Integrated Land Deformation and Groundwater Monitoring Using Synthetic Aperture Radar (SAR) Interferometry Processing

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Summary

Interferometric Synthetic Aperture Radar (InSAR), a remote sensing technique for measuring surface deformation, is associated with groundwater level and storage properties estimation in Bali Island, Indonesia. An integrated monitoring of the land deformation and groundwater is crucial for the sustainability of water supplies, especially in the small island developing areas such as Bali. The L-band ALOS PALSAR along with Sentinel 1-A SAR data, acquired between June 2007 and May 2016, were utilised for the analysis. The result showed consistency with the existing well data. It demonstrates the advantages of InSAR process for characterization of aquifer storage properties and groundwater levels.

KEYWORDS: Synthetic Aperture Radar (SAR), Interferometry Processing, Land Deformation, Groundwater Level, Aquifer Storage Properties

1. Introduction

Freshwater resources are becoming increasingly scarce globally and more so in small islands. Many Small Island Developing Sites (SIDS) face constraints to effective management of freshwater resources that are common in developing countries [UNEP, 2015]. In this case, efficient management of aquifers typically involves measurements of hydraulic head, the liquid pressure at a given location expressed as water level above a geodetic datum [Fetter, 2001]. Moreover, severe drought conditions lead to increasing reliance on water resources from the deeper confined aquifers [Chen, et al., 2016]. Nevertheless, the accuracy of groundwater flow simulations in confined aquifers limited by low temporal and a spatial resolution of head measurements [Harbaugh, 2005]. As a result, innovative techniques to enhance the storage properties of confined aquifers is a necessity.

Take into account of the interdependent correlation between the changes in the hydraulic head and land deformation, an integrated estimation based on the land subsidence could accomplish the need of the groundwater level data [Ljungdahi, 2015]. Lu and Danskin [2001] demonstrated that InSAR could be used to define the structure and essential hydrogeologic features of a groundwater basin. Further, Chaussard et al. [2014] demonstrated the benefits of InSAR measurements for basin-wide characterization of aquifer storage properties and groundwater levels using the Small Baseline Subset (SBAS) method [Berardino et al., 2002].

In work presented in this paper, the L-band of ALOS PALSAR scenes compiled with the C-band Sentinel 1A are processed to be able to evaluate the hydraulic head estimated from InSAR with the well measurement. The purpose of the analysis is to study the availability of both SAR L-band and C-band datasets to infer head over a broader region including vegetated areas. Further, the possibility of

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using the InSAR data is explored in order to fill spatial gaps in the existing hydraulic head data set on the Bali Island, one of the small developing islands in Indonesia.

2. Study Area

The study area is located in the Bali Island, Indonesia. Bali Island geographic is situated in the Indonesia Archipelagos in line with other island such as Java, Lombok and Flores. The island of Bali extend from 8^0 03' 140" to 8^0 50' 48" South latitude and 114^0 25' 53" to 115^0 20' 2" East longitude. Include within Bali Province are several smaller islands which are Nusa Penida, Nusa Lembongan, Nusa Ceningan, Sarangan and Menjangan. The total Bali Province covers an area of 5,632 km^2 equal to 0.29% of total Indonesian archipelago [BKPM-JICA., 2006].

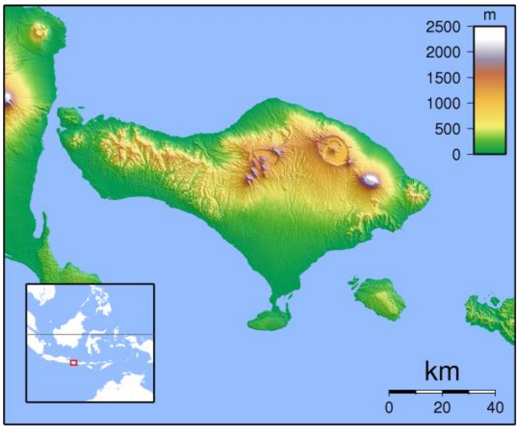

Figure 1 Location of Bali Island, Indonesia

3. Deformation to Head Relationship

Here we review the linear relationship between land deformation and groundwater levels in confined aquifers, which we refer as the deformation-to-head relationship [e.g., Galloway and Burbey, 2011]. A change in hydraulic head Dh due to pumping or recharge results in changes in pore pressure Δp and effective stress $\Delta\sigma^1$ as:

$$\Delta\sigma^1 = \Delta p = -\rho g\Delta h \qquad (1)$$

where g is gravitational acceleration and q is the density of water.

The integrated compaction over the entire depth of the aquifer system is what we measure as land subsidence at the surface, which can differ significantly based on aquifer material properties as well as the types of deformation. The total elastic deformation Δb_e can be related with the changes in hydraulic head Δh as:

$$S_{ke} = \frac{\Delta b_e}{\Delta h} \qquad (2)$$

where Ske is the elastic skeletal storage coefficient.

When the head drops below the preconsolidation head, inelastic compaction occurs in clay units, which causes irreversible loss of water storage due to permanent drainage and collapse of structure in the clay layers. The ratio of the total inelastic deformation Dbv and the change in hydraulic head Δb_v can be expressed as:

$$S_{kv} = \frac{\Delta b_v}{\Delta h} \qquad (2)$$

where S_{kv} is the inelastic skeletal storage coefficient.

We can further define the skeletal specific storage coefficients Ssk5Sk=b, where b is the thickness of the producing aquifer unit.

Table 1. A List of Confined Aquifer Wells in South Bali Area

Sample Number	Well Location	Latitude	Longitude	Elevation
1	PH1	115^0 17' 12.67"	08^0 38' 27.67"	11 m
2	VL1	115^0 17' 05 00"	08^0 38' 11.27"	28 m
3	VL2	115^0 16' 01.83"	08^0 39' 02.51"	16 m
4	VL3	115^0 15' 39.56"	08^0 39' 42.31"	14 m
5	HL1	115^0 14' 53.05"	08^0 42' 37.50"	14 m
6	VL4	115^0 15' 34.77"	08^0 42' 18.60"	24 m
7	HL2	115^0 15' 10.45"	08^0 42' 05.09"	25 m
8	HL3	115^0 15' 23.62"	08^0 38' 56.68"	41 m
9	HL4	115^0 15' 03.40"	08^0 40' 00.14"	33 m
10	HL5	115^0 15' 21.92"	08^0 40' 57.29"	27 m
11	HL6	115^0 15' 48.13"	08^0 41' 07.24"	20 m
12	PC1	115^0 12' 47.79"	08^0 43' 12.28"	10 m
13	HL7	115^0 11' 38.05"	08^0 43' 21.62"	20 m
14	SPA1	115^0 13' 08.94"	08^0 46' 04.14"	20 m
15	HL8	115^0 10' 42.52"	08^0 45' 57.22"	25 m
16	VL5	115^0 10' 06.06"	08^0 47' 04.79"	25 m
17	CE1	115^0 10' 10.73"	08^0 45' 37.40"	25 m
18	RSU1	115^0 10' 44.83"	08^0 43' 57.05"	18 m
19	PNT1	115^0 10' 04.99"	08^0 42' 54.33"	19 m
20	HL9	115^0 09' 56.15"	08^0 41' 58.84"	25 m
21	PNT2	115^0 09' 36.51"	08^0 41' 42.01"	18 m
22	VL6	115^0 13' 08.94"	08^0 46' 04.14"	20 m
23	VL7	115^0 11' 42.50"	08^0 48' 09.37"	69 m
24	PNT3	115^0 05' 31.24"	08^0 48' 58.43"	77 m
25	PP1	115^0 07' 89.92"	08^0 47' 54.98"	60 m
26	HL10	115^0 08' 52.34"	08^0 40' 36.88"	18 m
27	MM1	115^0 11' 06.30"	08^0 46' 59.12"	34 m
28	WR1	115^0 13' 14.02"	08^0 47' 26.36"	14 m
29	VL8	115^0 13' 29.49"	08^0 47' 01.29"	14 m
30	HL11	115^0 10' 02.44"	08^0 43' 57.79"	21 m
31	HL12	115^0 09' 59.47"	08^0 43' 50.44"	24 m

4. Results

The datasers for the analysis consist of 10 L-band ALOS PALSAR acquired between June 2007 to June 2010 and 10 C-band Sentinel 1A scenes over the Bali Island acquired from October 2014 to May 2016 from Alaska Satellite Facility. The data processing of all of the SAR scenes was conducted using GMTSAR application, an open source (GNU General Public License) InSAR processing system. The following is the image result of the land subsidence over the Bali region after applied a pixel-based InSAR SBAS time series analysis.

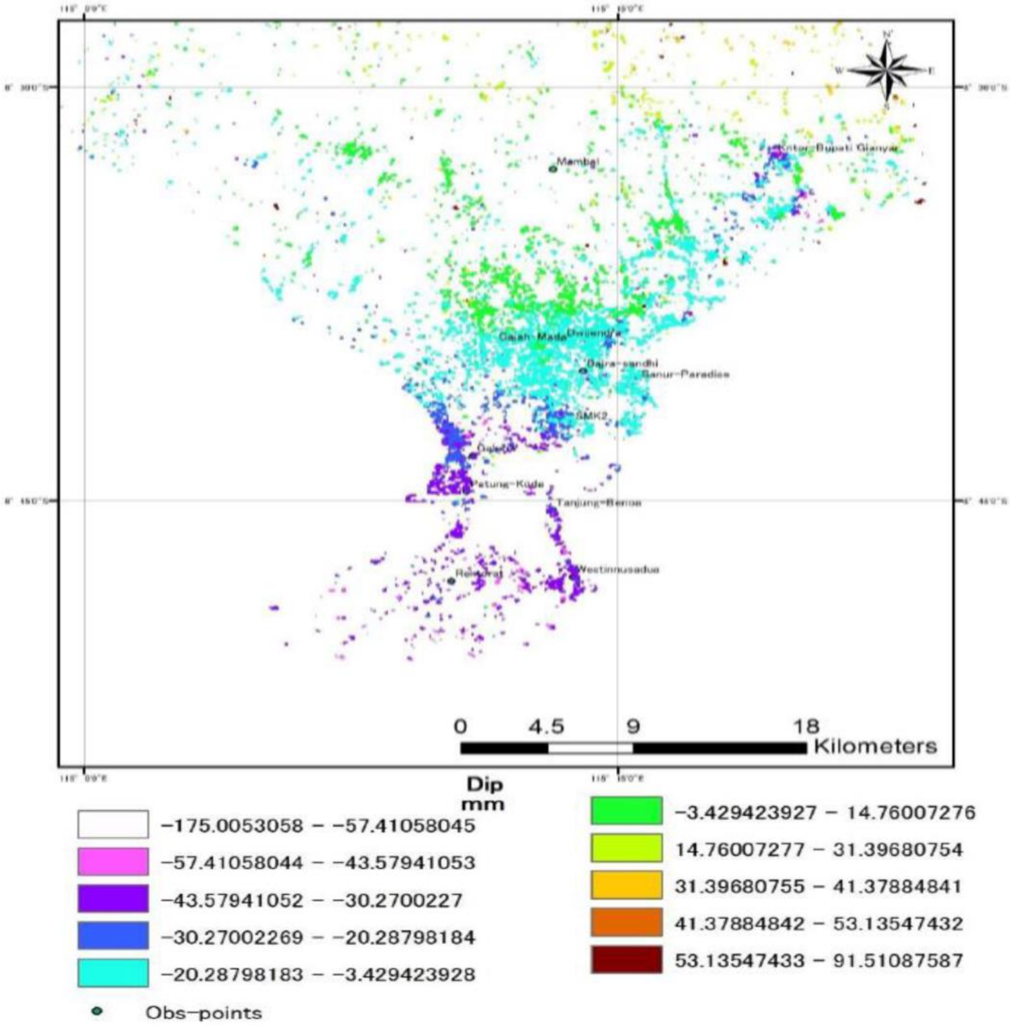

Figure 2 Land subsidence in the southern area of Bali Island as inferred from the SAR interferograms

4.1 Estimating Aquifer Storage Properties Through a Joint InSAR-Well Analysis

Water scarcity will have significant impacts on sustainable development in SIDS and could even hazard the continued human habitation of some islands. One of the response options is reducing the degradation and loss of freshwater resources through technical measures [UNEP, 2015]. Given the lack of direct head measurements, InSAR deformation data offer a new, spatially and temporally dense approach to obtain the needed heads without requiring significant disruption of water use practices. InSAR scenes over the Bali area were able to obtain accurate InSAR deformation measurements at 31 well locations. Figure 3. below showed the result of heads at a confined aquifer of one of the wells as measured using well data and InSAR data.

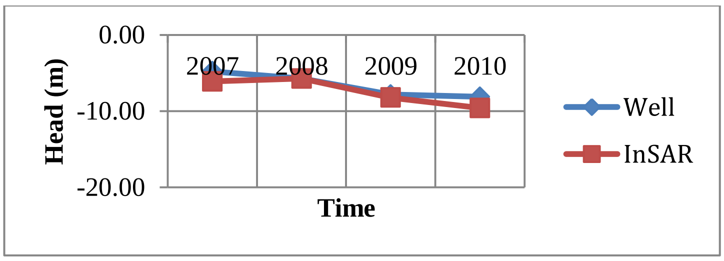

Figure 2 Head at a Confined Aquifer Well HL8 2007 to 2010

5. Biography

Author is a graduate student of the Doctoral Program in Environmental Science and Engineering at the Graduate School of Science and Engineering, Yamaguchi University. Author interests on researches related to remote sensing application for land and water monitoring.

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