International Journal of Technology (2016) 1: 114-122
ISSN 2086-9614

RAPID ASSESSMENT OF AGRICULTURE VULNERABILITY TO DROUGHT USING GIS

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(Received: July 2014 / Revised: September 2015 / Accepted: January 2016)

ABSTRACT

Food production, particularly rice, has been one of the major concerns in Indonesia. Primary threats to production include agricultural land conversion and climate change. In this paper, a GIS-based approach is presented to assess agricultural drought. This approach was developed using the water balance technique, which accounts for spatial population data. We found that agricultural fields in the Upper Bengawan Solo basin were fairly vulnerable to drought, mainly due to expanding Surakarta (Solo) city.

Keywords: Agriculture vulnerability; Drought; GIS; Java; Rice

1. INTRODUCTION

Most production centers of rice in Indonesia are located in alluvial plains such as West Sumatera and South Sulawesi. Java Island has been notably the most productive region, as previously reported by van Valkenberg (1925). Production centers in Java are situated in the Northern Coastal Region (NCR) with some localized spots in West Java (Cianjur Regency) and Central Java (the Upper Bengawan Solo Watershed). Despite their importance, agricultural fields have been facing tremendous threats and subsequently require better planning. The first, and possibly the ultimate threat, is agricultural land conversion, especially regarding the paddy fields surrounding Jakarta (Panuju, 2004). Land conversion is mostly due to strong pressure establish industrial parks or real estate.

Climate change has become more challenging to agricultural sustainability, especially for rain-fed fields (Boling et al., 2004), where reliable irrigation networks are lacking. Previous studies have demonstrated that remotely-sensed data are essential to observing the effect of changing climate. Patel et al. (2007) found a strong relationship between agricultural yield and Normalized Difference Vegetation Index (NDVI) data derived from Advanced Very High Resolution Radiometer (AVHRR) images. Temperature, as one of important probes from remote sensing data, has been essential for indicating drought when combined with vegetation indices. Belal et al. (2014) recently presented a complete review on the use of remote sensing data.

While remote sensing has been useful in providing baseline data for drought assessment, further analyses are often required, including spatial modeling and dissemination. In this case, Geographic Information System (GIS) technology plays a significant role in analyzing thematic

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Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v7i1.303

datasets. In most cases, hydro-meteorological variables, including rainfall, evapotranspiration and discharge, are used (e.g., Alam et al., 2014; Tripathi, 2006). However, information on specifically how drought is associated with agricultural vulnerability and water competition remains incomplete. This paper presents an adaptation of the spatial water balance model designed to assist local governments in identifying village-based agriculture vulnerability to drought.

2. METHODOLOGY

2.1. Test Site

Bengawan Solo is the longest and biggest river in Java. It covers two provinces: Central and East Java. The upstream region supplies water to a large portion of the paddies and fields in the upland provinces. The river provides necessary water to primary rice production centers, such as the Sragen regency. The Upper Bengawan Solo (UBS) River (Figure 1) flows from Mt. Lawu, at the Central and East Java border. Additionally, some tributaries are sourced from the Merapi-Merbabu Mountains Complex. In Ngawi, the UBS joins the Madiun River (also sourced from Mt. Lawu) to form the Bengawan Solo River.

The inter-provincial system creates water management difficulties, since almost all water supply companies (*Perusahaan Daerah Air Minum*) use the Bengawan Solo River as their main source. The latest field visit showed that domestic water use tends to increase, which creates competition against agricultural water use, especially in surrounding Surakarta.

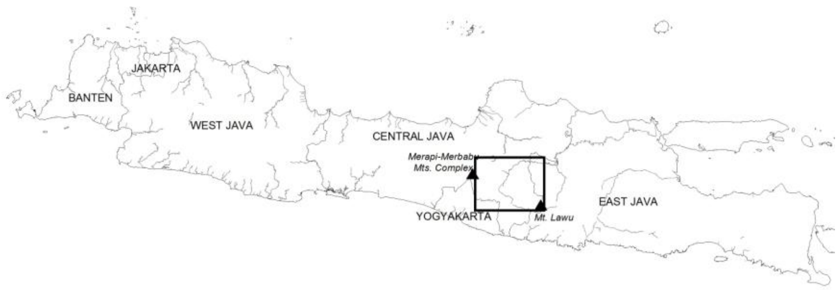

Figure 1 Study site

2.2. Data Analysis

The water balance model presented in this paper is a modified version of the Suwannee Water Balance Model (Tripathi, 2006). Basically, the model was developed using the simple formula shown below;

$$P - Q - ET - W - R = 0 \quad (1)$$

In the above equation, P, Q, ET, W and R denote precipitation, specific discharge, evapotranspiration, water consumption, and residual, respectively. This model could be implemented in a grid dataset for the sake of simplicity. In this research, however, we employed village-based polygons.

2.2.1. Precipitation

Datasets were collected from nine meteorological stations the in provinces of Central Java, East Java and Yogyakarta on a monthly basis since 2004. Using time series plots, we found that some of the data were missing, requiring an estimation based on time series analysis. Primary analysis on the data was spatial interpolation. In this research, we employed Inverse Distance Weighting using 6 neighborhoods. The interpolation creates an output in grid format. Data were then converted and aggregated into polygon representing each village.

2.2.2. Discharge

Six hydrological stations were available along the UBS watershed, and two of them were a short distance apart. The Colo station is located adjacent to Jurang Gempal station, so the data were excluded in the analysis. The following equation was used to compute the discharge (Tripathi, 2006):

$$Q = (O - I)/(AO - AI) \quad (2)$$

In the above equation, Q, O, I, AO and AI stand for specific discharge, discharge at outlet, discharge at inlet, drainage areas of outlet, and drainage areas of inlet, respectively. Using the same conversion as in precipitation, village-level polygon datasets were then constructed from the grid data.

2.2.3. Evapotranspiration

This research employed Actual Evapotranspiration (AET) in the water balance equation. To assist the estimation, we applied the Potential Evapotranspiration (PET) approach using the Stephens-Stewart equation, as shown below:

$$PET = 0.01476\,(T + 4.905)\,SRAD / \lambda \quad (3)$$

In the above equation, PET, T, SRAD and λ signify potential evapotranspiration, temperature (°C), solar radiation (cal/cm^2), and latent heat of the evaporization of water (59.59–0.055T) in cal/cm^2.mm, respectively. Unfortunately, temperature datasets were unavailable for all the aforementioned meteorological stations. Assuming no substantial difference in temperature between tropical regions in similar altitude and latitude, we employed data collected by the Bogor climate station.

The PET was then included into total AET estimation in respective village using all available land use classes (Tripathi, 2006), as in the following formula:

$$AET = \sum (PET \cdot Kc \cdot A) \quad (4)$$

In the above equation, AET, PET, Kc and A symbolize actual evapotranspiration, potential evapotranspiration, crop coefficient and area coverage. Since AET estimation requires crop information, its coverage was estimated using land cover information derived from remotely-sensed data. In this research, IKONOS images acquired in 2006 were utilized to capture urban land cover (especially in Surakarta city), while the rest was covered by early 2007 Advanced Land Observing Satellite (ALOS) Advanced Visible and Near Infrared Radiometer (AVNIR) scenes. Manual land cover interpretation was adopted, guided by previous land use map provided by the Geospatial Information Agency.

2.2.4. Water consumption

There were two basic fresh water retrievals commonly used in the study area. Urban inhabitants (especially in Surakarta), generally subscribe to a water supply company, while rural populations usually obtain fresh water from boreholes or springs. Unfortunately, the latter could not be observed properly and therefore was omitted in the analysis. However, fairly comprehensive data were obtained from the water supply companies, especially from Surakarta. Using simple regression analysis, the relationship between population and water consumption could be established. Employing the regression model, estimation of water consumption could be arranged at the village level.

2.2.5. Data screening

Many datasets were available in time series format, especially precipitation and discharge data. Nonetheless, we noticed that many missing data were found, so pre-processing was required to achieve proper results. In this research, following we employed the X-12-ARIMA

(Autoregressive Integrated Moving Average, Findley et al., 1998) technique to analyze precipitation and discharge time series data, and to estimate missing data from the seasonal pattern. According to Panuju et al. (2010), the algorithm was suitable for data with seasonality influence.

3. RESULTS AND DISCUSSION

3.1. Precipitation and Discharge

Figure 2 shows interpolated precipitation data from nine available meteorological stations (seven are shown). As presented, almost all regencies have a variety of precipitative water. Nonetheless, Klaten generally has lower rainfall than the others. Although vast drainage channels are found in the regency, field observation showed that the irrigation could evaporate completely during dry seasons. As the data suggests, low rainfall occurs in high altitudes, such as west Boyolali and northwest Klaten (both are in the Mt. Merapi-Merbabu complex), and east of Wonogiri and Karanganyar (Mt. Lawu).

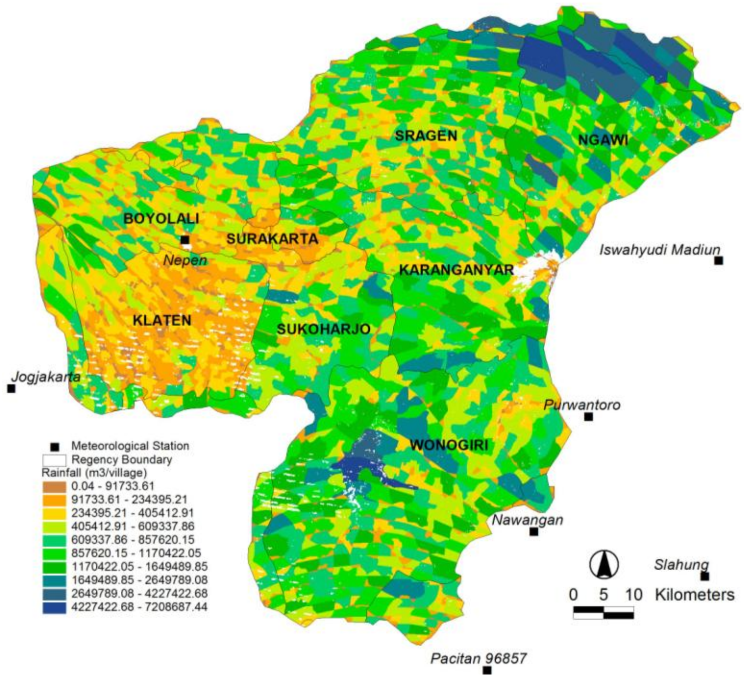

Figure 2 Interpolation of precipitation data

The figure also indicates that climate vulnerability is evident in some regions where intensive farming is being conducted. Limited access to fresh water has shifted farmers to less-intensive farming. To date, rice could only be transplanted once or twice a year, at most. The city development of Surakarta might also be contributing to the situation. The Surakarta water supply company has been operating the Cokrotulung water harvesting plant in Klaten, which directly affected the irrigation capability of the area.

Limited meteorological coverage has been prevalent in Java. As shown in Figure 2, only a few meteorological stations were found adequate for data interpolation. Many meteorological stations were situated outside the region. Using Inverse Distance Weighting, some artifacts are visible, especially in Ngawi, where the Iswahyudi Madiun is the only station used to interpolate the region. A similar condition also applies to Sragen. Estimation on the Northern region of UBS relied highly on the Semarang (not shown) station.

Lack of data also impacts the process of estimating discharge, as only 5 out of 6 stations were suitable for analysis. Village-based discharge is presented in Figure 3. The figure indicates that Wonogiri and Klaten were generally vulnerable to dryness, even during the rainy (monsoon) season. This is understandable, since both regencies are located in the upstream region of the, where the discharge is generally lower than the middle or downstream regions. Several programs to conserve water were implemented by the local governments, such as creating an agricultural terrace (locally known as *terasering*) and building a check dam. Nonetheless, a field survey observed that some dams were not in full-capacity operation.

Sragen and Ngawi have the full benefit obtaining large amounts of water, due to the extensive irrigation drainage built by local governments. Therefore, many rice fields were developed in both regencies; many of them with a triple, all-rice cropping pattern.

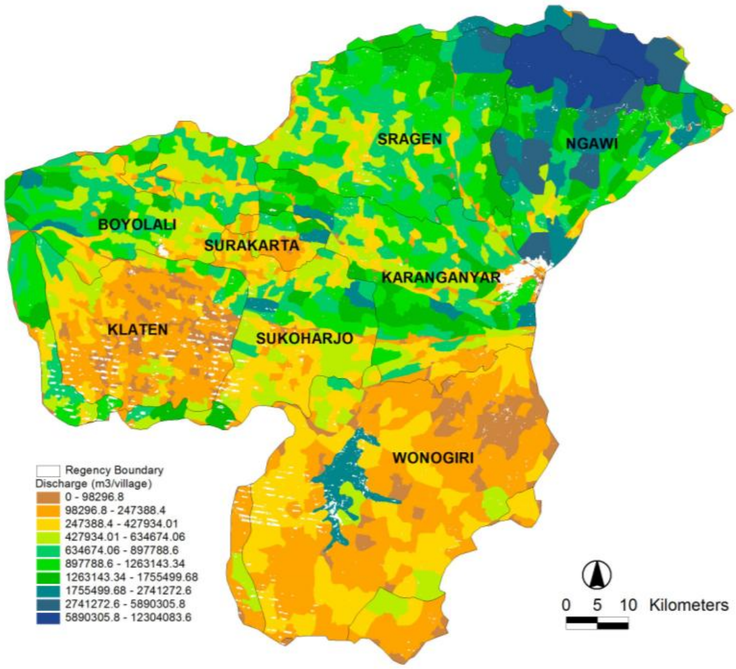

Figure 3 Spatialization of discharge data

3.2. Land Use and Evapotranspiration Estimates

Potential Evapotranspiration can be easily computed from the dataset. However, in this research, Actual Evapotranspiration was used. To assist the estimation, required crop coefficients were derived from land-use data. To update existing land use data, some high-resolution remotely sensed data were employed. The result is shown in Table 1, below.

As shown in Table 1, Mixed garden was the largest category of land utilization in the UBS. It is generally situated between settlements or along streams (riparian areas). The table also shows that rice fields dominated the agricultural areas, which were scattered across flat areas of the region, centered in Klaten, Sukoharjo, northwest Karanganyar, Sragen and northern Ngawi.

Using the crop coefficient, AET estimation was straightforward. Figure 4 presents the estimation of evapotranspiration across the study site. A fairly contiguous block of high evapotranspirative villages is shown in north of Ngawi. This was associated with large coverage of intensive, irrigated rice farming. Some villages that have extensive forest cover in Wonogiri are also visible.

Table 1 Land use and crop coefficients

Land Use	Acreage (Ha)	Crop Coefficient	Reference
Forest	16,534.02	0.68	Blaney and Criddle (1962) cited by Tripathi (2006)
Mixed garden	293,506.44	0.70	http://rpitt.eng.ua.edu/ Publications/Publications.shtml
Estate	39,861.52	0.82	Attarod et al. (2006) for Teakwood
Settlement	66,451.27	0.75	Blaney and Criddle (1962) cited by Tripathi (2006)
Upland field	38,635.21	0.70	Doorenbos and Kassam (1979); using soybeans at late season
Rice field	152,998.77	1.00	Doorenbos and Kassam (1979); averaged at late season
Bush	10,139.02	1.00	Blaney and Criddle (1962) cited by Tripathi (2006)
Bare soil	18,640.37	0.75	Blaney and Criddle (1962) cited by Tripathi (2006)
Water body	5,729.11	1.00	Blaney and Criddle (1962) cited by Tripathi (2006)
No data	11,899.00		
Total	654,394.73		

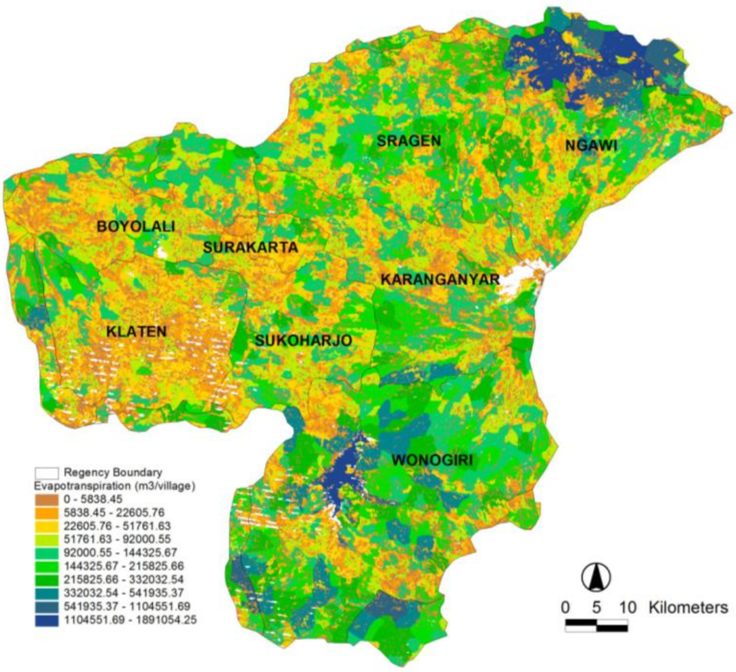

Figure 4 Evapotranspiration estimate

3.3. Domestic Water Requirements

In this research, domestic water requirements were estimated from the total populations in villages and consumptive water recorded by the water supply company in Surakarta. Although there were other companies available in regency townships, the data were unsuitable since they were not recorded at the village level. We found a relationship between village population and associated domestic water use was linear ($r^2 = 0.776$). Hence, we obtained a simple equation to estimate the domestic water consumption at the village level: $W = 1.8842 \times P$, where P is population. Using this equation, water consumption for each village could be estimated (Figure 5).

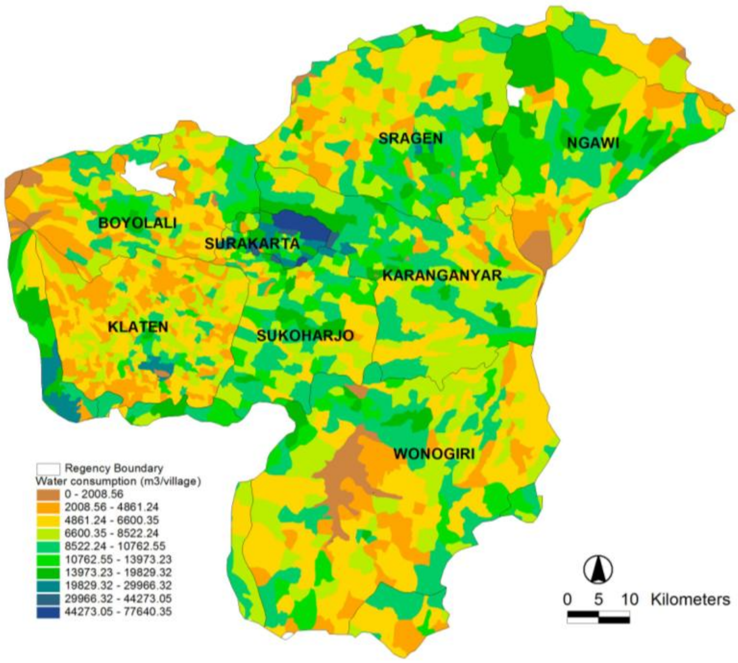

Figure 5 Domestic water requirements

3.4. Water Balance

Employing previously processed datasets, water balance can be computed using a simple arithmetic operation and the result is presented in Figure 6, below.

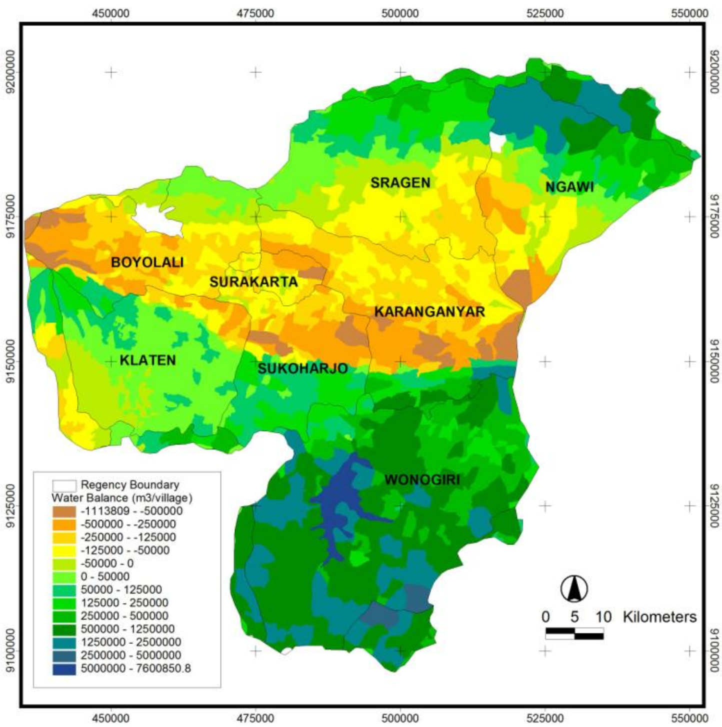

Figure 6 Water balance

The map indicates that the middle UBS region tends to be vulnerable to drought, even in rainy seasons. Field survey results suggest that expanding Surakarta city has played an important role in that vulnerability. Although we are unable to provide quantitative evidence of that at the moment, as buildings were constructed during the field visit, expansive development has been primarily noted in *ruko* (a shared-use building with a commercial store downstairs and housing upstairs) and real estate.

The figure also suggests that uncontrolled expansion of Surakarta city may have significant impact on surrounding areas, especially on the rising competition of water use with the agricultural sector. As UBS is one of the most important sources of water to the rice production fields, local (regency and municipal) governments need to collaborate to avoid the high risk of declining rice supply by diverting too much water for other purposes.

4. CONCLUSION

Drought and flooding have been prevalent in many areas in Indonesia, and have had severe impact on the agricultural sector. Mitigation of these factors is important to minimizing risks and avoiding further disadvantages. The first step includes developing an accurate vulnerability map, which should be regularly updated. In this paper, we demonstrate a possible rapid identification of vulnerable villages using spatial analysis functions in GIS technology.

The results suggest that variation of vulnerability exists in the UBS. We found that the central region has significant drought risk, while the upper and lower regions were less vulnerable. Therefore, existing agricultural lands in this test site are at risk and might reduce the future contribution of the Sukoharjo and Karanganyar regencies in rice supply, due to extensive domestic use by the local water supply company. This is especially true in Surakarta, where a high rate of development is taking place.

It has been demonstrated that the water balance model is straightforward and could be easily implemented. Nonetheless, limitations on surface water need to be improved in the future to produce more reliable information. Also, the research suffers from a lack of data.

Missing data in the time series framework could be minimized through the X-12-ARIMA procedure. Due to the limited number of meteorological stations, however, spatial estimation of precipitative water is fairly inadequate using Inverse Distance Weighting or perhaps on any other interpolation strategies. This would not be resolved by means of data analysis. It is important to resolve these data problems to ensure sufficient water is available in the future for domestic, commercial and food production purposes.

5. ACKNOWLEDGEMENT

We would like to thank Mr. Manijo for his support during field research.

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