Applications of GIS and Remote Sensing in Stormwater Management

Urban storm water runoff has been a problem of rapidly growing concern within the past two decades due to its deleterious impacts on ecosystem health. With increased urbanization comes increased impervious surface area (ISQA) such as roads, parking lots, and roof tops. During any storm event, these surfaces rapidly redirect precipitation into natural water bodies at high rates of speed. This can result in significant erosion and flooding, which negatively impact not only natural systems but human infrastructure as well. Additionally, stormwater runoff often contains nutrients, chemicals, heavy metals, pathogens, and suspended solids, which can also severely impair the quality of receiving waters. With the advent of the EPA NPDES Phase I and Phase II regulations, more is being done by municipalities and state governments to alleviate issues associated with stormwater runoff, typically in the form of best management practices (BMPs). BMPs can be both structural and non-structural, but typically have one or more of the following goals: reduce peak flow (through infiltration/retention/detention), reduce nutrient loading, and reduce erosion/sedimentation. As stormwater management strategies evolve, GIS and RS technologies are becoming more practical and accessible in assisting with technical stormwater related determinations. This paper describes the most common ways GIS and RS are currently influencing the field of stormwater management, based on a review of recent applicable literature (2005 to present).

When familiarized with the factors involved in planning BMP implementation, it becomes readily apparent how GIS can serve as an invaluable tool. Perhaps the most prevalent data model used when dealing with stormwater management is the digital elevation model (DEM), typically obtained from the US Geological Survey (USGS). Numerous stormwater modeling schemes utilize a DEM as a major component of their analyses because it is such a critical component of stormwater management on a site and watershed level (Lathrop Jr. 2012, Yang 2010, Roy 2009, Liu 2010, Moore 2012). Elevation is critical because it is the most significant factor in dictating the flow of water, which is the core concept of stormwater management. Utilization of a DEM can provide topography on a potential BMP site, delineate a watershed, identify flood plains, and determine flow paths from a desired point. For these reasons, a DEM is one of the most utilized and valued data sets in the field. Two additional, somewhat interrelated data sets frequently utilized are Land Use Land Cover (LCLU) and impervious surface area (ISA). National LCLU data is typically acquired from the USGS, though many states and municipalities possess their own specialized versions. These data sets are frequently used in analytical modeling because they directly dictate how stormwater will move across a particular surface (Yang 2010, Liu 2010, Roy 2009, Zhou 2007). LCLU data often plays a role in the genesis of ISA data by separating areas where ISA is high, and where it is low or not found. The Natural Resource Conservation Service (NRCS) SSURGO soils data also plays an important role in stormwater management because it provides very site specific information on how well soil will infiltrate runoff (Lathrop Jr. 2012). Recently, there has been a shift in focus from structural to non-structural BMP implementation, meaning that natural infiltration is preferable to detention. Given this shift in preference, soil data is extremely important in determining the location of BMPs as well as development activities in general. The last significant federal data set is the USGS National Hydrography Dataset (NHD), which contains detailed depictions of all US surface water, as well as USGS stream gauge data. Additionally, every segment of every river in the US had its own unique identification value. This data set is of great value to stormwater managers because it provides detailed information on water bodies receiving stormwater runoff.
In terms of non-federal data, perhaps the most basic utilization of GIS in stormwater management by a municipality would be location mapping. R. Lathrop Jr. et al. (2012) identified the lack of a comprehensive geospatial inventory of existing BMPs as a major stumbling block in their attempt to create a municipal stormwater management planning tool. The ease of using a geospatial tool to enter, locate, and store attribute data regarding BMPs is truly unparalleled when compared with a hard copy mapping or filing systems. Municipal stormwater managers also typically utilize local parcel and town boundary data. This data is important because it can link a particular BMP with an owner, which is very important when determining BMP maintenance activities. Additionally, this data can be useful in the planning stage, when a parcel owner must be contacted. Another important data set that often occurs at the municipal level is the location of storm sewer systems and combined sewer overflows (CSOs). The location of these systems is critical when attempting to determine how to reduce inflow quantity and spill events (Roy 2009). The last and likely most ubiquitous form of data used by any environmental manager is aerial and/or satellite imagery. Accurate imagery is vital because it helps to put other features in a more tangible context. It may also make it easier to see more site specific interrelationships between land coverage. Additionally, remotely sensed imagery at a high spatial resolution can be utilized to extract detailed impervious surface area data (Zhou 2007).

Once a manager has obtained all the desired GIS and remotely sensed data, it is commonplace to run various analyses and/or models to answer a specific question. In stormwater management, these questions typically include: where to site a BMP, which BMP will be most effective at performing a certain task, and actions necessary to meet a certain reduction goal, among others. Additionally, every question has numerous factors that play into the outcome, such as: budget, pollutant in question, site characteristics, typical rainfall volume, and many others. To accommodate these very complex circumstances, complex systems must be developed to weight all the necessary factors and determine an optimized outcome. Formulas created to meet this need within a simulation are known as algorithms. Zhen et al. (2006) utilized process based algorithms for their BMP analysis system, which included weir and orifice control structures, storm swale characteristics, flow and pollutant transport, flow routing and networking, infiltration and saturation, evapotranspiration, and general loss/decay representation for a pollutant. For such a system, all the aforementioned characteristics are obtained from GIS spatial and/or attribute data and utilized to simulate the best BMP for a user defined scenario. Young et al. (2011) used a similar, yet more complex analytical hierarchy process (AHP) decision support algorithm designed to minimize the inherent subjectivity found in many approaches currently used in BMP selection. Another typical simulation model used in stormwater management is the Automated Geospatial Watershed Assessment (AGWA) tool, which simulates long-term stream flow and peak flow discharges during single storm events. This model is very important to managers when determining baseline data, and allows them to make important decisions on general development, BMP placement, and BMP peak flow reduction. Despite the impressive complexity of these simulations, stormwater managers may be able to solve many problems using simple logic based queries of attribute or geospatial data. When determining a GIS based methodology for selecting stormwater disconnection opportunities, Moore et al. (2012) found that simple queries on slope and proximity were sufficient to make estimations on BMP selection, placement, and estimated efficiency.

The utilization of GIS and RS technology in the stormwater management field is constantly evolving. Most commonly, GIS technologies are utilized to help aid decision makers on the most efficient ways to manage stormwater based on selected criteria. Even in the most technically complex analyses however, it is still necessary for the human element to select appropriate criteria and make other subjective decisions (Young 2011). There will frequently be decisions made in stormwater management that reflect economic, political, social, and aesthetic components that may not always be
easily incorporated into a GIS analyses/modeling system. The juxtaposition between these technical and non-technical factors will continue to be a critical point in the future development of GIS related stormwater management tools. The interrelationships between these two factors must be studied in greater detail to provide a more comprehensive view of the overlap between user and software elements.

Both of these fields are rapidly evolving, with technical, political, economic, and social externalities constantly guiding their respective directions. On the national level, EPA NPDES regulations have drastically altered the course of stormwater management in recent history; especially with a recent push for greater non-structural BMP implementation. With countless units of data being collected on a daily basis, GIS is similarly advancing and evolving with incredible vigor. The number of large and small scale governments, NGOs, and private firms recognizing the utility of GIS and RS systems is growing seemingly every day. Given the growing nature of stormwater management and GIS/RS technologies, it will likely be very difficult to perfectly merge these two fields. On the most basic level, GIS/RS provided characteristics such as slope, soil type, water features, and imagery will always be critical to stormwater managers. Analytical tools and models however must be easily adaptable to accommodate a varying and evolving array of user needs. Despite potential challenges, GIS and RS are critical tools in the field of stormwater management. They can be utilized at many stages, including planning, testing, implementation, monitoring, general system management, and site specific management. These tools are quickly becoming an essential part of many stormwater management systems, and will only become more pervasive as future managers embrace this technology.
Annotated Bibliography


In this paper, Richard G. Lathrop Jr. et al. describe the process of creating a Stormwater Management Planning Tool (SWMPT). The main need for this tool is to place existing and proposed development and stormwater management in a watershed context. The SWMPT is a quick and easy geospatial tool for assisting municipalities, counties, and other managers in managing stormwater infrastructure. Initially, focus groups were held to determine what kind of mapping software should be used. It was then decided that a Google Maps style interface should be used because it would be a more familiar format, and less intimidating and expensive than ESRI based ArcGIS software. Other necessary components were then determined and incorporated into the system, including a web server, map server, and DEM database. Necessary attribute data and query tools were also added, including features such as project name, county, watershed, type of basin, name of water body being discharged into etc. One of the biggest issues identified with the SWMPT was the very time intensive first step of populating the database with hard copy file information. The finished product was ultimately tested and critiqued by a variety of potential users, and fully implemented in the pilot area of Ocean County, NJ. This article was especially valuable by comparison because it constantly included user input to determine the most effective SWMPT format.


In this paper, Liu Yang et al. discuss a more accurate, GIS based approach for obtaining reliable runoff coefficients for subareas within a larger drainage area. They do this by comparing actual subarea runoff rates with optimized GIS acquired subarea runoff rates in 18 sites in the Milwaukee area. In situ runoff rates were determined simply by dividing the weighted averages of runoff volume by measured precipitation volume. A variety of GIS data were used to calculate runoff values, including regional land use data, a raster DEM, aerial photographs, and storm sewer systems. These values were then compared, and rectified when necessary. Of all comparisons, only two were found to be significantly different due to an underestimated drainage area, and a lack of inclusion of pervious area within impervious area, i.e. grassy areas subdividing parking lots. With correction, the runoff coefficients for the 18 drainage areas were found to be well determined. The end result of this paper is an effective way to determine runoff coefficients for GIS subareas, which give consistency to estimates of particular subareas within a drainage area.


In this paper, S. L. Moore et al. describe a somewhat crude and simplified method for identifying how various LID retrofits may decrease CSO spills on a large scale (>100 ha). Though their methodology is less specific, the authors explain that there are numerous studies about LID effectiveness on a local scale, but none concerned with broad scale improvement. The first step in their method is to prioritize disconnection options in order to reduce CSO spill frequency, i.e. green roofs, disconnected impervious
area, rain barrels, permeable surface, etc. The next step is to then use a series of logic-based Structured Query Language (SQL) statements to determine areas that may be suitable for the implementation of the desired LID practice. Queries would typically utilize land cover, roof area, impervious surface area, total building footprint, and slope data. A case study using this method in three CSO catchments was performed, and carried out three simulations for each, including: 50% area transferred from impermeable to permeable, 50% impermeable area removed, and 5mm rainfall removed. This simulation then produced percent reduction in spill values by comparing generated storm runoff data against historic storm runoff data. The authors then note that this methodology does not make an attempt to model LID units themselves, but rather their sum benefit in stormwater runoff reduction. Additionally, they stress the importance of using detailed land use data, as well as the utilization of a large number of datasets. This article was valuable in that it provided a less technical, though still viable option for making stormwater management decisions.


In this paper, Allison H. Roy et al. discuss in detail the differences between total impervious area (TIA) and directly connected impervious area (DCIA), focusing on methodology for accurate measurement. They were primarily concerned with this distinction due to studies that suggest DCIA has a much more severe impact on stream ecology than TIA. They very thoroughly gathered information on TIA and DCIA areas in the Shepherd Creek catchment in Cincinnati, Ohio, using local and national land cover data and in depth parcel-scale field assessments. Once they had calculated percentages for their study area, they attempted to find relationships between percent impervious type and other factors such as type of parcel and date of building construction. They also compared their percentages against two previously published formulas that claimed to accurately predict percent DCIA based on a known TIA. The authors found that digitizing impervious surface from aerial photos should provide an accurate assessment of TIA within parcels, meaning that a field assessment is not necessary. Additionally, they found that the NLCD layer underestimates TIA, though they couldn’t determine whether a standard adjustment factor would be applicable. Lastly, they found that the two pre-existing formulas for calculating DCIA did not fit their study area, though they attributed this to the fact that the development was variable, and that their study was much more detailed. The aforementioned results of this study were intriguing, however many future studies need to be performed to assess the validity of these results in variable scenarios.


In this paper, Bo Yang et al. attempt to validate the effectiveness of Ian McHarg’s ecological planning tool by studying a site where it was implemented. The McHarg planning method emphasizes preserving soil that is highly permeable by developing around it, in order to increase infiltration and reduce runoff related issues. Additionally, they used several modeling tools to determine whether other factors such as housing density, precipitation events, and soil permeability were significant. They first acquired all applicable data including stream flow data from the watershed, average rainfall interpolated using Thiessen polygons, a raster DEM, LCLU data for four distinct years, and Land-sat imagery. The LCLU data from four separate years was of particular importance, as the authors wanted to determine whether runoff related issues increased in 1997 due to a departure from the McHarg method. Several analyses were then performed, the most important being a comparison of runoff issues before and after the transition from the McHarg method to a more traditional development strategy. The authors found that
the long term watershed outflows differed only slightly between the two development methods. However, the difference was extraordinary in extreme storm scenarios, with approximately 50% higher peak discharge in conventional development. Overall this was an excellent paper because it scientifically validated an ecological concept that until that point was simply assumed to be true.


In this paper, Kevin D. Young et al. describe the development of a complex mathematical model for selecting the most site appropriate BMP. A need for such a tool is justified by the authors given the fact that there is essentially an unlimited number of influential selection criteria assigned to a wide array of available BMP options, making the selection of a single BMP very difficult. The framework of their selection tool is twofold: an analytic hierarchy process (AHP) decision support algorithm, supported by input from a GIS. The user must first identify all BMP alternatives and identify all relevant criteria influencing the selection process. Then, they assign values to each criteria based on importance. They must then select the appropriate GIS data, for example: parcel boundaries, sub-watershed boundaries, land cover, soil type, and slope. The AHP is then run, and produces a ranked list of BMPs by constructing pairwise comparison matrices, extracting priority vectors, evaluating consistency, and ranking competing BMP alternatives. The authors tested their process using a demonstration site, where peak flow, total suspended solid (TSS), and total phosphorus (TP) reduction were compared across three scenarios: base flow (no development), generic basin BMPs, and the utilization of BMPs produced from the model. They found significant reduction in TSS and TP when utilizing the model produced BMPs, however, peak flow reduction was slightly less than that found when generic basin BMPs were used. The authors conclude that this is a useful model for reducing the vast quantity of user analysis required in selecting site specific BMPs. However, they advise close scrutiny when accepting model produced BMPs, given the fact that the models attempt to simultaneously satisfy potentially conflicting criteria may yield results that do not fully satisfy each criterion individually. The results of this paper were interesting in that their simulation produced a BMP which was superior on only two of three assessed factors. This further emphasizes the importance of site specific user defined parameters.


In this paper, Jenny Zhen et al. describe a GIS based decision making tool for placement of BMPs at strategic locations in urban watersheds based on integrated data collection and modeling. The system does this by utilizing GIS, integrating BMP process simulation models, and applying system optimization techniques. The system also provides interfaces for BMP placement, BMP attribute data input, and decision optimization management. The ArcGIS component is the main user interface, and includes the main application window with menus, buttons, and dialogue boxes. The BMP simulation module uses algorithms to simulate function and removal efficiency. The optimization component provides evolutionary optimization techniques to identify the most cost-effective BMP selection and placement strategies based on user defined decision criteria. The authors describe a case study in a two block area of Washington, DC, in which the system was used to identify the most cost effective options given two scenarios: a fixed budget value, and fixed runoff reduction percentage. The system produced a tradeoff curve, indicating the maximum total runoff volume reduction given a fixed cost, or the minimum cost given a desired runoff reduction volume. The system also produced a prioritized list of BMPs with
efficiency and cost taken into account. Though the system did produce a valid result, there is a need to further improve the interface, update the BMP module with additional information, and add a conveyance model, among others.


In this paper, Yuyu Zhou et al. discuss the process of obtaining impervious surface area (ISA) in state of Rhode Island based on aerial imagery. The authors justify the need for this research by discussing the growing concern regarding the negative impacts of impervious surface on ecosystem health. They produced their data by first obtaining ortho-rectified imagery with a 1 meter pixel resolution. They then used a multiple-agent segmentation and classification (MASC) algorithm, including sub-models of segmentation, shadow-effect, multivariate analysis of variance (MANOVA) based classification, and post-classification. This algorithm was designed to enhance object-oriented classification, separate shadows from the object that cast them, and to recover missing segments of impervious area caused by shadows. In order to then extract the ISA from the state efficiently, the authors developed a batch-process algorithm and applied it on the segmentation and classification process. Upon analysis of the final product, the authors concluded that of the 38 towns in the state of Rhode Island, 5 had ISA greater than 30%, 5 towns had ISA between 20 and 29%, 12 towns had ISA between 10 and 19%, and 17 towns had ISA less than 10%. They also found that ISA distributions were spatially uneven, being more extensive in major population centers and historical cities along the coast. Lastly, they concluded through buffer analysis that ISA was less frequent surrounding major rivers, and more frequent surrounding major road systems. This paper was excellent because it provided more detailed data about ISA in Rhode Island, and additionally, further analyzed the data to describe ISA distribution based on different factors.