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# CRP 514: Introduction to GIS

## Term Paper – Final Report

## *GIS APPLICATIONS IN WATER RESOURCES & ENVIRONMENTAL ENGINEERING*

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**TERM 111**

**Abstract**

Concepts and technologies of GIS are being extensively applied in the planning, design and management of water resources and environmental engineering (WREE) structures. An attempt was made to review GIS applications in the different sub-fields of WREE with particular emphasis on the methodologies for optimum siting of solid waste landfill sites. Multi-Criteria Decision Making and overlay analysis using geographic information systems (GIS) are the key tools for the accomplishment of this task. A case study of GIS-based approach for optimized siting of municipal solid waste landfill in Pondicherry, India, based on multi-criteria decision-making, was presented and discussed.

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## INTRODUCTION

Concepts and technologies of GIS are being extensively applied in the planning, design and management of water resources and environmental engineering structures. It is worth noting that information about water resources and the environment is inherently geographic in nature. Water resources engineering is built on the core science of hydrology, which deals with the occurrence, distribution, movement, properties, quantity and quality of water on the Earth's surface and underground [1].

GIS gives an integrating data and modeling environment for the realization of water resources and environmental specific tasks and projects. It provides a way of collecting and archiving data on the environment. Management of measured location, flow and distance by different devices are usually handled in digital formats and then integrated into spatial database. GIS can then be applied for data processing, synthesis and modeling activities and analysis results can be archived as well. Generation of reports and maps can then follow from the spatial and attribute database so as to reinforce decision making on the optimum design alternatives and its impacts. The development of documents in map formats and the use of map at different scales are typically done in water resources and environmental engineering (WREE) planning and design [1]. As an example, in the study of a river basin, map scale will cover several municipalities, some states and other jurisdictions. The river usually drains a specific geography having geologic, topographic, vegetative, and hydrologic characteristics. Man-made facilities and cities can be sited along the river and across the basin and transportation and pipeline networks will link these together. All of these data can be represented in a common geo-reference framework so that features that coincide can be identified and overlays of theme can be made in the planning and design phase. GIS can be used to manage all these data. It also provides an easy means of doing this that could otherwise not be possible manually, due to the large of amount of data. All the data can be captured and archived, with the ability to browse and retrieve data in color-coded map formats. It can identify, correlate and analyze the spatial relationship that may exist among any mapped phenomena. Thus, enabling policy-makers to relate disparate sources of information, perform sophisticated analysis, visualize trends, project outcomes and strategize long-term planning goals before hand [2, 3].

**Statement of Problem**

GIS has been known to provide comprehensive and best analysis tools and management of any geo-referenced information in different fields of endeavors. In many instances, it can be utilized alone for data capture and analysis, but in the field of WREE, it is usually used in conjunction with other hydraulic, hydrologic or environmental design and analysis packages. In this term paper, a spectrum of domains for the application of GIS technology to WREE intended to be covered together with the associated models that are usually used in conjunction with the GIS include:

- ❖ GIS for surface water hydrology (flood forecasting and floodplain management, river basin planning and management, water supply and irrigation systems)
- ❖ GIS for groundwater hydrology
- ❖ GIS for environmental engineering (solid waste management, water quality, wastewater systems)

**Objectives**

The objectives of this term paper are:

- ❖ to undertake extensive literature review on GIS applications in the different sub-fields of water resources and environmental engineering
- ❖ to highlight the different models (software) that are used in conjunction or integrated with GIS in solving WREE problems

- to present detailed methodology and case study for a GIS-based approach for optimal siting of municipal solid waste landfill sites

# LITERATURE REVIEW

## GIS for Surface Water Hydrology

Different components of the precipitation-runoff process in a catchment or watershed are represented using hydrologic models. These processes which include precipitation, evapo-transpiration, overland flow, infiltration and percolation, are all inherently spatial in character, hence the need to use GIS tools to organize the data and formulate hydrologic models. In the field of WREE, GIS has been most applied in the area of surface water hydrology [1].

Digital representations of landscape topography as digital elevation models (DEMs) or digital terrain model (DTM) may be assessed using specialized numerical algorithms together with GIS visualizations. DEMs can be used to determine landscape features such as slope, aspect, flow length, contributing areas, drainage divides and channel network [5]. Expanded treatise on DEM can be found from DeBarry [6] and Vieux [7].

Other surface water hydrologic models that utilize integrated GIS interfaces and databases include [1]: ArcHydro [8], HEC-RAS (Hydrologic Engineering Center – River Analysis System), HEC-HMS (Hydrologic Modeling System), Geo-HMS [9 - 11], HSPF [12], MIKE 11 UHM and MIKE 11 RR [13], WATFLOOD [14], SWMM 5 and SWMM (RUNOFF) 4.30 [15], Watershed Modeling System (WMS) [16], RiverCAD [17], GIS Stream Pro [18], FLO – 2D [19], TELEMAC -2D and 3D [20] and TUTFLOW [21]. A complete listing of hydrologic models may be obtained from the Hydrologic Modeling Inventory Web site [22].

White et al. [23] utilized GIS to model spatially distributed and time-varying data sets which include streamflow and precipitation measurements. This occurs as a result of the 1993 large-scale flood disaster of the Upper Mississippi River and its tributaries.

Rosenthal and Hoffman [24] used SWAT (Soil and Water Assessment Tool) to simulate flows, sediment and nutrient loadings into streams so as to locate water quality monitoring stations using input from GRASS (Geographic Resources Analysis Support System) and NRCS (National Resource Conservation Service) databases. Colby [25] applied GIS to determine the physical characteristics of the Navarro watershed in Costa Rica. The watershed's hydrologic response was simulated using GIS. Application of HEC-RAS to a reach of Waller Creek, Austin Texas, USA, for floodplain mapping was undertaken by Maidment and Tate [26]. Risk assessment resulting from possible dam break was studied by Seker et al. [27] using GIS linked to FLDWAV which models the overflow wave occurring upstream after the collapse of a dam. Other flood-related GIS application studies have been reported by Solaiman [28], Manandhar [29], Pistocchi and Mazzoli [30] and Chen et al. [31].

River basin authorities are responsible for water resources planning and development. They also provide geographic and functional context for many water-related applications. Reservoir water projects serve more than one of the primary purposes; water supply, irrigation, hydroelectric power, navigation, flood control, recreation, pollution control and wildlife conservation [32, 1]. HEC-ResSim (Reservoir Simulation) is an example of one of the popular river basin simulation system developed by the US Army Corps of Engineers (USACE) HEC [33]. GEO-MODSIM can be used for creating and analyzing georeferenced river basin networks inside ArcGIS [34].

The basic source of earth's water supplies is precipitation (rainfall), while the major consumer is evaporation. These are the most important climatic factors that significantly affect the occurrence of drought over an area. Otun [35] utilized GIS to analyze precipitation and evaporation data in Tanzania and delineate the country into drought-prone zones using drought severity index.

**GIS for Groundwater Hydrology**

Groundwater model developers are often confronted with choices on the extent to which GIS functions can be integrated with the groundwater model. The various ways by which GIS may be integrated into groundwater model include

- Using data transfer programs to link GIS to groundwater model
- Integrating a model with a GIS database
- Embeddng modeling capabilities within a GIS environment [36]

In some instances, MODFLOW or ArcHydro is used for the model simulations, while GIS presents the results in a color coded format. MATLAB can also be integrated within GIS environment as reported by Raterman et al. [37]. MODRSP, being a modified version of MODFLOW, can also be integrated with GIS to simulated spatially varied and time-lagged return/depletion flow from stream-aquifer interactions [38]. Arora and Goyal [39] shed more light on the use of GIS in development of conceptual groundwater model. GIS can also be used to monitor and model oil spill distributions through time. It helps to better understand hydrocarbon plume migration, tracking site treatment and remediation progress [1]. Li [40] developed a GIS planning model to characterize oil spills and determine preventive and control measures available. The US EPA (Environmental Protection Agency) distributes several public-domain groundwater models (software) as well as links to commercial products [41].

Water supply systems consist of different components for raw water collection, storage, treatment (if necessary) and subsequent release into the distribution system for consumer use [1]. EPANET [42] and InfoWater (H2ONET) [43] models provide GIS interfaces and functions for building pipe network simulation models. EPANET can also be used for water quality modeling. Szana [44] used the duo, to model a water distribution system. Taher and Labadie [45] developed GIS-based pipe network optimization software WADSOP (Water Distribution System Optimization Program) which is also linked with GIS. Another GIS-based modeling package called GISAREG [46] is aimed at improving irrigation system scheduling. Eom and Kusuda [47] constructed a GIS database used for the estimation of potential water resources in the Hakata bay watershed in Japan, after developing a stochastic precipitation model linked to GIS. Burst risk studies of water mains in the London supply area using GIS was undertaken by Ta [48]. Jaeger et al. [49] developed an integrated approach using GIS to provide a unique tool for assessing the consequences of water supply changes and distribution system operation and maintenance on the quality of supplied water. Linking pipeline leakage management using GIS was investigated by Schindler and Farley [50].

**GIS for Environmental Engineering**

Design and management of environmental engineering (EE) systems extensively utilize GIS databases, analysis functions and linked simulation models. These applications include initial planning and design of facilities, subsequent operations and maintenance, finance and administration [51]. Among the various EE software that integrate GIS, the following are worth mentioning [1]: ArcFM (manages and models facility data for water and wastewater) [52], GeoMedia [53], MIMS (Municipal Infrastructure management system) [54], Oracle Water Applications [55], etc. Models linked with GIS that try to model water quality change over time include: QUAL2E/QUAL2K [56], BASINS (Better Assessment Science Integrating Point and Non-point Sources) [57], WAMView (watershed assessment model with an ArcView interface) [58].

Diallo et al. [59] undertook a study to monitor and analyze the fate of waste-related pathogens (*Cryptosporidium parkum, Giardia Lambia and E. Coli*) using GIS. Yang et al. [60] investigated the use of remote-sensing, water quality model (QUAL2E) and GIS to forecast short-term water quality of the Te-Chi reservoir in Taiwan. Fraisse et al. [61] developed a GIDM (Generic Interactive Dairy Model) as a tool for creating alternative dairy waste management plans and evaluating the impacts of such plans on surface and groundwater quality degradation. GIDM uses a GIS-based interface to develop field level management plans, then, runs GLEAMS (water quality model). Gemitzi et al. [62] utilized GIS in siting area for construction of natural treatment systems such as waste stabilization ponds for domestic wastewater treatment in the region of Thrace, Greece. Several variables were considered such as topography, land use, type of geological formation, distance to major rivers or lakes, or existing cities and villages, existence of environmentally protected areas, mean monthly temperatures and required wastewater effluent characteristics. Zamorano et al. [63] investigated the use of EVIAVE (a landfill diagnosis method developed at the University of Grenada) in conjunction with GIS to evaluate the most suitable site for municipal landfill in Southern Spain. Combining GIS with fuzzy multicriteria decision making for siting landfill was investigated by Chang et al. [64], Sumathi et al. [65] and Sharifi et al. [66].

## CASE STUDY

### GIS-Based Approach for Optimized Siting of Municipal Solid Waste Landfill [4]

#### *Introduction*

In most developing countries, the phenomenon of urbanization in the past decade was accelerated by the ever increasing human population and the related anthropogenic activities. For instance, in India alone, between 1901 and 2001, there was increased urban population from 11 % - 26 %. Consequently, the rising population coupled with the associated unsustainable practices, many Indian cities were left lacking in basic infrastructural services including water supply, proper sanitation and sewerage, and solide waste management. These generated solid wastes (industrial, domestic or institutional) have become a year-round environmental problem leading to environmental pollution and degradation. Poor waste management which is associated with the hot climatic conditions gives rise to environmental problems with significant local and global dimensions. There is the need to provide an efficient solid waste management system whereby waste management planners and the authorities can tackle the rise in complexity, multi-objectivity, uncertainty and subjectivity related to this environmental menace.

Despite the increasing emphasis on solid waste reduction at the source, its disposal by landfill method remains the most commonly employed method. Landfill, being an engineered method of solid waste disposal, entails spreading the solid waste in thin layers, followed by compacting the solid waste to the smallest obtainable volume and then applying a cover at the end of the operating day. Large tracts of land are required for siting and development of a municipal solid waste landfill. The parameters influencing landfill siting decisions include environmental, geologic, hydrological, and socio-economic condition of the area. As such, site selection is usually based on a number of considerations and requires processing of a variety of spatial data.

The focus of this study is on an optimized land used site selection based on multi-criteria design analysis and GIS overlay feature. The study site is Pondicherry, an urban city in India. Important parameters or thematic maps developed using GIS software in order to arrive at the optimum site for the municipal landfill are;

- pre-existing land use
- location of sensitive sites
- infiltration
- water bodies
- water supply sources
- groundwater quality
- air quality
- fault line and geology

This is followed by assignment of weightings to each criterion depending upon its importance and ratings which in turn, depend on the relative magnitude of impact. Ultimately, GIS-based feature called overlay analysis was undertaken for the identification of the optimum landfill sites which fulfilled all the desired characteristics.

***The Study Area***

Pondicherry district has an area of 293 $km^2$ and is located between latitudes $11^0$64' N and $12^0$03' N and longitudes $79^0$36' and $79^0$53' E and lies along the Coramandal Coast of India as depicted in Fig. 1 (see Appendix I). From 2001 Indian census, the total population of the study area stands at 735,004 and has 2 % annual growth rate.

Major sources of municipal solid wastes in the study area include households, markets, bus stands, hotels, restaurants, marriage halls, government offices, parks, cattle and hospitals. The average total quantity of waste generated in Pondicherry is 300 tons/day, while the average per capita solid waste generation approximates to 450 g/day.

Sumathi et al. [4] report detailed background of the study area as contained in Appendix I.

### *Criteria for Site Selection*

In siting a sanitary landfill, the location has to comply with existing governmental regulations while minimizing economic, environmental, health and social costs. In the present study, the following guidelines were considered for site identification:

- Central Pollution Control Board, India (CPCB)
- Public Health and Environmental Engineering Organization (CPHEEO)

The following factors were considered for selecting the disposal sites:

- Rivers
- Water supply sources
- Groundwater table
- Groundwater quality
- Infiltration
- Air quality index
- Geology
- Fault line
- Elevation
- Land use
- Habitation
- Highways
- Sensitive sites

The following procedures were employed in digitizing the thematic maps using ArcGIS Desktop 9.0:

- Paper maps scanning
- Using the earth coordinates to geo-reference the scanned maps
- On-screen digitizing of the scanned maps in order to generate thematic maps
- Locating the GPS coordinates using longitude and latitude
- Converting the longitude and latitude coordinates into point data
- Adding the attribute data to the locations

Table 1 (see Appendix I) presents the classification of the air quality index of the study area. Buffer maps indicating areas of constraints were generated from the appropriate areas encompassing lakes, ponds, rivers, water supply sources, habitation, highways and fault lines. These maps are presented in figures 2 – 5 (see Appendix I).

The infiltration map presented in Fig. 6 (see Appendix I) considers the key soil types and their properties. The infiltration rate is an important parameter as it gives an idea of the potential risk of groundwater contamination and hence serves as a key criterion for landfill development at a given site. Other maps include the geology, elevation, waste land, groundwater quality, air quality index given by figures 7-11 (see Appendix I) respectively.

Buffer maps were created based on the parameters listed before. Buffer distances of 200 m, 100 m, 200 m, 500 m, 500 m, and 500 m were considered for ponds, rivers, roads, habitation, water supply sources and fault lines respectively.

***Criteria Rating and Importance Ranking***

Consequent upon the inputs from guidelines of CPCB, India, and CPHEEO, key policy makers of the different sections of the local government and literature review of previous works conducted, four categories of criteria were arrived at, viz:

- Land use criteria
- Hydrogeologic criteria

- Air quality criteria
- Constraint parameterization

The weights and ratings of each of these criteria are presented in Fig. 12 (see Appendix I), while the overall algorithms implemented for the optimized siting of the landfill is depicted in Fig. 13 (see Appendix I).

**Discussion**

Spatial Modeler of ArcGIS was employed for the multi-criteria analysis whose outcome is a final map indicating the most suitable sites for municipal solid waste landfill development based on these key criteria identified earlier. The map contains only 3 sites as the most optimum sites as indicated in Fig. 14 (see Appendix I). Initially, 17 potential sites were proposed, as indicated in Table 2 (see Appendix I), but after screening and fine-tuning, only 3 sites (1, 5 and 13) are the most suitable for siting new landfill for solid waste collection [4].

From the foregoing discussion, a small perturbation in the importance ranking and rating could have a great impact on the rank ordering of the optimum sites which may subsequently change the best choice. As such, sensitivity analysis ought to have been performed to determine the probability of changes in rank ordering. Such an exercise may be implemented using Monte Carlo simulation or Latin Hypercube Sampling. Fuzzy multi-criteria decision making may be more promising than just MCDM if the relevant input data would be available for undertaking fuzzy two sequential steps approach as against the full-integrated scheme implemented in this case study.

**Conclusion and Summary**

Different GIS applications in WREE were highlighted. In each case, emphasis was given on the different application packages (models) used in conjunction or integrated with GIS in solving WREE problems. A case study which implemented GIS with MCDM for optimal siting of municipal solid waste municipal landfill was exhaustively discussed and presented. The factors considered in the siting process include geology, water supply resources, land use, sensitive sites, air quality and groundwater quality. Assignment of ratings and rankings to each of the criterion was done depending upon its relative importance and magnitude of impact. A set of 17 potential sites were identified during the initial level of the analysis which reduced to 3 optimized and screened most suitable sites for the landfill construction in Pondicherry, India.

Conclusively, the importance of GIS in WREE cannot be over-emphasized. WREE can be considered synonymous with GIS, since every sub-field in WREE has a lot of GIS applications. This term paper was able to highlight only the most important of those applications, while numerous texts and articles have elaborated on this subject matter. Overlay analysis and MCDM were successfully and logically applied for solid waste landfill siting.

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# APPENDIX I