Utilizing Landsat Satellite Data (1990-2018) to Detect Water Inundation for the Management of Human Settlements in Coastal Zones

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Abstract

Objective: This study investigates water inundation in Semarang and Demak and Kendal regencies in Java, Indonesia, utilizing Landsat 5, 7 and 8 satellite imagery, in combination with the Seamless Digital Elevation Model and National Bathymetry (DEMNAS) data for 50, 100 and 150 year projections. Methods: Water inundation detection using optical methods (passive sensors) such as Landsat is an effective tool, more so when combined with the Normalized Difference Water Index (NDWI) method in Green Near Infrared (NIR) bands. Combining imagery from these remote sensing sources with DEMNAS land elevation data may strengthen future water inundation predictions and gauge land loss or degradation in regions subject to land inundation and sea level rise. Findings/Application: Semarang is currently subjected to coastal water inundation associated with losses of coastal infrastructure, resulting in the relocation of human settlements to more elevated areas. Sayung is a sub-distric, the most severely affected sub-district has previously experienced an increase of water inundation from 1434.7 ha (1990), 3489.1 ha (2002) to 4923.8 ha (2002), an approximate 1.5 % of land loss annually. This average water inundation increase equivalent to 32 cm annually is based on DEMNAS data from 1990 to 2018, which may be due to coastal infrastructure which supports inundation in surrounding coastal areas such as Sayung, Demak regency.

Keywords: Coastal Management, Land Inundation, Landsat, Normalized Difference Water Index (NDWI), Water Detection

1. Introduction

Monitoring coastal water for the future management of coastal zones is vital for management of coastal settlements¹ and should be considered in regards to effective mitigation and policy². The utilization of multi-temporal satellite imagery data assists in recognizing both spatial dispersion and dynamic changes in the coastal landscape³. Satellite data is an effective tool as it provides high resolution product and provides opportunities to monitor temporal variability⁴, while Landsat imagery is a main source of information regarding sea surface changes in the last decades⁵.

Water inundation in the coastal area of north Java is prevalent, particularly in areas with rapidly expanding coastal human settlements. Semarang, in particular, has been subject to increases in episodic flooding, land abrasion and accretion, the degradation of soil surfaces,
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and sea water intrusion\(^6\), with the natural potential for land loss commonly enhanced by human activities\(^4\), the main factor being urban structures\(^2\) which has been known to promote land subsidence of approximately 19 cm annually in the Semarang region alone. Semarang is especially prone to sea water intrusion due to the topographic geometry of the surrounding coastline. As such, monitoring these coastal zones in densely populated island nations such as Indonesia is necessary for effective management and mitigation\(^1\). The ability of multi-temporal analysis also plays an important role\(^12\) in detecting changes in coastal water surface for coastal inundation modeling. For example, previous studies which utilize a Single Band method mix the satellite image water pixels with a different lid\(^13\), while the development of NDWI is more compatible with water detection\(^14\). When combined with high resolution DEM inundation, prediction is strengthened\(^15\), while DEMNAS provides a further increase in resolution (7 m) necessary for effective monitoring of land loss or degradation.

2. Study Site

The port city of Semarang, is the capital of Central Java province, Indonesia (6°58’S 110°25’E; land area = 373.78 km\(^2\)) with a human population of 1.8 million people, while the Greater Semarang area has a population of approximately 6 million people. The study areas of investigation include Semarang city, Demark and the district of Kendal (Figure 1), which are particularly prone to coastal water inundation\(^18\), episodic flooding\(^12\) and land subsidence\(^5\). These combined impacts have already led to human population relocations to more elevated land in Semarang, Demark and Kendal, while impacted land has been found to be more severe in populated residential areas adjacent to the coast, commonly affected by seawater inundation.

3. Methodology

Satellite images sourced from 2002, 2010 and 2018 Landsat 5, 7 and 8 product (Table 1) were used for multi-temporal assessments, which were analyzed with QGIS geographic information system software, using correction radiometry and Dark Object Subtract (DOS). In addition, image data from Landsat 5 Thematic Mapper (TM; 1990), Landsat 7 with Enhanced Thematic Mapper Plus (ETM+ ; September 2002), and Landsat8 Operational Land Imager (OLI; 2018) were integrated for analysis. All Landsat image data was obtained from the United State Geological Survey (USGS) and all product was obtained from dry season months as to avoid cloud interference associated with the Indonesian monsoon season (typically > 80% cloud cover).

Furthermore, DEMNAS was chosen for its effectiveness in utilizing several data sources such as Interferometric Synthetic Aperture Radar (IFSAR; resolution = 5m), Terra SAR X-band satellite (resolution = 5m) and Phased Array Type L-Band Synthetic Aperture Radar (ALOS PALSAR; resolution = 11.25m), providing additional resolution by adding mass point stereo-plotting. Spatial data resolution for DEMNAS is 0.27-arcsecond, using the vertical Earth Gravitational Model (EGM, 2008). For Semarang and surrounding districts, DEMNAS provided a land inundation result with a Root Mean Square Error (RMSE) of 2.79m, and up to 3.24m and 3.71m (bias error = -0.13m, -0.63m and 2.21m respectively) in both DEMNAS and DSM analysis (http://tides.big.go.id/Demnas/).

Satellite water inundation detection from 1990 to 2018 indicated an extensive alteration of coastal area, particularly by surface water in the temporal adjacent coastline. Algorithms to calculate index performance were derived from satellite images using water index normalization, for extraction of surface water from Landsat Data images (1990-2018). The classification of the water margin was approximately determined in our investigations to enable visual interpretation. For Landsat data interpretation of water, we used Near Infrared (NIR) functions; as NIR is absorbed by water and reflected by\(^28\). Use of data from Landsat 4 band were chosen due to its higher band (4) which has previously been effective in distinguishing between water, land and dry areas, while NDWI indicates water as a positive value:

\[
(NDWI) = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}}
\]
4. Mapping Water Inundation

Water inundation points were calculated using a Geographic Information System (GIS), utilizing the raster function, which highlights roads and the boundaries, while water inundation data from Landsat imagery provided multi-temporal references. DEMNAS was used for mapping future water inundation projections, enabling modeling of water inundation with high accuracy, indicating present flooding of residential areas, in addition to its predictive potential. The former predictive potential may assist future planning and mitigation, more-so when combined with current regional urban planning (RTRW) in the Semarang and surrounding municipalities, which currently do not account for human settlement relocation which derive from land loss or degradation as a result of increasing water inundation events.

Landsat is very efficient in detecting land loss using multi temporal analysis. The results of Landsat data were acquired using Band 6 (SWIR), Band 5 (NIR), Band 4 (RED) from Landsat 8, and Band 5 (SWIR), Band 4 (NIR), and Band 3 (RED) from Landsat 7. For Landsat 5 analysis we used a combination of Band 5 (SWIR), Band 4 (NIR) and Band 3 (RED). This combination allowed more precise differentiations between land and water. This indicated the broad changes in coastal land loss from 1990, with increased water inundation in 2002 and increasing, particularly in the surrounding sub-districts of Sayung and Demak in 2002 forwards.

The method of normalization when differentiating, water is very efficient when performing comparative analysis with water inundation and the optical image. The green bands is particularly effective in emphasizing vegetation, and assessing vegetation health, while NIR is effective in assessing vegetation biomass and coastal shoreline changes, especially pronounced in the Sayung sub-district and Demak. Figures 2 and 5 highlight how water inundation, and resulting large volumes of surface water runoff, has affected Sayung, more-so than other areas in the region, as Sayung is dependent on its aquaculture industry and thus is subject to economic pressures.

Table 1. Effects of water inundation from 1990 to 2018 including annual land loss for each sub-district

| Distric  | Subdistrict | Area of Subdistrict (ha) | 1990 (ha) | 2002 (ha) | 2018 (ha) | Average Land Loss Per Year (ha) | Percent-age (%) |
|----------|-------------|--------------------------|-----------|-----------|-----------|-------------------------------|-----------------|
| Demak    | Bonang      | 8759.2                   | 552.2     | 2250.4    | 2802.6    | 80.4                          | 0.92            |
| Demak    | Karang Tengah | 5539.5                  | 151.1     | 885.5     | 1036.6    | 31.6                          | 0.57            |
| Demak    | Sayung      | 8611.4                   | 1434.7    | 3489.1    | 4923.8    | 124.6                         | 1.45            |
| Demak    | Wedung      | 12878.0                  | 73.0      | 1391.6    | 1464.6    | 49.7                          | 0.39            |
| Kendal   | Brangsong   | 3236.5                   | 104.6     | 248.5     | 353.0     | 8.9                           | 0.27            |
| Kendal   | Cepiring    | 2492.7                   | 38.5      | 456.9     | 495.4     | 16.3                          | 0.65            |
| Kendal   | Kaliwungu   | 9342.6                   | 209.7     | 1764.5    | 1974.2    | 63.0                          | 0.67            |
| Kendal   | Kangkung    | 3552.0                   | 13.5      | 430.2     | 443.7     | 15.4                          | 0.43            |
| Kendal   | Kota Kendal | 3121.2                   | 52.0      | 644.4     | 696.4     | 23.0                          | 0.74            |
| Kendal   | Patebon     | 4372.2                   | 129.9     | 1152.8    | 1282.7    | 41.2                          | 0.94            |
| Kendal   | Rowosari    | 2975.6                   | 1.1       | 47.3      | 48.3      | 1.7                           | 0.06            |
| Kota Semarang | Gayamsari | 612.8                   | 2.1       | 72.1      | 74.2      | 2.6                           | 0.42            |
| Kota Semarang | Genuk    | 2756.6                   | 72.0      | 722.0     | 793.9     | 25.8                          | 0.94            |
| Kota Semarang | Semarang Barat | 2222.8                  | 127.6     | 652.4     | 780.0     | 23.3                          | 1.05            |
| Kota Semarang | Semarang Tengah | 535.4                  | 0.0       | 46.7      | 46.7      | 1.7                           | 0.31            |
| Kota Semarang | Semarang Timur | 559.5                 | 6.2       | 88.4      | 94.6      | 3.2                           | 0.56            |
| Kota Semarang | Semarang Utara | 1072.9                 | 57.9      | 465.4     | 523.4     | 16.6                          | 1.55            |
| Kota Semarang | Tugu       | 3008.7                   | 121.8     | 1848.2    | 1970.0    | 66.0                          | 2.19            |
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Discussion

The ability of the Landsat satellite is indeed very profitable in research to detect the water body. Landsat with multitemporal of benefits also selects the data to be processed. The data weakness of Landsat optics which is vulnerable to the atmospheric conditions. The tropical regions such as Indonesia are very dynamic in atmospheric changes (clouds cover), especially the changes in the rainy months. The satellite data will be very hard use when the cloud covers are in the study areas the utilisation of the method water index will be very difficult.

Figure 2. Landsat imagery in: A. 1990, B. 2002, and C. 2018 showing increase of water inundation in the Semarang region.

Figure 3. A colour-coded representation of water inundation of the investigated area in 1990, 2002 and 2018.

Note: A. is an example of the condition in location 1, B. an example of the condition in location 2.

Source: Semarang City Government.

Figure 4. Water inundation prediction for 50, 100, and 150 years for Semarang, Kendal and Demark based on DEMNAS analysis.

Figure 5. Landuse map for Semarang, Demak and Kendal district.

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to differentiate between the huge volumes of runoff, water in the region of wet rice farming, and tidal flood. The detection of highly effective water bodies without cloud cover can be done with Synthetic Aperture Radar (SAR), with the airborne survey method, but it is very expensive. The use of SAR spaceborne vehicles has also been widely used in the detection of floods. Currently the European consortium provides free sentinel 1A-B SAR data, but recording began in late 2014. The same thing was done by the Alaska satellite facility providing access to Alos Palsar 1 data. Multitemporal analysis is still difficult because of the different platforms and types of sensors used. This is an advantage of using Landsat in long multi-temporal analysis.

6. Conclusion

Utilization of Landsat data is very beneficial in modeling water inundation. Multi-temporal analysis also greatly assists with future water inundation spatial mapping, however, has lacked in combining other methodology such as SAR methodology which is effective in denser cloud cover. Landsat is thus an ideal image product for monitoring land loss or degradation resulting from water inundation.

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