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DEVELOPMENT OF A GIS-BASED SYSTEM FOR IRRIGATION MANAGEMENT AND FLOW DISTRIBUTION

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ABSTRACT:

The systematic management of irrigation operation of medium and large gravity irrigation systems (IS) significantly affects the delivery efficiency of irrigation from the source to the farm level. An interactive spatial database that integrates system data handling and irrigation distribution assessment functionality can be implemented, which has not yet been developed in existing NIS in the Philippines. This study proposes a framework model in developing a geographic information system (GIS) database for irrigation systems that integrates a GIS-based irrigation network distribution analysis model. The creation of a model framework for the development of a functional GIS-based database for IS management and flow distribution is comprised of five stages namely: (1) selection and determination of significant irrigation system data, (2) determination of required estimation parameters, (3) GIS development, (4) irrigation network distribution model development, and (5) selection of applicable water distribution assessment techniques. The GIS-based database and integrated model for irrigation provide essential data records of the irrigation system that could easily be viewed systematically and integrated into any GIS. In addition, data packages can easily be shared and run even on low-end computers. Features of the proposed irrigation model include flow volume simulation, time of delivery simulation, irrigation scheduling, remote sensing model integration for automated evapotranspiration computation, volumetric assessment, assessment of the timing of irrigation, and distribution optimization.

1. INTRODUCTION

Medium and large gravity irrigation systems (IS) in the Philippines have progressively been performing inefficiently and below set expectations over time. The performance of these irrigation systems is mainly affected by the volume of water from the source and the efficiency of the delivery of irrigation to the farm level. The former depends on the seasonal supply from rainfall and the latter is mainly on system management and irrigation operation. The irrigation water must be utilized efficiently since supply from the source is very limited in most areas.

General concepts and existing methods for network irrigation flow are very complex but can be simplified if a GIS-based network model is utilized. Instead of a complex hydraulic-based model, a sensitivity analysis-based network model can be used using flow percent loss along the canal and percent diverted at each canal node. The GIS-based network model is considered a more practical approach than the hydraulic-based model since hydraulic structures that regulate and measure flow are limited and mostly in poor physical or not in functional conditions. A network analysis using the former can compute water delivered at the farm level given a supply volume at the main intake.

The development of a GIS-based system model with an irrigation database that can be easily updated will be significant in doing simple assessments and providing recommendations on how to further improve the condition of the current system.

Currently, IS lacks an interactive spatial database that integrates system data handling and functionality assessment. GIS has not yet been developed and utilized in system management and assessment of irrigation systems in the Philippines. In addition, there were no studies conducted based on the application of GIS-based network sensitivity modeling for the assessment of irrigation distribution.

This study proposes a model framework for the development of a GIS database (spatial relational database management system) for the irrigation system that can be easily shared, accessed, manipulated, and updated using free and open-source Geographic Information System software. In addition, it integrates a GIS-based model for irrigation network distribution analysis that will determine the volumetric and temporal components of irrigation for assessment and optimization of available water.

2. METHODOLOGY

The creation of a model framework of a functional GIS-based database for IS management and flow distribution was composed of five stages namely: selection and determination of significant irrigation system data, determination of required estimation parameters, GIS development, irrigation network distribution model development, and selection of applicable water distribution assessment techniques.

2.1 Selection and determination of significant irrigation system data

Available data were reviewed to identify entities, and attributes and facilitate the classification and coding of data which was a significant step to create normalized and non-redundant table structures. The irrigation system's different entities were identified concerning their function in the system, from the main intake up to the turnouts at the farm level to determine all components that will constitute entities for the irrigation system database. Irrigation data were determined based on record-keeping significance, criteria components for system management and irrigation distribution model, and as parameters for system assessment and optimization.

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2.2 Determination of required estimation parameters

Estimation parameters were determined to be used for system management and for the computation of derived metrics as a requirement for model development of irrigation distribution. These estimation parameters usually cannot be obtained directly from available data in the systems. These were computed or derived and used for the evaluation of system components. These parameters will be integrated into the constructed database in the GIS environment.

2.3 GIS development

GIS development involves the selection of the three most important components of the database: (1) GIS software that can store and edit the database, can run process analysis models, and can present stored data and the resulting analysis, (2) a relational database management system that is open-source (free), lightweight and can be easily shared, accessed, manipulated offline, and (3) construction of system geographic features, attributes and structures.

2.4 Irrigation network distribution model development

A network model was developed based on the existing actual flow distribution. Governing hydraulics and flow dynamics elements were used in consideration of the applicability to irrigation practices and operations, and to the available data on the field.

2.5 Selection of Applicable Water Distribution Assessment Techniques

The available irrigation indices were considered for the water distribution assessment of the irrigation system. These indices specifically described the volumetric, spatial, and temporal distribution performance of the irrigation.

3. RESULTS AND DISCUSSION

The prototype model framework for the development of a functional GIS-based database for system management and flow distribution of irrigation systems is presented in Fig. 1.

3.1 Selection and determination of significant irrigation system data

The irrigation data identified and must be collected for system database and distribution model execution were: (1) Canal networks such as canal names, network layout, physical characteristic (construction, siltation, geometry, dimensions, Manning's coefficient), canal type, turnouts, hydraulic structures; (2) Service areas such as layout, owner or farmers name, area, service turnout; (3) Soil data such as soil type, percolation rate, seepage rate; (4) Climate such as rainfall, evaporation, albedo, temperature, relative humidity; (5) Satellite data preferably free, with high spectral and spatial resolution, short return interval and have multiple spectral bands such as Landsat; and (6) High-resolution DEM covering the irrigation system for slope computation.

3.2 Determination of required estimation parameters

The estimation parameters are determined to be used for system management and for the computation of derived metrics for model development of irrigation distribution were conveyance efficiency (canal efficiency, diversion ratio), cropping pattern calendar and cropping flow distribution schedule, crop water requirement derived through remote sensing techniques using satellite data and climatic parameters, and farm application efficiency.

3.3 GIS development

The database and network model were created and implemented using QGIS, free and open-source GIS software. The database was developed using Spatialite which is an open-source relational database management system (RDBMS) that supports spatial geometries. Spatialite is a lightweight, small-sized file designed for storing large amounts of data. Most of the available data of the irrigation system are stored in MS Excel file which was used to populate data in the created database. Data was reviewed to identify entities, and attributes and facilitate the classification and coding of data. The irrigation system's different entities were identified concerning their function in the system, from the main intake up to the turnouts at the farm level to determine all components which will constitute entities for the irrigation system database. The irrigation network was generated from the

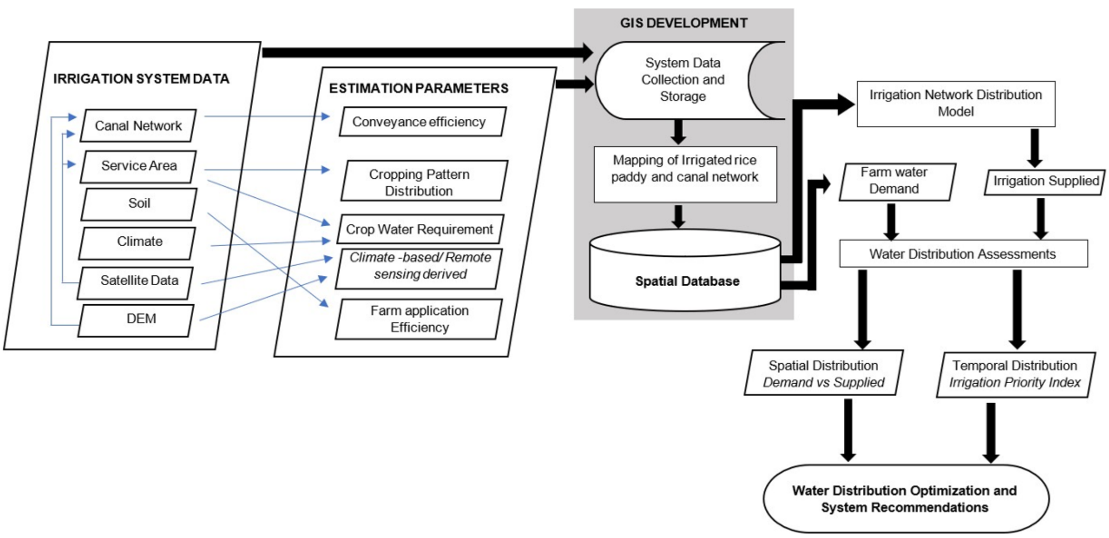

Figure 1. Model framework for the development of a functional GIS-based database for Irrigation Systems.

available system's map and further verified using high-resolution satellite images. The database will be imported to QGIS for flow network model creation and implementation.

The system database is composed of five main entities:

a. Structure – a georeferenced point vector representing all significant and functional hydraulic structures of the irrigation system that contain attributes like name, structure type, canal ID, and selected applicable hydraulic property and its respective values
b. Canal – a georeferenced line vector representing all canals in the system that contain attributes like name, canal type (main, secondary or lateral, tertiary), length, construction and lining, geometry (e.g., trapezoidal, rectangular), hydraulic characteristic (e.g., Manning's constant, conveyance efficiency, siltation, slope)
c. Canal Node – a georeferenced point vector representing flow points along the conveyance that are significant in flow estimation and validation, this contains flowrate values
d. Turnout – a georeferenced point vector representing flow exit structures or gates along the canal to the service farms which contains attributes flowrate values
e. Farm – a georeferenced polygon vector representing a serviced farm that contains data like owner, tertiary service area group, area, and other relevant information.

The sample GIS data structure and attributes are presented in Figs. 2 and 3, respectively.

3.4 Irrigation network distribution model development

3.4.1 Irrigation Supply Estimation Model

A network model was developed based on the existing actual flow distribution. A sensitivity analysis-based network flow model was used using percent loss along the canal and percent diverted at each canal node. At each offtake node, hydraulic flexibility was assumed proportional and linear which means a relative change in discharge in the parent canal generates an equal relative change in the branching canal. This approach was considered to simplify the hydraulic process in the network but precisely simulate the significant actual volume delivered. In addition, it is a practical approach to cover the unavailability of canal physical data and limited and damaged structures.

A network analysis using the model was used to compute water delivered at the farm level given a supply volume at the main intake. To determine the discharge flow (Q) distributed at the farm level, losses along the canal must be determined and subtracted from the input flow from the dam. The loss is dependent on the physical characteristics of the canal and remains constant unless the structure or condition of the canal is changed. The general equation for the flow along the canal is expressed as:

$$QIN = QOUT + QLOSS + \Sigma QTO \tag{1}$$

The canal can be divided into reaches based on the dominant or general physical condition. The loss in each reach can be estimated by subtracting the outflow from the inflow (Qloss = Qin – Qout). Inflow and outflow reach were computed using the velocity (v) at the point multiplied by the cross-sectional area (A) of the canal. The velocity on a point was measured using a flow meter. The loss was expressed in terms of

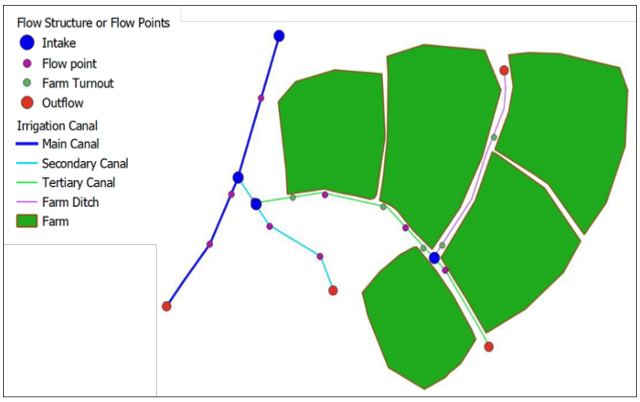

Figure 2. GIS data structure of Irrigation Systems.

Structure

	id	NAME	Prcnt_Div	Canal_ID
1	1	Lat_Gate	0.5	2

Turnout (TO)

	id	NAME	Prcnt_div	Flow	TO_id
1	1	TO_main	0.3	NULL	1
2	2	TO_Lat	0.2	NULL	2

Canal

	id	NAME	Conv_eff	Eff_id	Length	Slope	n	b1	b2	b3	b4	z1	z2	z3
1	3	SubLat	0.6	3	19.21	1.6e-06	0.03	4.000	4.000	3.800	3.700	2.00000	2.00000	2.50000
2	1	MainLat_Str1	0.75	1	12.19	1e-06	0.022	5.000	4.800	4.800	4.700	2.00000	2.50000	1.50000
3	2	MainLat_Str2	0.7	2	14.62	1.6e-06	0.025	4.700	4.600	4.500	4.300	2.50000	2.00000	1.50000

Canal Nodes

	id	NAME	Canal_ID	Eff_id	Flowrate	Link	TO_id	Type_flow
1	1	In_MainSt_	1	1	10.000	-1	NULL	In
2	2	Ot_mainStr	1	1	NULL	1	NULL	Out
3	3	In_MainSt1	1	2	NULL	1	NULL	In
4	4	Ot_MainSt1	1	2	NULL	-2	1	Out
5	5	In_sublat	2	3	NULL	1	NULL	In
6	6	Ot_Sublat	2	3	NULL	-3	2	Out

Figure 3. Attributes of irrigation entities.

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Conveyance efficiency which is the ratio of the volume of water delivered at the outlet point to the volume of water placed in the inlet point. The percent water diverted along the canal node is computed as the ratio of discharge in the branching canal to the parent multiplied by 100. Average velocity along stretch was obtained using Manning's Formula:

$$v = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (2)$$

R is the hydraulic depth and a function of water depth, canal side-slope, and water top width of the lower point of the canal can be directly measured on-site if no data is available. The roughness coefficient (n) was determined based on satellite and field survey data and the average slope (S) of the reach was obtained using high-resolution DTM. Average velocity can be validated by measuring actual velocity on multiple random points along the reach. The time of delivery from source to farm is the total time lag in each reach that is traversed which is expressed as:

$$T_D = \frac{d_1}{v_1} + \frac{d_2}{v_2} + \frac{d_3}{v_3} + \cdots + \frac{d_n}{v_n} \quad (3)$$

Validation of model simulation can be done by comparing simulated flow to available actual flow data. Statistics such as root mean square error (RMSE), relative root mean square error (RRMSE), and relative error (RE) will be computed.
The network analysis using the model was integrated into the GIS environment as "Geoprocessing tools" in the QGIS interface to compute water delivered at the farm level given a supply volume at the main intake. Schematic diagram of irrigation distribution model is shown in Figure 4.

$$Total\ CWR\ per\ SA = Daily\ ET\ x\ AreaSA \quad (4)$$

Total CWR will be computed per cropping stage (every 15 days): land soaking, land preparation, initial vegetation stage, vegetation stage, reproductive stage, and harvest stage. There is no plant transpiration in the early stage of farming since no crop is planted so water demand is due to average farm water depth and evaporation rate. The Farm Water Requirement (FWR) will be computed using the equation:

$$FWR = CWR + Standing\ water\ requirement\ + Lossapp \quad (5)$$

Where Lossapp is the Farm application Loss due to seepage and percolation which will be based on existing soil type. The model will be integrated into the QGIS environment as a component of the Geoprocessing tool incorporating R plugins.

3.5 Selection of applicable water distribution assessment techniques

3.5.1 Assessment of Volumetric Irrigation Distribution

The assessment of volumetric irrigation distribution was done using the Relative Water Supply (RWS) Index. It is the ratio of supply and demand used to determine whether the irrigation supply is adequate by comparing the volume of water available at the field level with the volume of water demand for crop production during the cropping period. The supply is the total irrigation release from the source and the demand is the computed farm water requirement

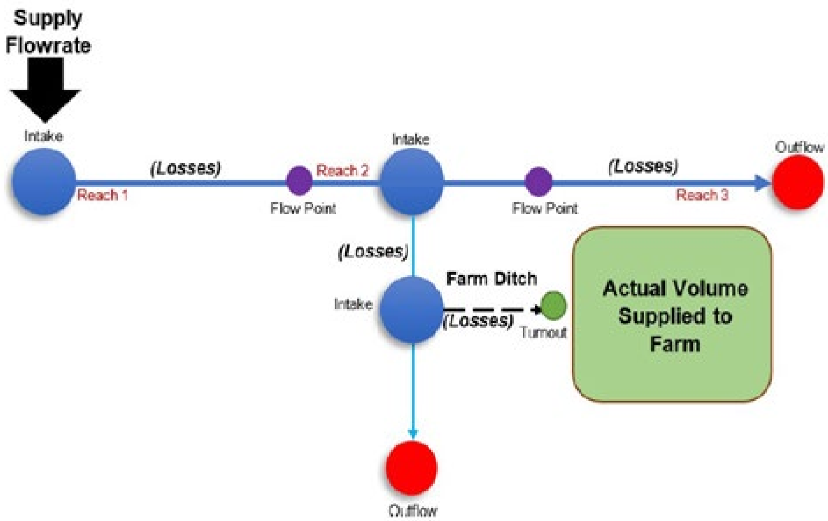

Figure 4. Schematic diagram of the flow process of the irrigation network.

3.4.2 Estimation of Crop Water Requirement using Remote Sensing

Crop water requirement (CWR) was estimated from crop evapotranspiration (ET) derived from remote sensing data using Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model developed by Allen et al. (2007). The schematic diagram of ET determination is presented in Figure 5. The METRIC model was applied to estimate ET using Landsat satellite imagery, DEM, service area, and weather data using the surface energy balance. The total CWR will be computed using Daily Evapotranspiration for each Service Area (SA) using the equation:

3.5.2 Assessment of Temporal Irrigation Distribution

Water efficiency in rice agriculture can be improved by good irrigation scheduling to avoid both excessive irrigation and crop water stress, which can affect plant growth and development. To describe the crop water condition, Water Stress Coefficient (Ks) will be computed. FAO indicated that the crop is said to be water-stressed when the potential energy of the soil water drops below a threshold value. Ks determines the amount of moisture in the soil which ranges from 0 to 1 where 0 indicates oven-dry soil and 1 as a penalty of water. It is expressed as:

$$Ks = \frac{Rn-G-H}{R-G} \quad (6)$$

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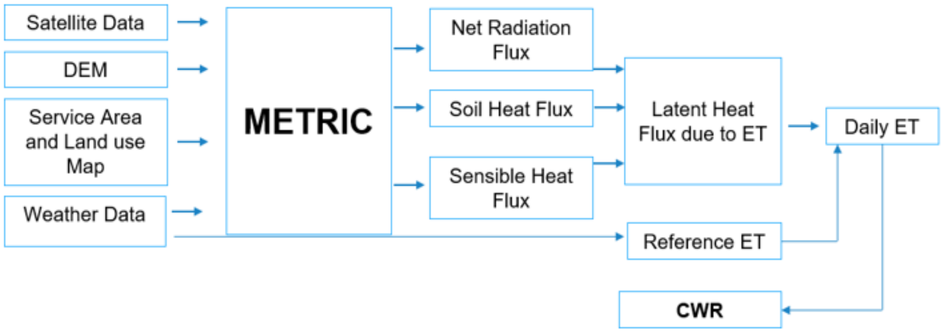

Figure 5. Schematic diagram for computation of Crop Water Requirement (CWR).

where Rn is the net radiation flux, G is the soil heat flux, H is the sensible heat flux

These energy fluxes will also be estimated using the METRIC model. The obtained Ks will be used for the computation of the Irrigation Priority Index (IPI). The IPI characterizes the priority irrigation of each plot at each irrigation round, for a given amount. It was calculated for each plot *i* and expressed as a function of two main terms: the water stress coefficient and the time (in days) between the start of the irrigation round and the irrigation of the *ith* plot. It is expressed as:

$$IPIi = \frac{Ks,i - Ks,min}{Ks,\max - Ks,min} - \frac{ti}{T} \quad (7)$$

Where: Ksmin and Ksmax are the spatial minimum and maximum for the entire area, at the time of computation which corresponds respectively to the most stressed plot and the less stressed one. T is the duration of the irrigation round. Values of ti may range between 0 and T and is the duration of an irrigation round in the ith plot. The T measures the relative level of water stress of the plot i. ti measures the time for irrigation water to reach the ith plot.

IPI values are between −1 and 1, with the value of −1 corresponding to the most stressed plot but irrigated on the last day of the irrigation round; a value equal to 1 corresponds to the less stressed plot but irrigated the first one (early irrigation); value equals 0 corresponds to the most stressed plot and irrigated at the first day and the less stressed plot and irrigated the last day. IPI close to 0 is ideal and can be considered as an indicator of a good distribution of water during an irrigation round. The methodology for computing IPI is presented in Figure 6.

This model is a component of the flow model integrated as a “Geoprocessing Tool” in the GIS environment.

3.6 GIS-based databased with integrated management and distribution model features and outputs

The GIS-based database system and integrated model for irrigation provide essential data records of an irrigation system that could easily be viewed systematically and integrated into geo-maps. In addition, data packages can easily be shared and can be run even on low-end computers. Developed irrigation model features included flow volume simulation, time of delivery simulation, irrigation scheduling, remote sensing model integration for automated Evapotranspiration computation, volumetric assessment, assessment of the timing of irrigation, and distribution optimization.

4. CONCLUSION

The current irrigation system in the country lacks an interactive spatial database that integrates system data handling and assessment functionality. GIS has not yet been developed and utilized in system management and assessment of irrigation systems in the country. This study provides a framework applicable to existing irrigation systems in the development of a functional GIS with an integrated model for management, distribution, and assessment. Important data and estimation parameters were determined and compiled in the Spatialite database which is imported into an open-sourced Quantum GIS (QGIS) environment. The proposed irrigation model comprises a sensitivity analysis-based network model for flow simulation, a model for automated ET computation, field supply estimation, timing simulation, volumetric and temporal assessment, and irrigation optimization. This GIS-based database system with an integrated model will be significant in doing simple assessments and providing

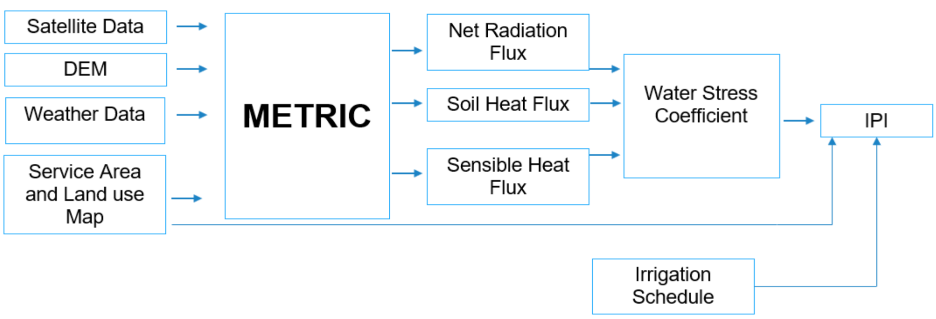

Figure 6. Diagram showing general methodology for computation of IPI.

recommendations on how to further improve the condition of the current system. Changes in the actual irrigation system can easily be simulated and reflected by editing a certain component in the database, and a specific adjustment to system management can be made based on the effect of the parameter changes. The database can therefore serve as the main reference for managers and decision-makers in crafting policies for system component rehabilitation and water scheduling. This can also be integrated into future developments for the automation of irrigation using sensors, automatic gates, and turnouts.

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