined. In another study, SGD has been investigated by Varma et al. (2010) in Geographe Bay in the south west of Western Australia. ASTER thermal-infrared images in combination with hydrological and modelling techniques have been used to improve the understanding of this phenomenon in the region. While ASTER images identified two plumes of water in the southwest of the study area as well as along the coastline, hydraulic analysis and modelling simulations estimated that nearly 80 million m^3/year of groundwater has been discharged to the Geographe Bay.

Kim et al. (2011) used space-borne synthetic aperture radar (SAR) for the first time to delineate SGD in tidal flats of mid-western coast of the Korean peninsula, Korea. Water puddles have been detected in a belt shape along the upper parts of the tidal flat which were the possible areas of groundwater discharge. They demonstrated that SAR images can also be a powerful tool in the study of submarine groundwater discharge.

Different satellite and airborne techniques have been applied to the study of submarine groundwater discharge. This validates the significance and applicability of remote sensing techniques in this field. The outcome will give an overview to decision makers about the location at which this phenomenon is occurring, allowing them to choose according to the importance of those sites about the further investigations. This technique can help in designing groundwater monitoring networks, sampling sites in groundwater and surface water and establishing a baseline for future ground base monitoring systems.

3 CONCLUSIONS

New Zealand has precious water resources, which contribute effectively to the agricultural base economy of this country. The value of freshwater has not been fully appreciated in New Zealand due to its abundance compared to other parts of the world. However, recently, the level of pollution in New Zealand’s lakes and streams has been increased over the last few decades due to agricultural and industrial developments (Verburg et al., 2010, Unwin et al., 2010). As groundwater and surface water are hydraulically connected, surface water bodies can gain water and pollutants from groundwater systems or vice versa. Accordingly, integrated management of surface and subsurface resources is necessary in view of growing demand with limited resources in New Zealand. As remote sensing has proved to be a valuable tool for revealing the spatial pattern of groundwater/surface water interactions internationally, it can be applied to New Zealand’s river, lakes, wetlands and estuaries to identify the extent of discharged groundwater which can carry pollutants in some cases. Depending on the significance of those sites, further investigation can be organized for detailed studies of the groundwater and surface water connectivity afterwards. The observations during analysis of the thermal images can be considered as a base line for more rigorous spatial analysis and fieldwork.

In the study of groundwater/surface water interactions, several methods have been used, which can deliver small scale results. Unlike other methods, remote sensing can be a useful technique for determining the location of direct discharge from aquifers to the different surface water features as well as revealing regional groundwater patterns in large scale. This method can quickly evaluate large regions and improve our knowledge about the spatial distribution of groundwater discharge through detecting the changes in temperature, chemistry, and salinity. However, quantifying the amount of exchanges in the remote sensing of groundwater/surface water interactions is still challenging. As Becker (2006) suggested, the most accurate result in remote sensing is attained where this is combined with geographic information systems (GIS), numerical modelling and field study.

Different satellite and airborne methods have been used in the study of groundwater/surface water interactions. While, airborne thermal imaging has a resolution of meters, that of satellite imaging is tens of meters. The choice of the ideal alternative depends on the spatial and temporal extent of investigation as well as required precision. Satellite data are particularly suitable for large geographic areas. Using satellite remote sensing data with more comprehensive maps or aerial photography enables a better understanding than either source alone (Ozesmi and Bauer, 2002). It is recommended that thermal imaging of groundwater be implemented in warm or cold seasons and maximum or minimum diurnal temperatures, respectively, to obtain accurate results (Deitchman and Loheide, 2009).

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