Development of Data Quality Improvement Method for Hydrodynamic Model of Urban Drainage System Using GIS Capabilities

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***Abstract*—The pressure on urban drainage systems has increased in recent years due to population growth, urbanization, industrialization, and climate change. The rise in impervious surfaces, such as buildings, roads, and parking lots, as well as airports, ports, and logistics centers, exacerbates the situation. This situation can cause overflows, particularly downstream, as the increase in impervious surfaces leads to shorter periods for surface runoff to be collected and quickly diverted into the drainage system, resulting in large increases in peak flow rates. To plan the existing urban drainage system with current and accurate data using hydrodynamic model tools, it is essential to consider accurate and based on real conditions planning of urban drainage systems and the application of hydrodynamic models that can simplify complex structures into mathematical expressions. In this regard, Geographic Information Systems (GIS) are an effective method for the preparation of various input datasets in accordance with the format and precision required by the hydrodynamic models. This study proposed a methodological approach to prepare critical large-scale data for the hydrodynamic model set up in a GIS environment, aiming to improve the accuracy of analysis results and reflect the real-world situation. Through geospatial analysis and the use of GIS environmental capabilities, key input data, such as Digital Elevation Models (DEMs), land use, buildings' polygons, and catchment areas, were prepared to represent real-world conditions in the model scenarios. The prepared data in the GIS environment provide a detailed and precise representation of complex structures for mathematically realistic simulations. The main finding of this work highlights the importance of using geospatial analysis and GIS tools to prepare input data for hydrodynamic models of urban drainage systems, leading to improved accuracy and efficiency of urban drainage services.**

Keywords—Geographic Information System; sustainable urban drainage; urbanization; stormwater system; climate change.

I. Introduction

Accurate data that reflects real-world conditions play an important role in planning sustainable urban drainage systems. In metropolitan areas, population growth and unexpected urban development lead to increasing challenges, difficulties, or insufficient planning to meet the future demands of urban infrastructure services, such as urban drainage systems [1] [2] [3]. In line with this, the existing urban drainage systems need to be improved to comprehensively utilize the simulations of different complex and large-dimensional data to incorporate all the dynamics of the real situation.

Improvements of the physical data sets of the existing stormwater system (ground elevation, flow elevation, size, route, etc. of pipe and manhole system elements) and creeks (route, cross-section, profile, etc.) prior to the integration of these data into the hydrodynamic model are the subject of much more detailed studies. To this end, with engineering approaches the GIS environment is an efficient system for the preparation of input datasets in accordance with the format and precision required by the hydrodynamic models. With the improvement of the quality of input data and incorporation of hydrological information, hydraulic analysis of urban drainage systems can be efficiently performed. However, such analyses are generally performed on models of systems that are independent of each other. The hydrodynamic model and its hydraulic analysis are performed either for the Stormwater Collection System (SWCS) alone or for the creeks individually, and the system capacity and its dimensions are determined by the rainfall data used.

The hydraulic analyses may not always reflect the interaction with time according to the existing conditions in the model results due to the site characteristics. Accordingly, the analysis results either encounter over-design upstream and downstream of the system or insufficient sizing in the downstream portion. Furthermore, since the evolution of downstream conditions over time cannot be clearly defined in non-integrated models, it is difficult to obtain holistic simulations. However, in 2-Dimensional (2D) models, time-dependent and dynamic solutions of integrated holistic models of the stormwater collection system and creeks, the relationship of the systems with their environment can be analyzed in terms of time variables, especially by defining additional data reflecting real conditions to the models. In this way, mainly at the points where the systems are connected to each other (i.e., junctions), and towards the upstream or downstream impacts can be analyzed closer to the actual situation. Hence, the improvement of the data to quality and accuracy that can be integrated into the model, especially focusing on the required data for the hydrodynamic models, ensures the model's precision and effectiveness in reflecting the real condition. The important data include the physical data for stormwater and creeks, as well as hydrological inputs that are the main data for any 1D or 2D hydraulic models. The DEM with a certain precision, land use data including geometry and land use types, buildings' polygon, and surface

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water catchment areas are fundamental data for hydrodynamic models and thus for the efficient urban drainage system design and implementation.

The DEM data, which digitally represents the earth's surface topography, is used for many different purposes. One of the applications of DEM data is to create hydraulic or hydrodynamic models. The analysis of these models' results leads to obtaining different outputs for monitoring and investigation of the hydraulic and hydrologic process of the system, such as pipeline capacities, flood maps (flood extensions, depth, and velocity), etc. Hence, terrain data plays an important role in determining the accuracy of floodplains. Different methods are available for creating and obtaining the DEM data. One of them is Light Detection And Ranging (LiDAR) to make high-resolution maps for digital 3-D representations of areas on the earth's surface. It has been stated by various researchers that the floodplain maps derived from this dataset give much more accurate results than the maps obtained using other available topographic datasets in the world due to their very high resolution [4] [5] [6].

Land use maps, on the other hand, contain different information related to land, such as land use types and geometries, and are mainly obtained from the Coordination of Environmental Information (CORINE) land cover maps [7]. Land use maps provide geographic information on land cover, including land use/cover characteristics and changes, vegetation state, water cycle, and earth's surface energy variables, to a wide range of users in environmental terrestrial applications. In addition to these maps, some numerical boundaries should be integrated into the model in order to define the existing conditions in the hydrodynamic model.

The objective of this study was to enhance the accuracy and efficiency of urban drainage services by utilizing geospatial analysis and GIS tools to prepare input data for hydrodynamic models of urban drainage systems. Specifically, the study proposed a methodological approach to improve the physical data sets of the existing stormwater system and creeks prior to their integration into the hydrodynamic model. The remainder of the paper is structured as follows: Section II details the methodology employed to enhance the physical data, including its integration into the hydrodynamic model and preparation in the GIS environment. Section III highlights the significance and contributions of this work in improving hydrodynamic models for urban drainage systems, resulting in the provision of efficient and adequate urban drainage services.

II. METHODOLOGY

The impact of surface runoff on urban areas can be reduced through the implementation of Low Impact Development (LID) techniques and a Sustainable Urban Drainage System (SUDs), which integrate traditional drainage systems with LID methods. This approach will make urban areas more resilient and sustainable in the face of climate change and contribute to Water Sensitive City (WSC) targets and Integrated Urban Water Management (IUWM). Monitoring and evaluating the effectiveness of the SUDs is crucial for ensuring their long-term success. The preparation of input data for a hydrodynamic model using GIS capabilities involves several engineering approaches that aim to ensure the continuity of physical datasets from upstream to downstream. These methods resolve stability issues that may arise from using DEMs, prepare relevant hydrological and hydraulic parameters, such as rainfall patterns and runoff coefficients, and create design data, such as rainfall catchments. Hence, these techniques enable the hydrodynamic model to run smoothly and provide accurate results. Therefore, the focus of this study was to develop a method for improving the data quality of hydrodynamic models of urban drainage systems using GIS capabilities. The hydraulic modeling process for the assessment of the adequacy of existing stormwater collection systems and creeks includes the following steps.

- Transferring the physical data of the urban drainage system, including the stormwater collectors and creeks, which have been improved and of sufficient quality, to use in the hydraulic model.
- Definition of initial condition boundaries for each hydrological scenario.
- Definition of surface flow coefficients.
- Defining the surface roughness coefficient.
- Identification of the surface model (i.e., DEM).
- Definition of the land use map.
- Defining buildings' polygon to the model.
- Identification of sub-basins to the hydraulic program.
- Running the hydraulic model of the relevant basin.

In general, urban drainage system analyses are performed by integrating the data of the system into the model and defining the hydrological/hydraulic inputs. Whether the physical data for the system is obtained from relevant institutions or generated from classified data, these data are necessary to improve the quality and convert it into the appropriate format for entry into the hydrodynamic model. In the improvement of data quality and to ensure upstream-downstream continuity, the information of all system elements from the upstream of the system to the discharge point is transferred to the database. The next step in the setup of the model is the introduction of hydrologic data into the model, identifying initial conditions, such as rainfall intensity, and the collection time (time of concentration). By introducing surface discharge and roughness coefficients into the model as hydraulic parameters, the model setup process is completed at a level sufficient for a general analysis of the system. However, more precise planning is needed because of the global trend of planning for the WSC targets through the SUDs, an important pillar of IUWM, and the LID framework. Accordingly, for a sustainable urban drainage system, the actual conditions need to be defined mathematically in order to analyze the hydrodynamic model of the system more precisely. These inputs containing real conditions are primarily DEM data and land use maps, buildings' polygon, and catchment areas for the stormwater collection systems.

LiDAR data, which is used as a digital elevation model and includes precise elevation information of the earth's surface needed is important data for 3-D modeling the terrain features, such as buildings, transportation, flow channels, etc. The use of LiDAR data is to carry out accurate engineering calculations along with the analysis of the current situation, to plan the urban drainage system. For the analysis and planning of urban drainage systems, in addition to the surface digital model, land use data including land use type and geometric shape and their attribute information is required in the hydrodynamic model. The land use data provide the possibility to evaluate the results of the analysis based on the land utilization of the existing system. In order to define the actual condition of the terrain in the model, buildings' polygons representing the densest structures need to be integrated into the surface model along with land use data. In addition, the sub-basins, which form the accumulation areas of the superficial flow of rainfall, need also to be introduced into the model. The urban drainage system areas covered by rainfall and resulting runoff are defined in the model to accurately calculate the model's flow and to allow the model to identify the actual flow from the defined precipitation rate. The workflow schema for setting up and running the model is shown in Figure 1. The workflow diagram outlines the process from model setup to model runtime, and shows the datasets defined and integrated into the model.

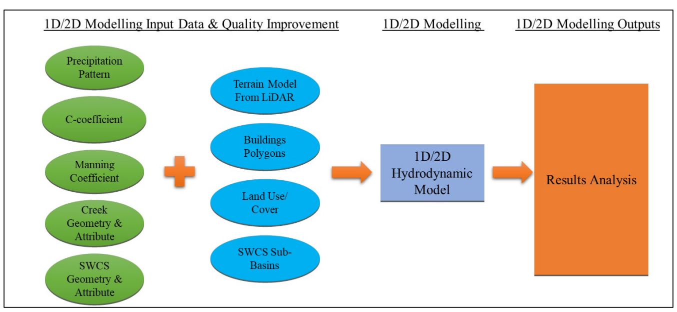

Figure 1. Workflow diagram for setting up and running a hydrodynamic model of an urban drainage system.

In the first stage of the urban drainage system modeling setup, the main inputs are rainfall patterns, runoff and roughness coefficients, and the physical data of the system, as indicated by the green clusters. For more accurate modeling results as specified earlier, the inputs that reveal the actual situation are shown in cyan color clusters (second stage) and include LiDAR, buildings' polygon, land use, and sub-basin areas. After the model setup, the process of running the hydrodynamic model includes both the optimizations in associating the model with the input data and the control and validation of the process steps in the input-run-outcome process (third stage). After all arrangements and controls, the results of the analysis are captured and interpreted for the urban drainage system planning (fourth stage). The procedures for preparing input data in a GIS environment prior to hydrodynamic model installation and processes are discussed in detail in the following sub-sections.

This study has performed the GIS operations and geospatial processing and analysis with the potential use of the open-source Quantum Geographic Information System (QGIS) [8] software.

A. Digital Elevation Model

In general, a DEM derived from any remote sensing data source represents the elevation of the bare ground surface, excluding features, such as buildings and trees. This is because the technology used to generate DEMs is primarily designed to capture elevation information of the ground surface, rather than the elevation of other features above the ground. However, with LiDAR data, it is possible to generate a DSM (Digital Surface Model) that includes the elevation of all features on the surface, including buildings and trees. The DSM can be derived from the same LiDAR data that is used to generate the DEM, by including all the points in the LiDAR point cloud, rather than just the ground points. It is important to note that while the DSM provides a more comprehensive representation of the surface, it may not be suitable for some applications that require the elevation of only the bare ground, such as hydrological or hydraulic modeling. In these cases, the DEM derived from LiDAR data needs to be modified and improved with the applied techniques.

Although the LiDAR data with a resolution of 0.25x0.25 meters provided in the study was perfectly well for the hydraulic model, however, this data was not used in both hardware and temporal terms due to its need for a very large memory capacity. Hence, the resolution of this data has been used for the urban area with a resolution of 2.00x2.00 m by various optimization processes. There have also been several procedures to reflect creeks on the surface model to calculate the superficial flow. For processing the rehabilitated creeks to the DEM, by using the required items (i.e., the starting end codes, cross-sections, and dimensions), the rehabilitated creeks' base and its slop guidelines (i.e., top and upper boundary lines) are defined according to the width, slop inclination and cross-section types. The height values of the points in the creek base are calculated along the creek, depending on the slope of the stream, by creating a point every 1 m on the lines. The values of the points on the upper slope and boundary lines on the slope of the creeks were calculated by determining the elevation at the relevant location, taking into account the base slope of the creek. LiDAR data was primarily converted into a point data type for each basin. Then, the points were deleted within the region up to the threshold value (50 cm) outside the outer part of the rehabilitated creeks (on-slope boundary lines). Points excluding these removal points are merged with the set of points created for the rehabilitated creek. As shown in Figure 2 the merged file is the final data to be used as a modified surface model to input to the hydrodynamic model.

B. Land Use Map

An assessment of an urban drainage system by overlapping an existing land-use map is a priority process. There are critical assessments of the impact of drainage systems

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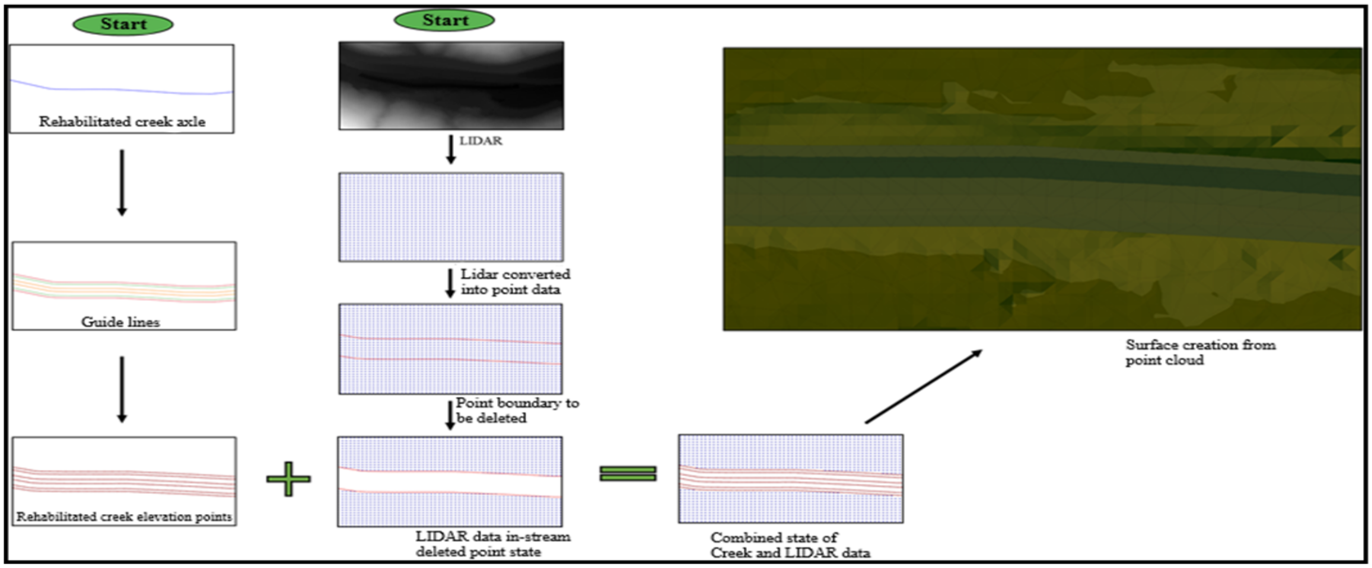

Figure 2. Surface model modification processes.

overlapping with land use, such as different types of settlements, industrial-commercial-public areas, infrastructure facilities, such as roads-ports-airports, and zoning plans involving different types of uses, such as agricultural and forest zones. In this study, the CORINE land cover map is used as the land use data. The analysis of how the extent of the land use boundary including the existing urban drainage system or the impact on the land use type in the model has been conducted through the GIS.

C. Buildings' Polygon

In the improvement process of buildings' polygons, which is an important input to the model, topological analysis is performed first. In these analyses, the ”must not overlap”, ”must not have gaps”, and ”must not have duplicates” rules were applied. Without these corrections, the meshing process produces a large number of triangles formed in small areas of geometrically and hydraulically insignificant dimensions, including small areas that cannot be detected easily. Hence, it maximizes the meshing time and modeling time, distorts modeling stability, and may even cause the model to fail. There is no existing ready-made GIS application or plugin to eliminate errors detected in the analysis. For this reason, the ”Aggregate”, ”Simplification” and ”Deleting Holes” functions were used in GIS for the buildings' polygon dataset. The detailed specifications of the ”Aggregate”, ”Simplification” and ”Deleting Holes” functions for buildings' polygons are provided below.

Buildings that are too close together cause small triangles during the meshing process. In the experiments, it has been seen that it is necessary to simplify the buildings closer than 2 m, which do not cross streets, into a single polygon. To this end, different GIS methods have been applied, however, the ”Aggregate Polygons” process has resulted in favorable results. In order to convert the shortest side of the building into two or three cells, the cell size should be small enough. The values of the input cells encompassed by the coarser output cells are aggregated by one of the maximum, minimum, mean, median, and sum statistics for the input cells' value. No data values were ignored by the aggregation calculation.

The ”Simplification of polygons” as the generalization operation of the boundaries was used to remove the extraneous bends and small intrusions and extrusions from the buildings' polygon boundaries without destroying their essential shape. The ”Point remove” and ”Bend simplify” algorithms were applied for non-orthogonal polygon boundaries. The ”Point remove” is efficient for data compression and for eliminating redundant details; however, the line that results may contain sharp angles and spikes that reduce the cartographic quality of the line. The ”Point remove” algorithm is used for compression or small amounts of data reduction and when high cartographic quality is not needed. The ”Bend simplify” was applied for shape recognition to detect bends, analyze their characteristics, and eliminate insignificant ones. In this method, a bend that's too narrow is widened slightly to satisfy the tolerance. The resulting line is more faithful to the original and provides better cartographic quality. In order to achieve the minimum triangle size of the mesh, it needs to reduce the number of fractures on the buildings' polygon without distorting their shape. Simplifying buildings' polygon is used for reducing the detail at the boundaries of buildings while maintaining the basic shape and size of the buildings. Buildings are usually rectangular areas; therefore, the simplification process preserves and maximizes rectangularity. Each individual building itself has been simplified. Buildings connected by straight lines were not simplified as a group but on the whole boundary of a building. Thereby, this method describes buildings as topologically discrete, connected by straight lines close to parallel to each other, and connected by more complex paths.

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The boundaries of discrete buildings or buildings connected by straight lines were modified so that all angles close to 90 degrees still remained exactly 90 degrees. Some edges were smoothed, reducing the number of fractures, but the areas remain roughly the same as the original [9]. The maximum degree of simplification is reached when a building is reduced to a quadrilateral. Once the simplification tolerance is relatively large relative to the size of the building, the building is simplified directly to a rectangle centered on its center of gravity, but the area remains the same. The sides of the resulting rectangle are in the same ratio as the sides of the bounding box aligned to the longest side of the original building.

Areas between buildings or adjacent building blocks are considered as the terrain surface in the model and if these gaps are not cleared before being imported to the model, during the meshing, the model fills these gaps with triangles. accordingly, these areas are going to fill up like puddles during modeling. In order to avoid this problem, it has been accepted to include these spaces as building areas. For this process, the holes were deleted or filled using a GIS operator called ”Deleting holes”. This operator generates a new output feature class containing the features from the input polygons with some parts or holes of a specified size deleted and exploded into single parts. The ”Deleting Holes” operator combines both of the above functionalities which can optionally specify a maximum area of hole to delete. In this algorithm, the maximum area parameter refers to the maximum size of the hole to be filled. Hence, an optional minimum area parameter allows only holes smaller than a certain area threshold to be removed. For instance, leaving this parameter at 0.0 the algorithm removes all hole sizes. An example of the described generalization of buildings' polygon is shown in Figure 3.

Figure 3. Illustration of used GIS operations to buildings' polygon data quality improvements and their results for the sample dataset. (a) Original data, (b) the aggregated polygons, (c) simplified polygons, and (d) deleted holes from the buildings' polygon.

Therefore, the created new output data created from the outer boundaries contained polygons of filled holes with preserved attributes of the data. The resulting polygons were then manually checked and loaded into the hydrodynamic model.

D. Water Collection Catchments

In a 2D hydrodynamic model for analysis of an urban drainage system involving major stormwater collection lines and creeks, modeling can be performed on a macro-scale with only the terrain model and urban drainage systems without additional definitions of terrain specifications. However, the use of large basins in 2d modeling to avoid the impact of minor network pipes not entering the model, and therefore, using large basins as sub-basins in 2d modeling in the planning of a micro-scale urban drainage system provides more detailed and realistic results. For this, different tools and plugins are used (e.g., SWAT, SWAT+, ArcGIS Hydrographic Tools, SAGA Terrain Analysis- Hydrology, etc.) prior to running the hydrodynamic model.

The delineation of sub-basins is a time-intensive process that requires a high level of computing capacity due to the size of the surface model data and the abundance of components. Figure 4 shows the terrain surface model improved from LiDAR data (right) and the system's physical data defined in the hydrodynamic model including stormwater collection systems (i.e., pipelines networks) and delineated sub-basins and collection basins by Voronoi (Thiessen) polygon's method in the GIS environment (left).

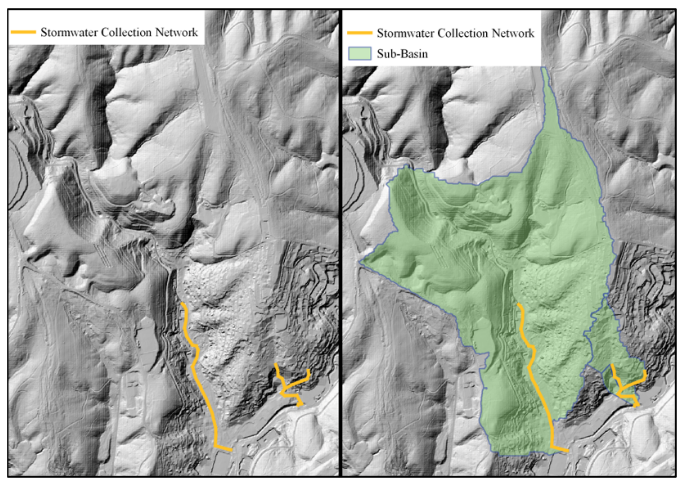

Figure 4. Example of a sub-basin delineated with SWAT+ plugin.

In this study, the delineation of sub-basin boundaries was mainly carried out on QGIS, an open-source GIS software, and through its compatible hydrological processing and analysis plugin called SWAT+ [9]. In the delineation process, the improved DEM data (i.e., eliminated above-ground features) derived from LiDAR data was used as the surface model. In the sub-basin delineation procedure, the outlets and discharge points, the definition of upstream-downstream continuity in physical data, and the stormwater collection system (the program considers the stormwater collection system as a streamline) are also introduced to the model allowing the program to establish sub-basin boundaries accordingly. In

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order to distribute the incoming flow to the manholes, the delineated basins were divided also into collection basins of manholes by Voronoi (Thiessen) polygon's method which is also available in QGIS [8].

E. Mesh Corrections Based on the Buildings' Geometry

Buildings are not located within stormwater collection systems and the building's polygons have been excluded from the calculation since the building's polygons are defined as void and without meshing as shown in Figure 5 (left). Hence, the buildings' geometries needed to be defined in the model as a component of the stormwater collection systems. In other words, each building's block is introduced into the model using GIS as a discrete catchment. Additionally, to transfer the roof rain waters to the surface mesh, as shown in Figure 5 (right), the buildings' roof drainage points are defined and the outlet flow elevations were adjusted to form a 1/100 slope depending on the mesh elevation code. Therefore, by using this method the buildings' polygons have been defined to be considered in the hydrodynamic analysis. Mesh Corrections Based on the buildings' geometry and definition of buildings' roof drainage points to the model. Figure 5 shows the building's polygons as void and without meshing (left), and the definition of buildings' geometries in the model as the component of the stormwater collection systems (right).

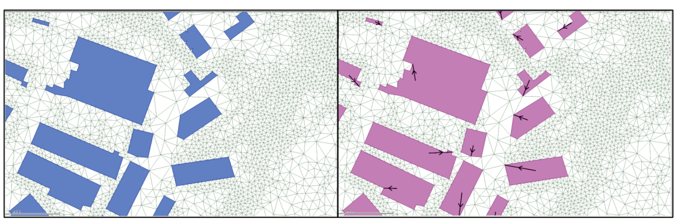

Figure 5. Mesh corrections for buildings' geometries.

The symbols with black lines and arrows in Figure 5 (left) are indicating the buildings' roof water drainage points on each building's block, and the outlet flow to transfer the roof rain waters to the closest surface mesh.

III. CONCLUSION

The achievement of long-term planning and sustainable stormwater management systems in terms of environmental, and economic to ensure adequate and efficient urban drainage services is important in order to adapt to today's fast-growing conditions. In terms of sustainable management practices, precise planning with accurate and actual data that represents reality needs to be targeted throughout the engineering, administrative and economic measures for the continuity of service quality in which investment and operation strategies are in accordance with the smart city concept. To meet the needs of urban drainage systems to adapt to the predicted circumstances and changes that vary depending on the population growth trend, fast development of cities, and climate change issues, It is appropriate to conduct an analysis of the actual situation of the system. In this framework, it is necessary to use a hydrodynamic simulation to take into account integrated and dynamic conditions, as well as to ensure that the existing system's data are correctly and appropriately defined in the model. This study presented a methodological approach to the preparation of important large-dimensional data in the setup of a hydrodynamic model to reflect the actual conditions and achieve more precise analysis results. In this regard, the high potential use of GIS and its capabilities as well as geospatial processing and analysis in a GIS environment play an important role in performing data preparation and quality improvement. Therefore, the development of a methodological approach for the preparation of accurate data as the input of the hydrodynamic models of urban drainage systems, using GIS capabilities ensures adequate and efficient urban drainage services to adapt to the fast-growing conditions in a metropolitan city.

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