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Addressing Italy's urban flooding problems through the holistic watershed approach by using blue/green infrastructure

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Highlights

- Holistic approach to watershed management.
- Goals to reduce flooding and improve water quality.
- Data collection and analysis.
- Modelling to achieve goals.
- Development of a comprehensive holistic watershed management plan

Abstract

Water resources have been neglected and stressed for many years, as anthropogenic changes in watersheds have increased runoff, decreased infiltration and aquifer recharge, caused stream incision and streambank erosion and degraded water quality and water resources. The watershed is the management unit to begin to solve stormwater problems and flooding issues. Reversing the mismanagement from the past is a complicated process and must consider a holistic approach factoring in all the processes that cause the aforementioned problems. There are many technological tools such as GIS and hydrologic, hydraulic and water quality models that help pinpoint the sources of problems in the watershed and help derive at a comprehensive solution. The objective of this paper is to provide researchers and practitioners a systematic, methodical and proven approach to documenting and solving water management issues cause by unmanaged anthropogenic changes that have occurred in rural and urban watersheds. There are many regulations and literature about flooding and watershed plans with very detailed guidelines composed by state authorities, however, there are few that completely address the comprehensive, inclusive approach to watershed management to solve a variety of problems. For example, the State of Pennsylvania, USA has separate flood plain management, stormwater management, erosion and sediment pollution control and nonpoint discharge and elimination system (NPDES), and water supply / wellhead protection programs and regulations as opposed to one single "water resources management" regulatory program. This paper defines an innovative approach to overcome some of the restrictions placed on engineers and planners by regulatory programs.

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1. Introduction

2018 was a historic year of flooding in Italy. From Sicily to Venice, devastation and destruction from unprecedented rains occurred. Flooding not only causes financial damage, but washes pollutants off of our roofs, roadways and highways. Although 2018 had very unusual rainfall patterns, intensity and storm event totals, preparing our watersheds for an ever-increasing frequency of occurrence of such events is going to be mandatory. On the other hand, droughts are also reason for concern. This paper outlies the process of identifying problems, analyzing the physical processes of the watershed through GIS and modeling processes, and developing a "Watershed Plan" to help minimize, reduce or eliminate these problems in the future. The Plan should include a description of the evaluation process, data and GIS maps, results and recommendations for implementation of watershed management measures.

2. Watershed processes

In order to fully understand how to manage a watershed to reduce stormwater runoff, minimize flooding and improve water quality, one needs to fully understand the physical processes within the watershed. Land cover, soils, geology, topography, floodplains and hydrology all play important roles in how a watershed responds to storm events. Land cover (impervious area) affects runoff evapotranspiration (ET), soils also affect runoff and infiltration, geology affects aquifer recharge and stream baseflow, topography and slopes affect runoff travel times which all affect the hydrologic response of the watershed. These can all be mapped within the GIS to determine spatial patterns and help pinpoint causes of problems. Other features such as lakes, reservoirs, dams, levees, storm sewer systems, riparian buffers (or lack thereof) etc. that would affect the hydrologic response of the watershed should also be inventoried and mapped. If as-builts of storm sewer systems are not available, it is oftentimes very expensive to collect the information of the systems. One should evaluate the need and see if it meets the goals of the watershed Plan.

These physical features of the watershed can all be mapped, processed and overlayed in the GIS to develop hydrologic model parameters and determine locations of water resource patterns. This GIS analysis, coupled with watershed hydrologic, groundwater and/or water quality modeling provides the engineer, planner or government official with a blueprint of where each problem originates, the type of problem and allows one to formulate solutions. The entire process as described in this paper in more detail can be schematized as shown in Figure 2.

3. GIS data

Many of the phyical features such as topography, soils and land cover that make up the watershed can be mapped to aid in analysis and management. A few of those "layers" are described below.

3.1 Digital Elevation Models (DEMs)

There are various sources of digital elevation data for Italy that can be utlized to assess the watershed and develop hydrologic data for modeling. The European Digital Elevation Model, version 1.1 (EU-DEM v1.1) is available in GeoTIFF 32 bits format. It is a seamless dataset divided into 100x100

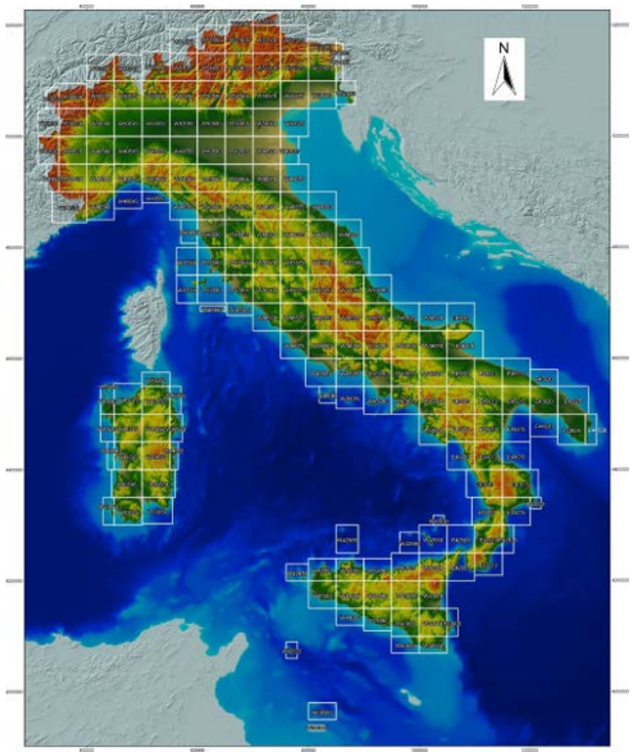


Figure 1: DEM coverage of Italy. INGV, 2019.

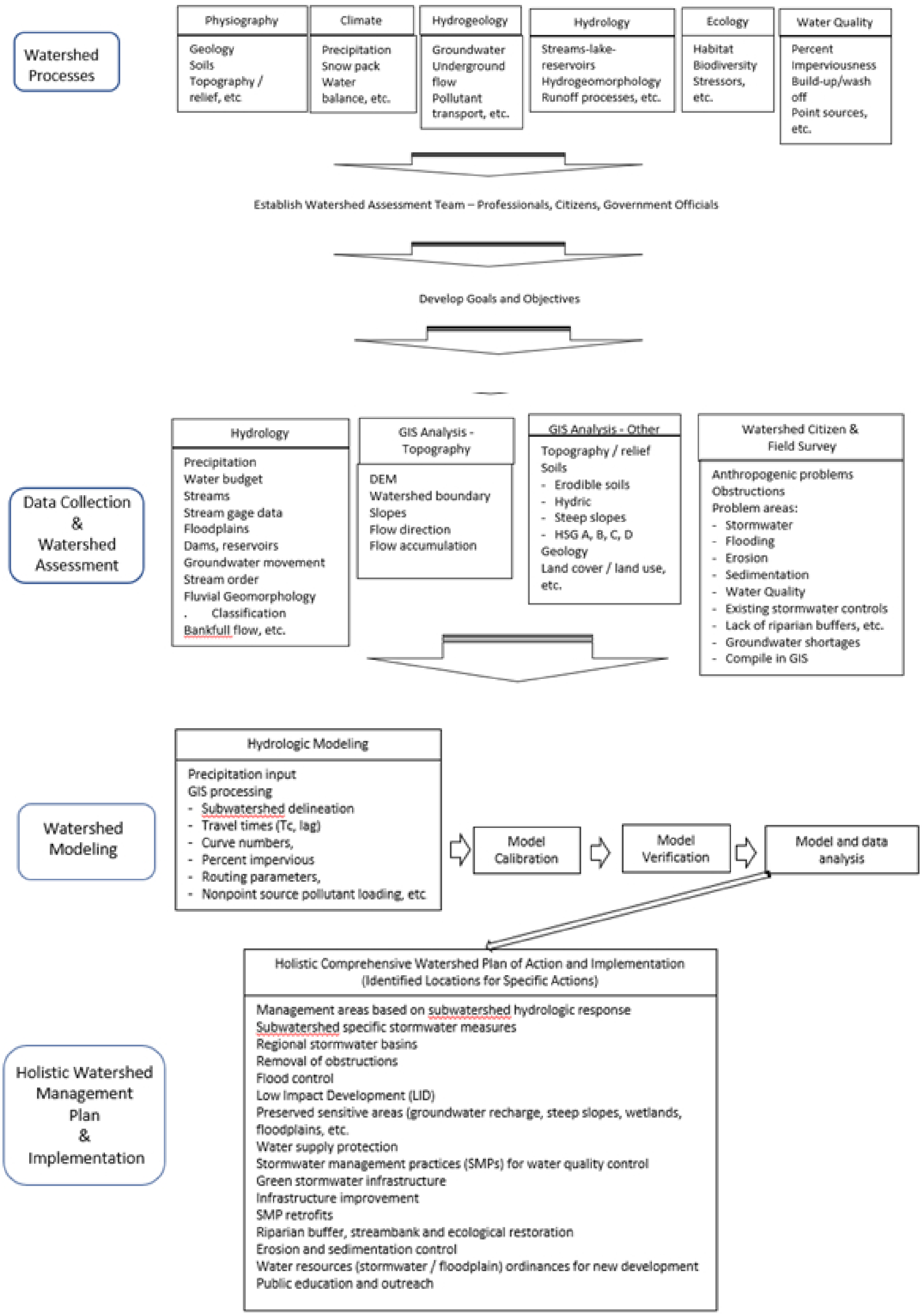


Figure 2: Schematic of comprehensive, watershed processes, assessment, and management. *Source: the author.*

km tiles at 25m resolution with vertical accuracy: +/- 7 meters RMSE as shown in Figure 12. The tiles have been grouped by regions and can be downloaded directly. The x, y-coordinates in the tiles are based on the EPSG:3035 (ETRS89-LAEA) projection. The 1000 x 1000 km tiles are provided as zipped GeoTIFF files with LZW compression.
Another contiguous digital elevation model of the whole Italian territory is TINITALY/01 (Tarquini et al., 2007). This DEM originated from the DIGITALIA project, which previously involved the Istituto Nazionale di Geofisica e Vulcanologia in a conjuction with the Italian Ministero dell'Ambiente e della Tutela del Territorio. The DEM database is available as a 10 m-cell size grid in the UTM WGS 84 zone 32 projection.
DEMs are invaluable in watershed processing and can be processed in the GIS to delineate the watershed and subwatersheds, determine flow direction, flow accumulation and flow paths, determine slopes, time-of-concentration (Tc), travel times (Tt), etc. Depth grids can be developed showing the extent and depth of flooding, which also aids in problem area determination, and solutions.

3.2 Soils

As with DEMs, there are various sources for locating soils data for Italy including Soils of Italy (Romano et. Al, 2013), Sardinia (Vacca et al., 2014) and for Sicily (Fantappie et al., 2015).
As described by Fantappie, if soils data are available, it may not have hydrologic properties (hydrologic sol groups) associated with it. Hydrologic properties can, however be developed if the soil texture is determined through USDA's hydrologic soil group classifications (Fig. 3) as follows.

- Group A. Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.
- Group B. Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.
- Group C. Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.
- Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

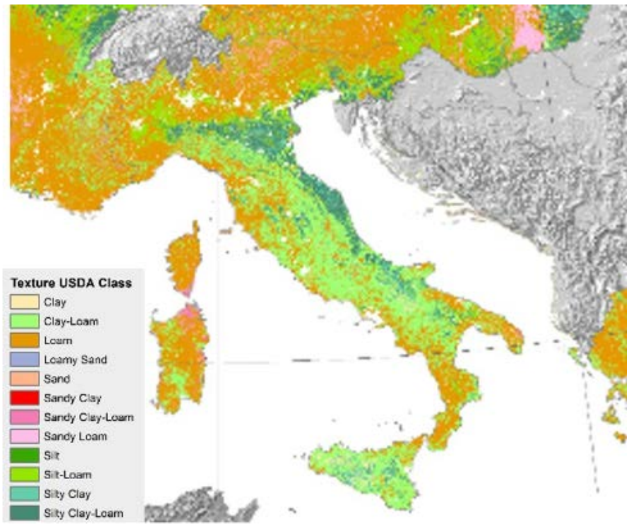


Figure 3: USDA soil texture class for Italy. *Source: Romano et al., 2013.*

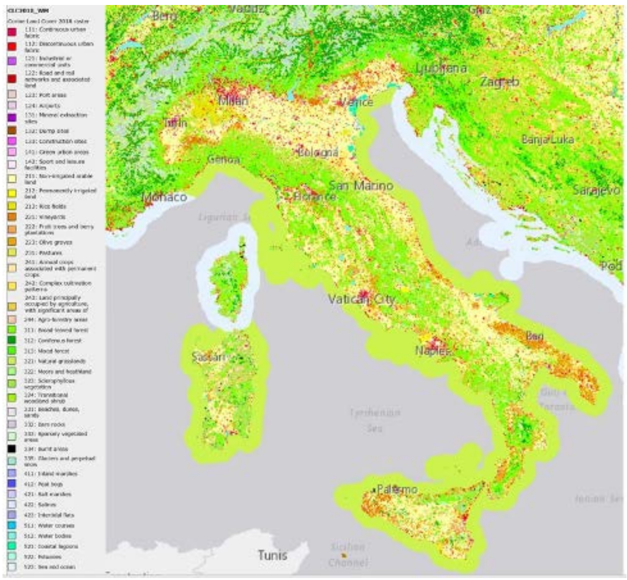


Figure 4: Corine Land Cover for Italy, 2018. *Source: author's elaboration based on Copernicus CLC soil data. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018*

In addition, new soil hydraulic pedotransfer functions (PTFs) were recently developed by Toth et al., 2014 and allows soil hydraulic properties to be analyzed.

3.3 Land cover

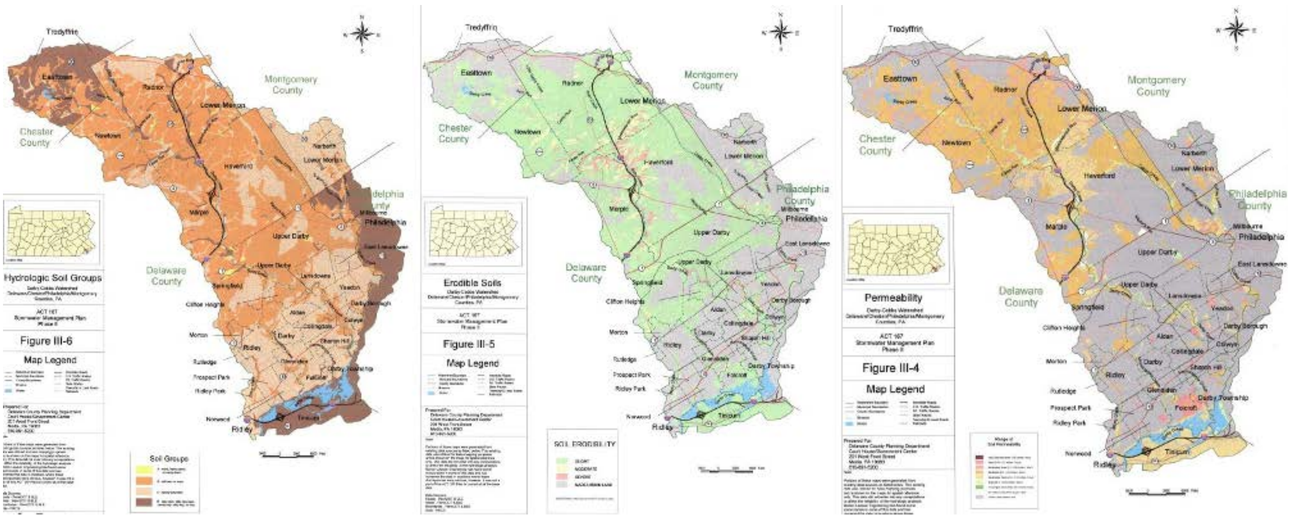
Land cover is available from the Copernicus Land Monitoring Service as Corine Land Cover (CLC) in both seamless raster (100 and 250 meters resolution), and vector (ESRI and SQLite geodatabase) format as shown in Figure 4. The Minimum Mapping Unit (MMU) for the CLC is 25 hectares for aerial features and 100 meters for linear features. The latest year of the dataset is 2018. Once the DEM, soils and land cover are established in the GIS, processing can provide the hydrologic model input parameters such as subwatershed area, length and width; curve number; Tc and Tt; etc.

Figure 5: Typical colored hillshade of a watershed DEM. *Source: the author.*

4. Watershed data processing

Once the natural physical and anthropogenic data has been entered into the GIS, processing of the data can begin to show patterns and solutions to problems begin to be formulated. Just visualizing the hillshade of a DEM allows one to determine where steep slopes, floodplains, and stream patterns are as shown in Figure 5. A DEM of watershed not only allows for a visual representation of the watersheds, but as described earlier, also provides the data for processing, such as watershed and subwatershed delineation, time-of concentration and travel time computations.

The resolution of the DEM is important and should



(a) (b) (c)

Figure 6: Soils of a watershed displayed as hydrolgic soils groups (a), soil erodability (b) and permeability (c). *Source: the author.*

Table 1: Typical DEM resolutions for watershed processing

Cell size (m)	Resolution	Coverage (Arc-second)	Minimum Drainage Area (SQ Kilometer)	Application
1	High	1/27th	0.052	Local drainage problems
3	High	1/9th	0.57	Local watershed Analyses
10	Medium	1/3	6.21	Most watersheds
30	Medium	1	57	Larger watersheds
100	Low	2	N/A	Large river basins

Source: author's elaboration.

be selected based on the watershed size as shown in Table 1. Garbrecht and Martz (2004) found that a grid cell coefficient, which they defined as the grid cell size / basin area of 0.05 or 5% of the basin area gave results within 10 % accuracy of baseline reference values. Seybert (1996) suggested a grid cell coefficient of 0.01 to be an acceptable threshold of spatial resolution for reasonable model results (DeBarry et al., 1999). Using the 0.01 threshold, Table 1 displays rules of thumb for each DEM resolution can be applied, although results will vary. Also, for instance, utilizing the GIS attributes, soils can be displayed as hydrologic soil groups, hydric soils, erodible soils, or steep slopes (Fig. 6). Utilizing these physical features to develop hydrologic model parameters such as hydrologic soil groups and curve numbers, time-of-concentration, travel times, along with rainfall totals and distribution in a model, allows a detailed analysis of the response of the watershed to rainfall patterns.

5. Watershed assessment

Once the variables that make up the physical features of the watershed have been mapped in the GIS, one should begin to survey the anthropogenic changes and obstructions that cause problems in the watershed. Anthropogenic changes would include channelization, concrete channels, diversions, agricultural practices, and urbanization. Obstructions would include culverts, bridges, channel obstructions that may cause streambank overflow backwater or flooding. Problem areas could be categorized as:

- Drainage problem
- Flooding
- Water quality
- Groundwater problems
- Erosion
- Landslides
- Agricultural Runoff
- Streambank erosion
- Sedimentation, etc.
- Etc.

Combining these evaluations, in combination with a potential survey of citizens in the watershed of their problems would produce a problem area map of the watershed. Each problem area should be populated within the GIS attributes such as type of problem, frequency and duration of occurrence, owner, the year that if first occurred, amount of rainfall that caused the problem if available, depth of flooding, etc. The spatial distribution of the various types of problems allows an analysis of what the cause of the problem might be. For instance, a grouping of flooding problems indicates that there is a regional flooding problem most likely caused by something in the upgradient watershed, urban encroachment in the floodplain or a combination thereof. Conversely, a grouping a stormwater problems may be an indication of localized obstruction or undersized storm sewer system. Photos of the problem can be attached to the GIS database as well.

6. Watershed modelling

6.1 Watershed subdivision

Once the physical features of, and problems areas within the watershed have been mapped, the watershed should be subdivided into several subwatersheds. The subdivisions should be based on points of interest (POIs) which are defined as a downstream point on a river, stream or tribu-

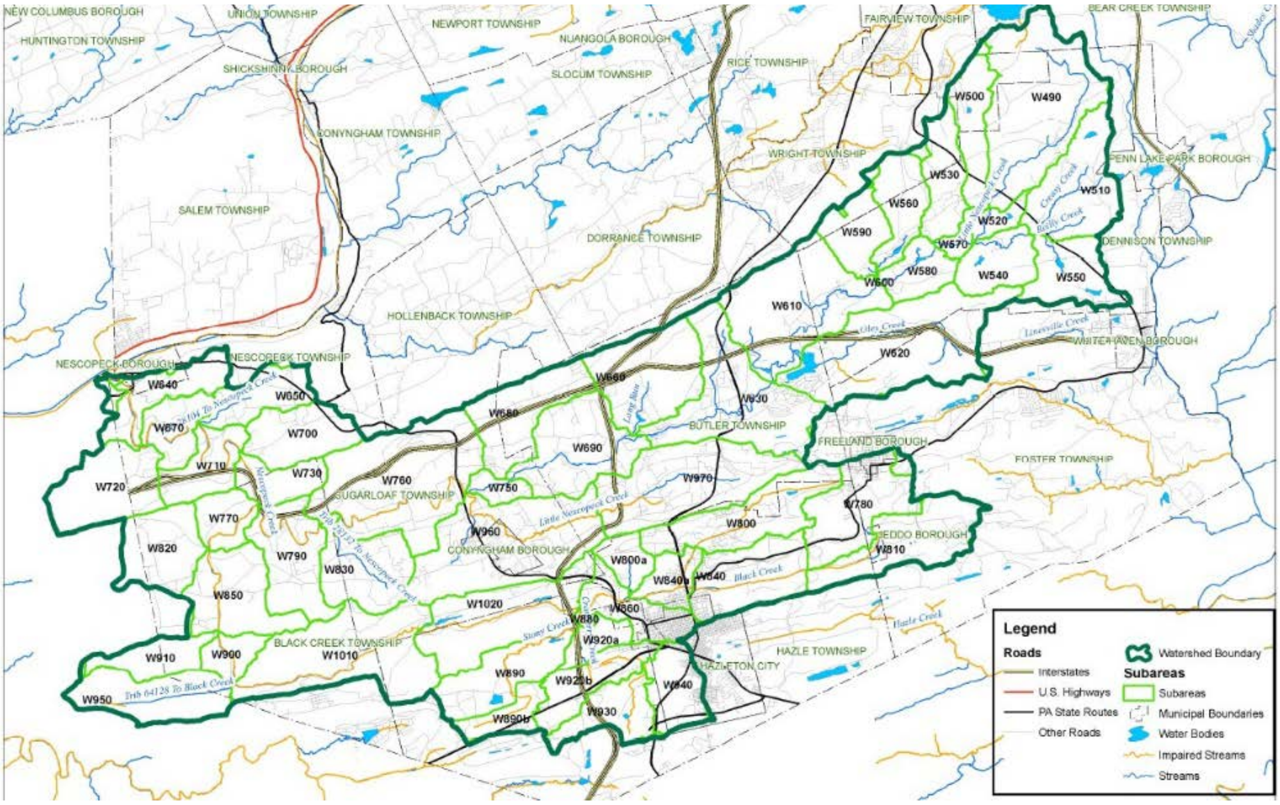


Figure 7: Watershed subdivided into subwatersheds for flow timing and management purposes. *Source: the author.*

tary where there is a reported problem area, obstructions, confluences, dams or reservoirs where routing is required, steam gage (for calibration) or other location where flows would be needed. The watersheds can be subdivided using the DEM in either ArcGIS, GeoHMS, WMS or other GIS based processing tool. A typical subdivided watershed is shown in Figure 7. Once the data is set up, the parameters required for watershed modeling, i.e. curve number, time-of-concentration or lag, travel times, subwatershed basin dimensions, slopes, etc., may be obtained. Parameters calculated will depend on what model will be utilized. The required model input data can then be created from the GIS processor, whether it be the HEC-HMS, SWMM or other model.

6.2 Model calibration / verification

In order to model with confidence and reliability, one must be sure the model is as accurate as possible, not only for the peak flow, but for the timing of the hydrographs. The model generated peak flows and hydrographs should be compared to stream gage data if available, and model parameters adjusted to match the hydrographs as closely as possible for several storm events where localized rainfall data is available. The detailed calibration process is beyond the scope of this paper. If stream gage data is not available, comparison of flows to regional regression equation results should be applied.

Once the model is calibrated, the model should be run for standard design events using the localized rainfall distribution to produce results. The location of the subwatershed hydrograph in relation to the time-of-peak of at the POI provides an indication as to the amount of stormwater detention might be required to reduce flows at the POI.

7. Interpretation of Results. Development of the comprehensive watershed management plan and implementation

By utilizing the overlaying power of the GIS, and evaluating mapped watershed problem area patterns, one can begin to determine the causes of

Figure 8: Depth grid developed in PCSWMM-2D in an urban area pinpoints problems areas and magnitude (depth) of flooding. *Source: the author.*

those problems. For instance, based on the collection of GIS data, one area of the watershed may have a streambank erosion and sedimentation problem. Evaluating the soils in the area may yield highly erodible soils. Therefore, the solution to this area may be a combination of reducing flows and in turn velocities upstream, coupled with natural stream channel restoration measures at site. Another area of the watershed may have severe overbank flooding. Analysis of the watershed yields a highly urbanized area upstream, with no stormwater controls. Therefore, the urbanized area should be evaluated closer for areas of potential regional stormwater detention, promotion of infiltration of runoff from impervious areas. Problems can oftentimes be classified into local problems, such as undersized storm drains, and regional problems, such as stream overbank flooding. The depth grids, as shown in Figure 8, provide a great pictorial of the magnitude of the problem and can help pinpoint upstream solutions. The priority for correction of the problems should be based on human safety, economics, and environmental preservation, most often, but not always in that order.

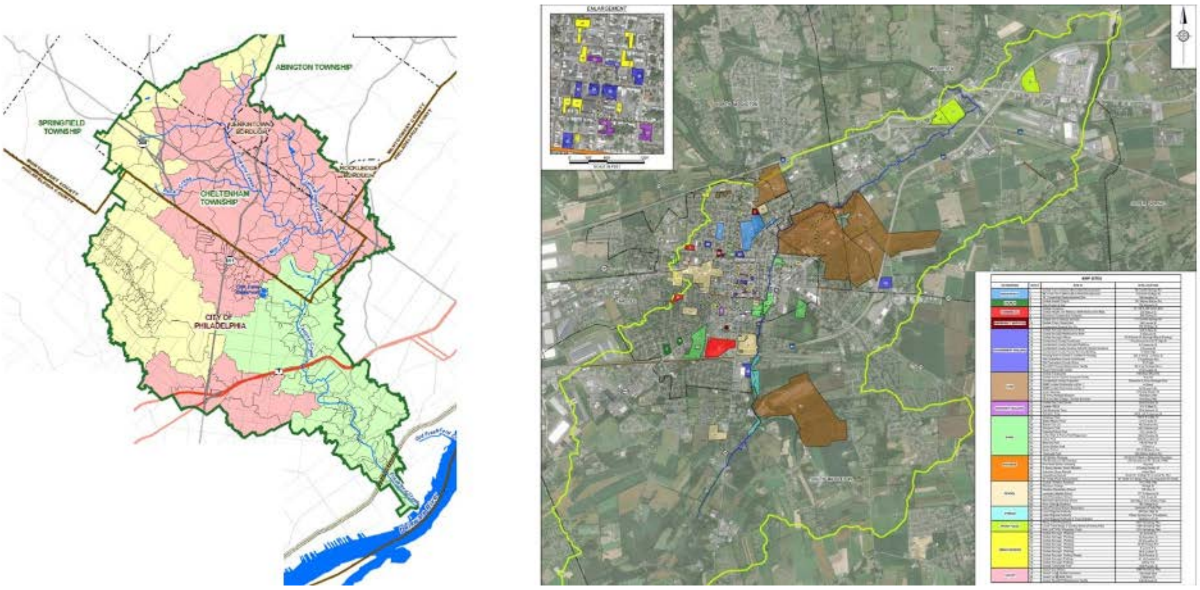
The watershed should be divided into "management areas" whereas the priority in one area may be erosion and sedimentation, another area local drainage issues, and yet another area regional flooding. Based on the modeling, it may be advantageous to subdivide the watershed into various stormwater detention management districts where some areas may need to overdeteain stormwater to reduce flows downstream, and other areas it may be best not to detain stormwater at all, such as is typically the case near the mouth of the watershed as shown in Figure 9 (a).

Green stormwater infrastructure (GSI) plays a huge role in accomplishing the goal of achieving the natural hydrologic regime of a watershed, which then naturally prevents or mitigates the problems caused by antrhopogenic changes discussed in this paper (DeBarry & Longenecker, 2014). Strategically placed GSI should be a major emphasis in the development of a watershed plan as is being implemented in Philadelphia's green acres program (2019) after development of their watershed plans. GSI promotes infiltration, thus replenishing stream baseflow and recharging aquifers, traps the first flush (most highly concentrated portion) of stormwater runoff pollution, mitigates the Streambank erosion storm (that storm that causes the most erosion) and aids in flood reduction due to the infiltrated and temporary storage / detention of stormwater. Areas where LID, BMP and/or GSI measures will be most effective can be highlighted within the GIS as shown in Figure 9 (b).

A schedule of implementation with priorities should be established. The author has developed over 30 such watershed plans throughout the States of Pennsylvania and Delaware for such entities as the City of Philadelphia (4 individual watershed plans), Allegheny County (Pittsburgh, PA), Luzerne County (Wilkes-Barre, PA) and the State of Delaware. References section provides the links to two such plans.

8. Conclusions

Compiling information described above should provide a plan of action to begin to solve the problems in the watershed for sustainable water resources, with well-defined goals, whether they be improved water quality (pollution reduction plan), minimization of erosion, reduced flooding, etc. The Plan should include a summary of the procedures utilized, the modeling results, GIS maps of the physical features of the watershed, problem areas, obstructions, subwatersheds and any other map that may help explain causes and solutions. Areas of proposed green stormwater infrastructure (GSI) or proposed low impact development (LID) should be a major component of plan implementation, with what specific measure will work where described. The Plan should be a plan of action, not just a report of the findings, with priorities, an implementation schedule, funding sources and means to achieve the goals. One funding source could be a stormwater fee assessed on the amount of a landowner's impervious area (determined through the GIS). The development of the comprehensive Watershed Plan is an involved and complicated process, but long term, provides a systematic approach to sustainable water resources management.



(a) (b)

Figure 9: Watershed subdivided into various Stormwater Management Districts (a) and one with LID/BMP/GSI recommendations spatially located (b). *Source: (a) the author; (b) DeBarry & Longenecker, 2014.*

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