Multi-source spatial-temporal information fusion for urbanized watershed flood hazard risk assessment

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Abstract. Urbanization is taking place rapidly in developing countries. There are many problems of urbanization, and flood hazard is one of the serious problems. Flooding events and hydrologic process are complex in urbanized watershed. Current methods for urbanized watershed flood hazard risk assessment exist shortage. With the advance of observation technology and geographic information system technology, the multi-source spatial-temporal data have been collected increasingly. The data driven methods have provided a potential solution for the complex urbanized watershed flood hazard risk assessment. The paper has discussed the complexity of urbanized watershed flood hazard. The framework of observation based modeling of urbanized watershed flood hazard risk assessment has been given. Multi-source spatial-temporal information fusion approach for watershed flood hazard risk assessment has been discussed. A case of Hanyang urbanized watershed has been developed based on the multi-source information fusion method of local weighted linear combination.

1. Introduction

Urbanization is taking place rapidly in developing countries. Mega regions in China, such as Pearl river delta, Yangtze river delta, have been rapidly developed into metropolitan area. Urbanization in flood plain areas increases the risk of flooding due to increased peak discharge and volume, and decreased time to peak [1]. Urban flood problems have been well studied in many countries. However, urban watershed flood modeling is complex because of climate change and uncertainty, land use change, and there are technical problems in urban flood design [2, 3].

Several urbanized watershed flood models, such as SWMM and HEC-HMS, exist shortages of considering both urban storm drainage systems and natural hydrological phenomena. Urbanized watershed, generally includes cities, sub-urban area and natural watershed, and storm water flood and river flood may be coexist.

Spatial-temporal data for urban watershed have been rapidly collected by the new observation technology, such as remote sensing for precipitation and land use change, in situ observation, Internet of Things and GIS database. Data driven approach has provided a potential method for urbanized watershed flood hazard risk assessment.

The paper will discus the flood hazard risk problems and the complexity of urbanized watershed, presented the factors in observation and modeling of urbanized watershed flood hazard risk. The framework of multi-sources information fusion for urbanized watershed flood hazard risk assessment and methods will be given. Finally, the case of study of Hanyang urban watershed will be given based on the proposed approach. The following of the paper is organized as Section 2 the floods hazard of urbanized watershed, Section 3 the multi-source spatial-temporal information fusion for urbanized
watershed flood assessment, Section 4 the case study of Hanyang of Wuhan urbanized watershed, and finally the conclusion.

2. Floods hazard of urbanized watershed
There exist the problems of complexity of urbanized watershed flood. How to model and assess the urbanized watershed flood hazard risk are still a challenge task. We will discuss these problems and propose observation and multi-source data based methods.

2.1. Urbanized watershed and complexity of floods process
The concept of urbanized watershed is different from urbanization, the water cycle and hydrologic processes are the main problems of urbanized watershed. We will discuss about the concept of urbanized watershed, and the problems of hydrologic process complexity and flood design.

2.1.1. Urbanized watershed.
There is no simple definition of what constitutes an urban catchment. The impervious cover percentage are often used as the basis of the definition of urban catchments. However, literature-based values of the impervious cover percentage can significantly vary, ranging from 5% to 98% [2]. So, several factors of urbanized watershed are discussed [2], including (1) housing and population density in relation to the catchment size; (2) high percentage of the catchment area covered by housing and industries; (3) modification of rivers; (4) high impervious coverage; (5) high pollution of river water quality; (6) wastewater treatment facilities. Urbanization has changed the landscape of natural watershed.

Urbanization affects catchment in many aspects, such as watershed water quality and environment, ecology, and flood hazard. An urban catchment constitutes of a high heterogeneous mixture of natural and artificial surface covers. From the view of watershed flood hazard risk analysis, the natural and anthropogenic-modified processes interact with each other are illustrated in figure 1 (adapted from [2]).

2.1.2. Complexity of floods processes of urbanized watershed
Hydrologic process of urbanized watershed flood hazard is complex. Urban areas face global challenges of flood risk not only due to climate change but also due to the continued densification of residential areas, infrastructure development, and urban sprawl [4].

Hydrological modelling of urban catchments is highly challenging as urban catchments are strongly heterogeneous and have very specific hydrological processes. The circulation of rainwater within
urban areas has not yet been described in a detailed manner, as studies on this topic often remain limited to the runoff on impervious surfaces. There is little agreement so far on a universal concept or methodology for simulating the urban water cycle at the catchment scale [2].

2.1.3. The problem of urban flood design
On the other hand, there are technical problems in urban flood design. The frequency of surface flooding for storm sewers is not a design criterion, is often not known, and will vary greatly for different systems. There has been a lack of technical capability to address this problem [3].

But in the past few years, models have been developed to represent the surface routing of overland flows, and associated storm sewer interactions, supported by high resolution topographic data, for example from LIDAR airborne remote sensing systems [3]. This offers exciting potential for a paradigm shift in the design of the urban environment to manage flood risk.

However, climate change of urbanized watershed has uncertainty. Many studies tried to quantify urban-induced changes in precipitation by comparing pre and post urbanization conditions and concluded that seasonal changes locally increased the precipitation between 5% and 15% [2]. However, these estimates have a high degree of uncertainty due to the scarce data and the non-quantifiable impact of other atmospheric processes.

2.2. Observation and modeling of urbanized watershed flood hazard risk
Urbanized watershed include high degree developed catchment with natural hydrology and complex human activity. And different types of flood hazards exist, such as urban flooding caused by local intensity precipitation (Pluvial flood) and urban flooding caused by high flows in adjacent river systems (fluvial flood). Though the complexity of hydrologic processes of urbanized watershed flood exists, there are several models could be used for urbanized catchment modeling, such as SWMM (Storm Water Management Model), HEC-HMS (Hydrologic Engineering Center’s Hydrologic Modeling System), etc. [5, 6].

SWMM is a city scale flood analysis and modeling tool, which has rigorous formulation of hydraulic principles for surface runoff, storm drainage systems, and sewers. However, natural hydrological phenomena are less rigorously treated; the application of SWMM is small-city scale [2]. HEC-HMS could be used for natural watershed or catchment flood analysis and modeling. However, HEC-HMS has Limited treatment of artificial pathways (sewers, stormwater system, water supply, etc.). The Application of HEC-HMS is catchment scale [2].

With the rapid development of remote sensing observation, ground based observation (in situ station, Internet of Things), and GIS database, the data driven methods provide powerful potential for urbanized watershed flood hazard assessment. We give a data driven multi-source data fusion procedure for urbanized watershed flood hazard risk assessment and modeling, and the framework is shown in the figure 2.
First, the factors of urbanized watershed flood modeling are presented, including catchment factors (such as land cover, topography, river, soil type and precipitation, etc.) and urbanization factors (such as land use, impervious area, drainage, modification of rivers, dike, etc.).

Second, the observation and measurement by remote sensing, in situ observation, and GIS database will provide data about the flood related factors, processes and pattern of catchment and urbanization.

Third, based on the multi-source observation data, data integration and multi-attribute fusion algorithm (or aggregation operators) are employed for flood hazard assessment. Data integration (linkage) involves combining data residing in different sources and providing users with a unified view of them. Multi-attribute fusion algorithm, such as weighted linear combination operator, will be discussed in the paper.

3. Multi-source spatial-temporal information fusion for urbanized watershed flood assessment

3.1. Multi-sources information fusion

Data fusion is a wide concept and several definitions have been proposed in the literature [7]. In data integration of heterogeneous database, data fusion is the process of fusing multiple records representing the same real-world object into a single, consistent, and clean representation [8]. In target recognition and monitoring with multisensory from military applications to nonmilitary applications, data fusion techniques combine data from multiple sensors, and related information from associated databases, to achieve improved accuracies and more specific inferences than could be achieved by the use of a single sensor alone [9]. In the decision making process for rating and ranking alternatives, Information fusion is defined as methods to combine data or information supplied by multiple sources, and aggregation operators are some of the functions that can be used for combining data [10].

In general, we can say that “Data Fusion” is any process of aggregating data from multiple sources into a single composite with higher information quality [7] or with the final goal of rating and ranking alternatives [11]. It can be viewed from different perspectives by different domains, being the most common branches: image fusion, multi-sensor fusion and information fusion [12].

Different from military application of multi-sensor data fusion with the goal of improving information quality, the information fusion for urbanized watershed flood assessment has the goal of rating and ranking flood hazard risk alternatives from multi-source data.
Aggregation of several input values into a single output value is an indispensable tool in many disciplines and applications, such as fuzzy rule based systems, pattern recognition, expert and decision support systems, multi-criteria decision, information retrieval, decision making, etc. [13,14,15].

The well-known classical aggregation (combination) operators (functions) include: averaging functions, conjunctive and disjunctive functions, generalized mean methods (e.g. weighted sum and weighted product), outranking methods (e.g. conjunctive method), mixed functions, and the pairwise comparison methods [16,17].

The most used methods for multiple attributes aggregation include weighted linear combination [18] and Ordered Weighted Averaging [19].

Combination procedure of multi-source information is that associates with the ith decision alternative (location) a set of criterion weights, \( w_1, w_2, ..., w_n \), and combines the weights with the criterion (attribute) values, \( a_{i1}, a_{i2}, ..., a_{in} \), \( (i = 1, 2, ..., m) \). A weighted linear combination operator is defined as follows:

\[
V(A_i) = \sum_{k=1}^{n} w_k v(a_{ik})
\]

where \( V(A_i) \) is the overall value of the alternative at location \( i \).

We give a multi-source information fusion architecture for urbanized watershed flood hazard risk assessment based on multiple attributes aggregation, as shown in figure 3.

3.2. Multi-sources information fusion for urbanized watershed flood hazard risk assessment

According to the discussion of the catchment factors and urban factors of urbanized watershed flood hazard risk, the multi-sources data collection about those factors includes following:

1) Rainfall and water regime information: i.e. 12-hours precipitation and river water level (high, low)

2) DEM and flow data: elevation, slope, TWI (Topographic Wetness Index), flow accumulation, Depression point density

3) Land use/land cover: Land use, cover, soil type, SCS-CN (Soil Conservation Service-curve number), impervious area.

4) Urban flood defense: dike protection area (yes, no), pumping/drainage density, pump station distance, river distance,

The procedure of multi-source spatial-temporal information for urbanized watershed flood hazard risk assessment is show as figure 4.
Local Weighted Linear Combination (WLC) is used as an adaptive aggregation operator of multi-source information fusion.

Given the local criterion weight, $w_k^q$, defined on the basis of the range-sensitive principle, the local weighted linear combination can be written as follows [20]:

$$V(A_i^q) = \sum_{k=1}^{n} w_k^q v(a_{ik})$$ (2)

where $V(A_i^q)$ is the overall value of the i-th alternative estimated locally (in the q-th subregion), $v(a_{ik})$ is the value of the k-th criterion measured by means of the local value function in the q-th subregion, and $w_k^q$ is the local criterion weight.

4. Case study of Hanyang of Wuhan urbanized watershed

Wuhan is located as the central area of China with the crossover of Yangtze river and Hanjiang river. The city rainstorm flood and river flood happened frequently. In the case, the urbanized watershed of Hanyang, located at the west of Wuhan, has been selected for test. The location of Hanyang is shown in figure 5.
According to the available dataset, we collected the data of the case study area, including the data set of DEM, land use/land cover, and city flood defense. The features of catchment and urban factors of urbanized watershed flood risk are extracted and normalized according to the aggregation procedure of local weighted linear combination. The normalized multiple criteria are shown in figure 6.

![Figure 6. Normalization of multiple criteria value](image)

Based on multiple criteria value of figure 6 and local weighted linear combination methods, the urbanized watershed flood hazard risk of Hanyang has been assessed (as shown in figure 7). The weights of the criteria are determined by AHP (analytic hierarchy process) approach. The assessment results of urbanized watershed flood hazard risk are represented as five grades: Very high, High, Moderate, Low, Very low. We have compared 38 past records of history flood inundated points, about 70% of the inundated points are located in the area with the “Very high” and “High” grade.

![Figure 7. Flood hazard risk map based on local weighted linear combination](image)
5. Conclusion
Urbanized watershed hydrologic modeling is complex because of climate change and urban catchments are strongly heterogeneous and have very specific hydrological processes. On the other hand, there are technical problems in urban flood design. The frequency of surface flooding for storm sewers is often not known, and will vary greatly for different systems.

Currently, there exist shortages of SWMM and HEC-HMS for urbanized watershed flood modeling. SWMM is based on rigorous formulation of hydraulic principles for surface runoff, storm drainage systems, sewers, and natural hydrological phenomena are less rigorously treated. HEC-HMS has limited treatment of artificial pathways.

With the advance of observation and measurement technology, remote sensing, in situ observation and GIS database have provided multi-source spatial-temporal data. The multi-source information fusion approach has provided a potential and valuable method for urbanized watershed flood hazard risk assessment. The paper has given the framework of observation and modeling of urbanized watershed flood hazard risk and multi-source information fusion procedure for urbanized watershed flood hazard assessment. The case of Hangyang urbanized watershed is tested based on the proposed approach, and the results are good compared with the historic flood records.

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