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Community-based groundwater and ecosystem restoration in semi-arid north Rajasthan (3): Evidence from remote sensing

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ABSTRACT

Community-based measures recharging groundwater in semi-arid India has historically underpinned rural socio-ecological resilience, though are declining through technological, policy and other changes. Nevertheless, exemplars of community action are achieving catchment regeneration, including in Alwar District (Rajasthan) since the mid-1980s. This study analysed satellite remote sensing (RS) data to detect trends in groundwater and linked ecosystem services. Data from Landsat satellite missions offered a long time series and free access, though data gaps in the LandSat archive prior to 1997 limited time series analysis. ISODATA (Iterative Self Organising Data Analysis Technique) was used to analyse land cover trends, detecting increasing vegetation cover but not river rejuvenation due to limited spatial and spectral resolution. Analyses of NDVI (Normalised Difference Vegetation Index) and MSI (Moisture Stress Index) were used to assess change in vegetation cover, vigour and moisture stress over time. Analytical outputs were equivocal, although inter-annual fluctuations were observed to follow antecedent rainfall as vegetation responded to rising soil moisture and groundwater. Despite these equivocal conclusions, the research strongly suggests that analysis of RS data with improved resolution can provide surrogate indicators of change in groundwater and associated ecosystem services, supporting formulation of flexible policies incorporating local action to regenerate socio-ecological systems.

1. Introduction

Water security is and will remain a pervasive challenge in the face of a rising global population and a changing climate, particularly across the developing world. Over 1.7 billion people globally live in river basins where overuse of water contributes to depletion at a rate that exceeds natural recharge; were this trend to continue, two-thirds of the global population will be living in water-stressed conditions by 2025 (USAID, 2015; United Nations, 2015a; Chenworth, 2008). Water is consequently an underpinning resource for a number of the UN Sustainable Development Goals (United Nations, 2015b), both in terms of indirect access to clean, safe water and in its roles in sanitation, health, food and energy production and other human needs. Groundwater has played a significant role in increasing India's agricultural output and progress with water security, supporting 62% of India's total irrigated agricultural area and over 80% of rural and urban water supplies in 2009–2010 (Central Water Commission, 2013; Kidwell, 2015). Overexploitation of groundwater, particularly for irrigation, has resulted in substantial, widespread depletion of water tables and also increased the vulnerability of groundwater to pollution and increasing salinity and other forms of contamination (Postel, 2015). However, the 2030 Water Resources Group (2009) predicts that the national supply will fall 50% below demand by 2030, deepening what is already recognised as a water security crisis. Aside from its direct uses, water is a vector of a wide range of ecosystem services upon which ecosystem and human wellbeing depend. Understanding groundwater trends is crucial if more sustainable management is to be achieved, particularly in arid and semi-arid areas where water is often a principal limiting factor to development.

In the face of declining groundwater trends across India, there have been a number of localised successes in regeneration of ecosystems and closely linked socio-economic fortunes. One such regional example has been achieved by community-based activities regenerating groundwater and the wider socio-ecological system in a number of adjacent catchments in Alwar District, Rajasthan, north India (Everard, 2015, 2016). Assessing groundwater trends and the efficacy of local measures to regenerate it over wide geographical areas is challenging. For this reason, cheaper and broader-scale methods must be found to inform more sustainable approaches to the management of water and ecosystems, with detection of groundwater by direct or surrogate means a proxy for a broader set of linked ecosystem services vital for human

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development and ecosystem resilience.

The potential of remote sensing (RS) for groundwater monitoring has been explored extensively over the past thirty or so years (Heilman and Moore, 1982; Meijerink, 1996; Edet et al., 1998; Rosenberry et al., 2000; Jin et al., 2007; Lv et al., 2013; Chinnasamy et al., 2015) and reviewed by Becker (2006) and Pérez Hoyos et al. (2016). Becker's (2006) observation regarding the key constraint on RS application in groundwater studies remains true today: current space and airborne sensors have little capacity to penetrate the ground surface. Consequently, RS approaches to groundwater monitoring have focussed principally on the use of multispectral observations of the earth surface, relying on proxy indicators of groundwater such as vegetation or thermal fluxes. As a more recent alternative approach, the launch of the Gravity Recovery And Climate Experiment (GRACE) satellite mission in 2002 enables detection of changes in the gravitational field of the Earth, which is affected by the presence of large volumes of water.

Chinnasamy et al. (2015) used GRACE data to investigate groundwater storage and recharge within different agroclimatic zones in Rajasthan, India. Their methodology proved useful for detecting large-scale trends, but found trends were highly dependent on antecedent moisture conditions. Jin et al. (2007) used Normalised Difference Vegetation Index (NDVI) data at 250 m spatial resolution from the Modis (Moderate Resolution Imaging Spectroradiometer) satellite mission correlated with groundwater depth interpolated from a series of observation wells to assess the relationship between vegetation growth and groundwater in the arid Yinchuan Plain in China. Their findings suggest a relationship exists in areas with relatively shallow groundwater (NDVI values of 0.4 and above), suggesting that green vegetation characterised areas where depth to groundwater was less than 6.2 m. The highest NDVI values were associated with a groundwater depth of 3.5 m. In the arid Ejina area, Jin et al. (2007) found that NDVI peaked at groundwater depths of 3.4 m. More recently, Lv et al. (2013), using LandSat TM data (30 m resolution), found that higher NDVI values in the semi-arid Hailutu River catchment were highly dependent on groundwater availability when groundwater depth was less than 10 m. These findings suggest a stronger relationship between vegetation growth (measured using the NDVI) and a shallower water table in arid areas, than in semi-arid areas. All these studies highlighted concerns about the influence of local factors and contaminating variables, such as the local species composition influencing NDVI values, or climate (e.g. antecedent moisture conditions), or local soil characteristics and topography.

Becker (2006) notes that surface expressions of groundwater are usually identifiable through vegetation, either as stress in waterlogged soils or as vigour in water-resistant species. In arid areas in particular, where water is the main limiting factor controlling plant growth such as our study area, vegetation can provide important clues regarding the occurrence of groundwater. However, Becker (2006) also notes that it is often difficult to separate such expressions of groundwater from seasonal or event-driven surface water. The review by Pérez Hoyos et al. (2016) confirms a strong coupling between rainfall, water table depth, vegetation and soil. Tóth (1963) conceptual model of groundwater flow has implications: if the adopted RS approach is reliant on surface expressions of groundwater or groundwater proxies, characteristic of systems with relative shallow groundwater flow, then the shallower the groundwater flow, the smaller the surface expressions of the flow are likely to be, and the higher the required resolution of the RS imagery becomes.

Resolution of satellite imagery can be considered in three realms: spatial resolution; spectral resolution; and temporal resolution (see Box 1). There is an inevitable tension between the resolution of the sensors and the scale of the phenomena being investigated. For example, GRACE, with a ground resolution of approximately 300 km is of little use in local or sub-regional projects, while Landsat with a spatial resolution of 30 m is appropriate for vegetation studies, however, the 60 m resolution of the thermal bands is probably too coarse to resolve local surface expressions of groundwater such as springs. The use of any higher resolution imagery sources (such as QuickBird or IKONOS) is generally constrained by cost. The implication of the above is that, in a cost-constrained context with a local focus, the use of vegetation fluxes as a proxy indicator of groundwater fluxes is a defensible, possibly inevitable, choice.

This study interpreted satellite remote sensing imagery as evidence to test trends in groundwater and ecosystem regeneration in Alwar District, Rajasthan, reported by Everard (2015). We chose to use a time series of Landsat5 TM and Landsat8 OLI data because of the catchment scale of the project, the available record length of data, its suitability for vegetation studies (due to its spectral resolution) and the fact that access to the data is free.

2. The case study area

Rajasthan is India's largest state, occupying 10% of India's land

Box 1–Spatial, spectral and temporal resolution of satellite imagery.

Spatial resolution determines the detail discernible, generally defined by the smallest feature that can be detected. Remotely sensed images comprise a matrix of pixels (the smallest units of an image, normally square, representing a specific area of the image). Spatial resolution is related to pixel density on the sensor as well as the distance between the target being imaged and the sensor platform (satellite altitude). The spatial resolution of passive sensors, as used for example on the Landsat missions that provided images used in this study, depends primarily on their Instantaneous Field of View (IFoV: the angular cone of visibility of the sensor). Each recording cell on the sensor detects average brightness across all sensed features within the cell, so the relative brightness of even small features can dominate what is detected within a particular cell. Satellite images are divided into three classifications of spatial resolution: low resolution (30–1000 m^2 for each pixel); medium resolution (4–30 m^2 per pixels); and high resolution images (0.6–4 m^2 pixel size) (NRCAN, 2012; Satellite Imaging Corporation, 2015).

Spectral resolution describes the ability of a sensor to define fine wavelength intervals. Broad classes of sensed terrains, such as water and vegetation, can usually be separated using very broad wavelength ranges (such as the visible and Near-IR) though discerning more similar Earth surface types requires comparison of much finer wavelengths. Most satellite remote sensing systems are multispectral, recording electromagnetic energy over several separate wavelength bands at different spectral resolutions.

Temporal resolution relates to the collection of imagery of the same area of Earth's surface at different periods of time. The temporal resolution of a sensor depends on a variety of factors, including the satellite/sensor capability, swath overlap (a swath is the width of images sensed, wide swathes allow more rapid revisit and greater overlap whereas narrow swathes typically allow for higher spatial resolution but revisit time is less frequent) and latitude. Temporal resolution is an important consideration when persistent cloud cover obscures the view of the Earth's surface, potentially obscuring short-lived phenomena (floods, oil slicks, etc.) (NRCAN, 2014).