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REMOTE SENSING AND GIS IN INFLOW ESTIMATION: THE MAGAT RESERVOIR, PHILIPPINES EXPERIENCE

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ABSTRACT:

In managing a multipurpose dam, knowledge of inflow is essential in planning and scheduling discharges for optimal power production and irrigation supply, and flood control. Utilization of satellite imagery improves inflow estimates provided by digital spatial data instead of those from calculations on drawn maps; the former yields measurements over an area instead of extrapolations from point measurements. Using remote sensing data, GIS techniques, and programming in Java®, an Inflow Monitoring from Basin Assessment Calculations (IMBAC) system was developed to estimate inflow in the Magat watershed; its dam is one of the largest multipurpose dams in Southeast Asia. Magat's 117-km^2 reservoir stores water to irrigate roughly 850 km^2 of farmland and its 360-MW hydro-power plant contributes electricity for Luzon, the Philippines' largest island. The reservoir and dam facilities are jointly managed by the National Irrigation Administration and the SN Aboitiz Power Incorporated; but authorization of discharges during extreme weather conditions is with the country's meteorological agency, the PAGASA. With the complex nature of Magat Dam's multi-stakeholder management involving public and private entities with different discharge motivations, a vital decision support system that concerns inflow estimation is paramount.
This paper presents the results of the developed methodology, IMBAC, to estimate inflow using remote sensing data as an alternative to the water-level approach that is currently being used. IMBAC simulations achieved results which capture the behavior of the Magat watershed response. With more field information to further calibrate the approach, it can be used to build scenarios and simulate inflow estimates under varying watershed conditions.

1. INTRODUCTION

Dams are structures built to create a water reservoir, a hydraulic head and a water surface (Vischer & Hager, 1998). Reservoir operation involves water allocation planning, intake and storage, and discharge control. Knowledge of intake or inflow parameters is essential in planning and scheduling dam discharges, measuring and anticipating current and future power production, optimizing its hydropower operations, and preventing floods. Inflow is a measure of the amount of water entering a reservoir (USACE, 2007). The lack of accurate estimation of inflow parameters is one of the main difficulties in real-world reservoir operations management (Fourcade and Quentin, 1994).

Developments in Remote Sensing (RS) have triggered numerous studies on hydrometeorological model creation and calibration due to the ability of RS in providing spatially-distributed input data (Becker & Jiang, 2007; Kongo & Jewitt, 2007; Wu et al., 2007). Utilization of satellite imagery can improve reservoir inflow estimates by providing digital spatial data instead of calculating from drawn maps, and yielding measurements over an entire area instead of extrapolating from point measurements. Patterns from RS imagery can be translated into a deterministic distribution of input data over a wide area on a pixel-by-pixel basis (Brunner et al., 2007). Coupled with the improving capabilities of Geographic Information Systems (GIS) for simulation and data visualization, RS becomes a powerful source of information that can aid decision makers in the management of reservoirs (Kunstmann et al., 2008).

There are a number of efforts to improve inflow estimation using computational methods such as neural computing (Gilmore, 1996; Kote & Jothiprakash, 2008). Researches involving low resolution satellite images for the characterization of watersheds around a reservoir (Gupta, 2002) have been completed and some of them are focused on certain parameters such as land cover, rainfall (Li et al, n.d.), land surface temperature (Rawls et al, n.d.), surface geology (Ticehurst et al, 2006), soil moisture (Vivoni et al, 2006), vegetation (Bormann, 2007), topography and hydraulic roughness (Aberle & Smart, 2003). These researches are used to improve existing decision-making and discharge policies (Avakyan et al, 2002).

Reservoir managers in the Philippines base their inflow estimates on water level information. With the lack of alternative estimation and forecasting abilities the Magat reservoir managers adapt their management policies to the current water level measurements and rainfall statistics. In this paper, we present the integration of satellite-derived information from Remote Sensing (RS), and Geographic Information System (GIS) visualization and simulation capabilities in improving the Magat Dam inflow estimation process.

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2. THE STUDY AREA

2.1. Spatial characteristics

This case study was conducted in the watershed of Magat River in Luzon, the largest island of the Philippines. It is bound by the latitudes 17°02'08" and 16°06'05" and the longitudes 120°50'00" and 121°30'00". The watershed is 4463.27 km² in horizontal area and is administratively divided between the provincial governments of Ifugao, Isabela and Nueva Vizcaya. The reservoir is approximately 350 kilometers from the capital city, Manila.
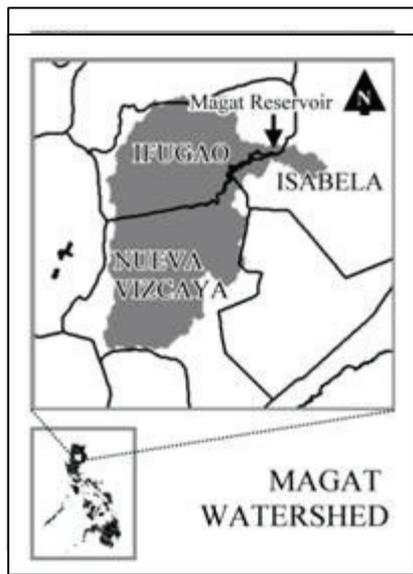
Figure 1. The study area.

2.2. Physical characteristics

The climate of the SW portion of the watershed has two pronounced seasons: wet from May to October and dry from November to April. The rest of the watershed doesn't have pronounced seasons but May to October is relatively wet and the other months are relatively dry (Bato, 2000).

Various forms of clay loam and silt loam soils characterize the whole Magat watershed. Igneous rocks with high silica content (granite and rhyolite) and rocks with low silica content (basalt) as well as scattered sedimentary rocks abound. Four major sets of fault lines run in across the watershed (Palispis, 1979).

2.3. Reservoir structures

Magat Dam is a multipurpose dam which impounds a large reservoir of water from the Magat river. It has a storage capacity of 1.08 billion cubic meters for irrigation to 950 km² of land and 360-MW hydroelectric power generation (Elazegui & Combalicer, 2004). Its flood spillway has a capacity of 32,000 m³/s.

2.4. Human activities

Agriculture is the most prevalent type of land-use in the watershed. Gold and copper mining interests are also present in Nueva Vizcaya (Elazegui & Combalicer, 2004). Some areas of Ifugao and Isabela are noted for tilapia production and other aquaculture activities.

2.5. Reservoir operation and watershed management

Magat Dam is owned and operated by the National Irrigation Administration. They provide the discharge policy based on a weekly Irrigation Diversion Requirement (IDR). In April of 2007, the operation of the hydroelectric power plant was transferred from the National Power Corporation (NPC) to SN Aboitiz Power (SNAP) after a privatization sale enabled by Republic Act 9136 or the Philippine Electric Power Industry Reform Act (EPIRA) of 2001.

3. MATERIALS AND METHODS

3.1. Landsat imagery

We used the archived 1991, 2002, 2005, 2008 and 2009 8-bit GeoTIFF format images of the study area from Landsat 4, 5 and 7 (L4, L5 and L7). They are designed to capture images over a 185 km swath and gather data at an altitude of 705 km. The study area is within the World Reference System (WRS-2) path 116, rows 48 and 49. The 30m spatial resolution gives sufficient information for the purposes of our study.

3.2. ASTER GDEM

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument has an along-track stereoscopic capability to acquire stereo image data with a base-to-height ratio of 0.6. B-H ratios between 0.5 and 0.9 are found to be optimal for DEM creation from satellite stereo pairs (Hasegawa et al., 2000). It provides a 1 arcsecond (~30m) resolution, which bodes well with that of the Landsat images. From the ASTER GDEM, the Slope Raster was derived and the Flow Direction Raster was produced using the D8 method.

3.3. TRMM data

TRMM is a joint project of the US National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). It was launched from Japan's Tanegashima Space Center on November 27, 1997. The primary purpose of this mission is to observe and estimate rainfall.

3.4. Software

We used ESRI® ArcGIS™ v9.3 (2008) and ITT Industries® ENVI™ v4.3 (2006) as our platforms and Java® for our programming needs.

3.5. Brief overview of the methodology

Let

Qa	= reservoir inflow during time, t
Qb	= reservoir outflow during time, t
Qr	= reservoir storage during time, t

note that

$$Q_b = A \frac{dh}{dt} \tag{1}$$

where

A	= surface area of reservoir
dh	= change in water level height

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dt   = change in time

We then get the relationship for the storage volume, V.

$$\int (Q_a - Q_b)dt = \int Q_r dt = V \qquad (2)$$

If the outflow is zero, we get the relationship:

$$Q_a = Q_b = A\frac{db}{dt} \qquad (3)$$

Eq. (3) shows the basic relationship between the water level and the inflow. Through the long experience of the dam managers, they can estimate how much and when the water will enter the reservoir given the rainfall data received from the rain gauges. The volume of the water that enters the reservoir is based on a graph derived from the bathymetry data. A discrepancy due to a time lag variable, the inflow's arrival delay caused by abstractions such as surface roughness (Stephenson & Meadows, 1986), is expected from this procedure because the current method does not account for watershed characteristics quantitatively.

One of the primary uses of remote sensing in this study is the mapping of the Magat watershed's land cover. The eleven classes used were a mix of artificial (cultivated/man-made) and natural features: Cloud, shadow, water, riverwash, fallow field, medium growth field, mature growth field, bare ground, dense forest, sparse forest and built-up.
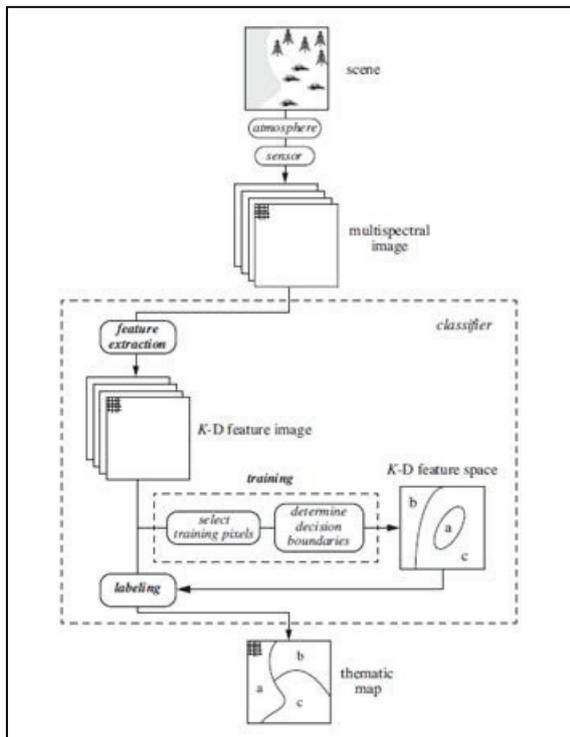
Figure 2. Data flow in a classification process.
(Schowengerdt, 2006: p.389)

We tested four types of supervised classifiers (Parallelepiped, Minimum Distance, Mahalanobis Distance and Maximum Likelihood) and two types of unsupervised classifiers (Isodata and K-means). The Maximum Likelihood Classifier produced the highest overall classification accuracy.

Classifier	Overall Accuracy	Kappa Coefficient
Parallelepiped	86.9176%	0.8303
Minimum Distance	86.6824%	0.8260
Mahalanobis Distance	78.1741%	0.7211
Maximum Likelihood	94.7671%	0.9301
Isodata	69.5529%	0.5996
Kmeans	68.8941%	0.5909

Table 4. Overall Accuracy Table

We used the Maximum Likelihood Classifier because it produced the highest overall classification accuracy (Table 4). The classifier assigns the pixels to their corresponding class based on the odds or likelihood that they fit in to that class. The function for each image pixel is calculated by the formula offered by Richards (1999: p.240),

$$g_i(x) = -\ln p(\omega_i) - \tfrac{1}{2}\ln|\Sigma_i| - \tfrac{1}{2}(x - m_i)^T \Sigma_i^{-1}(x - m_i) \qquad (4)$$

where i = class
          x = n-dimensional data (n is the number of bands)
          $p(\omega_i)$ = probability that class w_i occurs in the image
          $|\Sigma_i|$ = determinant of the covariance matrix of the data in class w_i
          Σ_i^{-1} = its inverse matrix
          m_i = mean vector
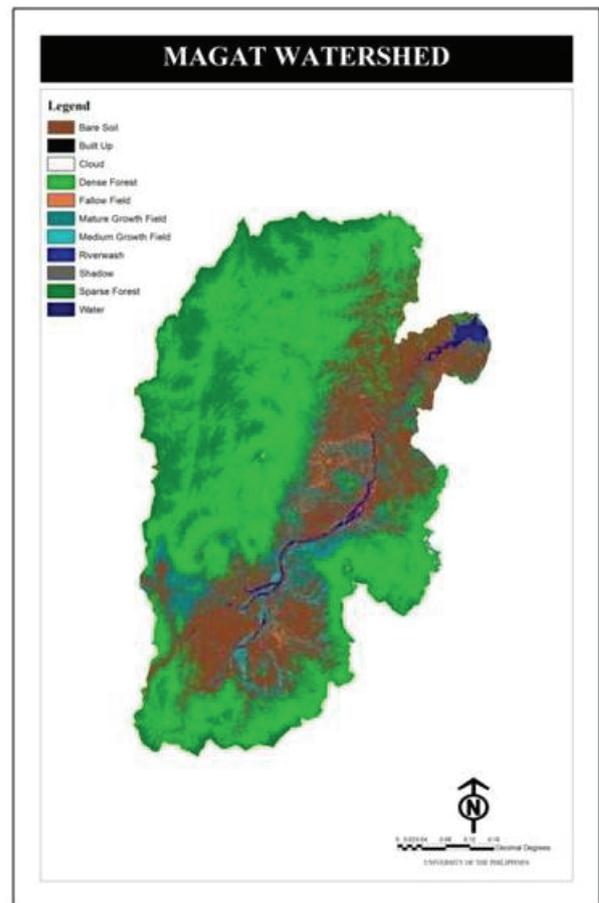
Figure 4. Maximum likelihood classification land cover map of the Magat watershed.

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Enhancement and mosaicking of the digital elevation model were done. Thereafter, database building and preparation of the layers in a spatial software environment; Initial extraction of information such as flow direction, accumulation, watersheds and subwatersheds, drainage networks etc., were done using primitive and modified programming scripts.
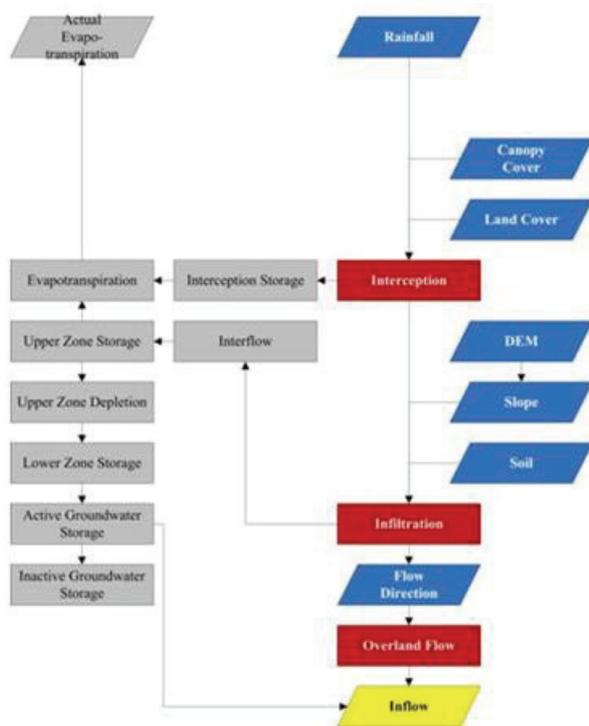
Figure 5. The IMBAC application flowchart

The next stage features the latter part of the hydrologic processing in Java[®]. The purpose of this application is to create a system that estimates inflow using raster datasets as input. The raster layers are subjected to operators representing hydrologic processes. Figure 5 shows the assembly of the program skeleton and the coding process in its alpha stage.

The initial layers required as input are the rainfall data, canopy cover data, soil cover data and elevation data. The rainfall data from TRMM were combined in a single text file. For the soil and land cover rasters, each class was assigned with representative integers.

From the DEM, the Slope Raster was derived and the Flow Direction Raster was produced using the D8 method. An additional text file representing the digitized reservoir was also included for the application to perform some of its functions like termination.

The Maximum Interception Storage is calculated from the formula modified from von Hoyningen-Huene (1981),

$$S_{max}^{c} = 0.935 + 0.498(LAI) - 0.00575(LAI)^2 \qquad (5)$$

The Interception Loss for the timestep is therefore calculated using an exponential function by Hedstrom and Polmeroy (1998),

$$I = min\left\{ P(1 - f_{th,d}) \cdot \left[\frac{S_{max} - S_i(t-1)}{\Delta t}\right] \cdot \left[1 - exp\left(-\frac{P(1-f_{th,d})}{S_{max}}\right)\right]\right\} \qquad (6)$$

where
P = precipitation
S_{max} = maximum interception storage.
$S_i(t-1)$ = interception storage remaining from the previous time step.
$f_{th,d}$ = bypassing fraction.

The infiltration loss model used is proposed by Horton (1939),

$$F_t = f_c t + \frac{(f_0 - f_c)}{k}(1 - e^{kt}) \qquad (7)$$

where
F_t = infiltration volume at time t.
f_0 = maximum infiltration rate.
f_c = minimum infiltration rate.
k = decay constant.

After calculating for the losses, the resulting virtual run-off matrix is subjected to the flow algorithms. The flow direction raster is one of IMBAC's key-ins. To generate this raster, we used the eight-direction (D8) model described by Jensen and Dominique (1988) wherein a water drop on non-edge pixel can move to that pixel's eight neighbors. It is assumed that the direction of steepest drop is the direction of flow. In order to solve this, we compute for the maximum drop (E_{max})

$$E_{max} = \frac{\Delta z}{D} \qquad (8)$$

where
Δz = change in the z-value
D = distance between pixel centers
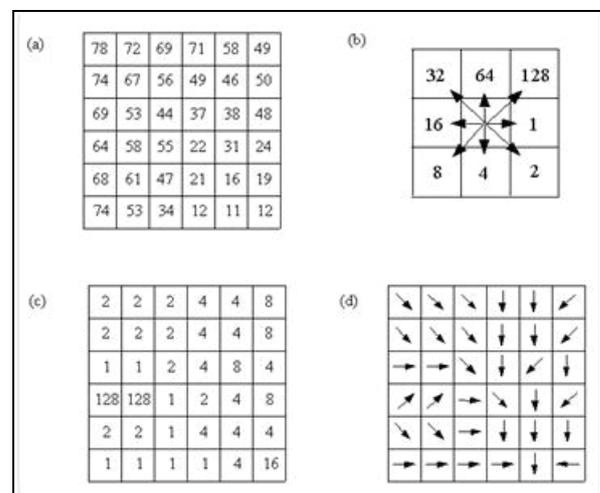
Figure 6. Assignment of flow directions using the D8 model. a. elevations, b. flow direction codes, c. flow direction grid values, d. symbolic representation of flow directions. (NWS, 2008)

The value of the output pixel is specified to indicate the direction of the steepest drop. The following convention (Jensen and Domingue, 1988) is used for the eight valid flow direction representations (E = 1; SE = 2; S = 4; SW = 8; W = 16; NW = 32 ; N = 64; NE = 128). A 5 by 5 expanded neighbourhood is used for instances of more than one pixel having E_{max} values. If the processing pixel is lower than its adjacent pixels, the flow will be undefined – indicating a depression or sink.

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4. RESULTS AND DISCUSSION

The graph below shows the comparison of our program's computed inflow and the NIA inflow record for the month of April 2002.
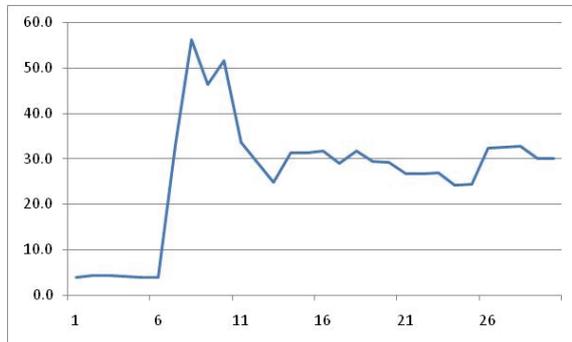
Figure 7. Magat inflow estimates (in m^3/s) using the NIA records.
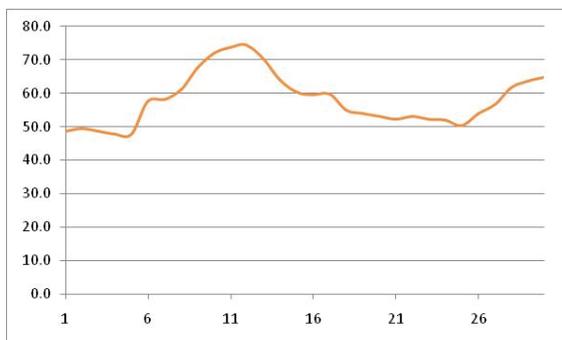
Figure 8. Magat inflow estimates (in m^3/s) using IMBAC.

Differences between the inflow estimates using the current method and the simulated IMBAC inflow estimates can be observed. While IMBAC incorporated the watershed's physical characteristics (canopy cover, slope, soil), meteorological conditions (rainfall), and hydrological processes (infiltration, interception, overland flow), the water level method solely relies on the indicated water level in the dam which corresponds to a tabulated water surface area and its calculated volume. The water level method is purely computational and no modeling or understanding of the watershed hydrology was involved.

It is worth noting however that though there is a discrepancy in the magnitudes of the values produced, the trend of the simulation graphs is similar to the current method graph. The difference during the first week of the simulations and the water level method can be attributed to the discharges made at that time. A discharge cut-off was made on April 6, 2002, and since they base inflow calculations on water level it explains the sudden jump of the graph. The simulations produced by IMBAC produce estimates with a temporal resolution of 30 minutes. This is significantly better than the current method which estimates inflow per day because they capture more detail of the watershed response temporally.

IMBAC simulations achieved results which capture the behavior of the Magat watershed response. With more field information to further calibrate the approach, it can be used to build scenarios and simulate inflow estimates under varying watershed conditions.

5. CONCLUSIONS

Using RS and GIS, we have created a reservoir inflow estimation system, IMBAC, which can be used by the dam managers as an alternative to the current water level-based method. The results produced by IMBAC simulations are promising. The program is proven capable of handling datasets with large extents, thus, it is useful for estimation inflow involving reservoirs with large watersheds. It is capable of preserving the satellite images' pixel characteristics. Each pixel can contain characteristics that are hydrologically relevant; qualitative interpretation of these information is useful in dealing with the scarcity of geographical data at a regional scale. By preserving the pixel characteristics, we can determine the effects of precipitation in one area of the watershed to the inflow estimates--something that the current method cannot do.

In a large study area such as the Magat watershed, logistics play a big role in prioritizing the inclusive activities in this research. The vast size of the study area makes it very difficult to set up streamflow measurement gauges for each sub-watershed. With more time available, more fieldwork to measure streamflow and water velocity should be carried out. Cross-section surveys for each of the drainage segments are also recommended.

An updated source of soil information will also help in refining the inflow estimates. Hydrologic investigations on the study area that focus on infiltration, percolation and groundwater recharge should be done as well.

The densification of the watershed's rain gauge network and an increase in the frequency of recording measurements will also refine inflow estimation efforts. A better system of archiving and securing digital rainfall records is recommended as well. These will also help in assessing the performance of the models used.

The main contribution of this research lies in taking the first steps in realizing the potential of integrating remote sensing and GIS information in reservoir inflow estimation process and Philippine reservoir management in general. We took the first steps in developing a decision support system customized for our country's data situation, economy, policies and multi-stakeholder setup. Studies in improving this framework are currently being undertaken to further refine inflow estimates.

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