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Article

Seamlessly Coupling Hydrological Modelling Systems and GIS through Object-Oriented Programming

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Abstract: Coupling hydrological modelling systems (HMS) with a geographic information system (GIS) can significantly enhance hydrological research and expand its applications. The calculation for HMS requires geographic information data; however, the current GIS data structure is not equipped to support the object-oriented hydrological modelling. Due to different objectives and design concepts, the differences between HMS and GIS have been profound, especially in their data structures from the perspective of object-oriented programming (OOP). This research introduces a novel approach to extend ArcGIS data structures for HMS, facilitating seamless coupling. This approach employs Microsoft Component Object Model (COM) technology to construct custom data structures that align with hydrological OOP principles. These can then be integrated into ArcGIS through a custom ArcGIS layer as an add-on. As a result, the HMS can leverage the full functionality of ArcGIS without the need for re-coding existing modelling systems. Moreover, HMS can be readily developed by using COM compatible computer languages, enabling the easy adaptation of this coupling approach to other HMS to ensure computational efficiency and to maximise the benefits of ArcGIS features. This new approach has been successfully implemented with the Xin'anjiang model, and the results validate its effectiveness in coastal areas.

Keywords: hydrologic model systems; ArcGIS; custom data structures; COM technology; add-on technology



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1. Introduction

Nearly all countries have been suffering from water pollution and water shortage problems in their coastal ecosystems (e.g., [1,2]). Hydrological models have become crucial tools for understanding and modelling water movement and storage at local, regional and global scales. Especially in recent decades, tremendous efforts have been made for the development of physical-based and spatial-distributed hydrological models to advance more sophisticated and comprehensive hydrological studies (e.g., [3,4]), which requires a vast amount of geological, meteorological, and geographical data across a range of space-time scales (e.g., [4]). Consequently, a key challenge in the development and application of physical-based spatial-distributed hydrological models is how to efficiently incorporate the spatial datasets into the modelling systems and manage them more effectively (e.g., [5]).

Since hydrological systems are essentially spatial variants, modern GIS naturally becomes the most appropriate tool for data acquisition, storage, and processing, as well as the analysis and display of results (e.g., [6,7]). Several methods for integrating hydrological models and GIS have been explored by scholars (e.g., [8]), and they can be categorised into three types (e.g., [9,10]). The first type is Loose Integration (LI), in which hydrological modelling systems and GIS are developed and executed separately, and communicated offline with each other through intermediate data files such as the ASCII files (e.g., [11–14]). The second type is Embedded Integration (EI), in which hydrological models are coded with

built-in the macro or scripting language of GIS and executed within GIS as a sub-component (e.g., [15–18]). The third type is Full Integration (FI), in which hydrological models are coded with high-level programming languages (e.g., [19,20]) and fully integrated with GIS as packed Dynamic Link Libraries (DLLs).

In contrast to the other integration strategies, the development of the PIHMgis framework is notable in the sense that it introduced an advanced coupling strategy, which was achieved by a shared data model between open source GIS (QGIS, <http://www.qgis.org> accessed on 3 November 2023) and Penn State Integrated Hydrologic Model (PIHM) (e.g., [5,21,22]). Obviously, data access is the first challenge in integrating GIS and hydrological models (e.g., [23]). Due to the different objectives and design concepts, differences between data structures in hydrological models and GIS are remarkable. For example, existing hydrological models have been developed according to hydrologic data structures that are different from GIS data models and are difficult to be accepted by modern GIS platforms directly (e.g., [22]). Nevertheless, from a hydrologist's perspective, integrating model-compatible data structures into a robust GIS framework can streamline the coupling between GIS and hydrological models, leading to great advancements. When constructing and calculating a hydrologic model, it is necessary to establish a correlation between the actual state of its foundational elements and their mathematical abstraction. Geographically, watersheds are composed of basic elements, like points, lines, and planes. Yet, when layers in a GIS are employed to topologically connect these basic elements, the cohesive operation of model objects is not always assured. In such instances, it becomes imperative to assemble the basic elements—points, lines, and surfaces—into a singular object with an inherent hydrological connection.

In this study, we developed a new approach to couple the widely used ArcGIS with hydrological modelling systems (HMSs) by developing a new custom and extensible GIS feature (hereafter referred to as HydroFeature) suitable for the needs of HMSs. By analysing common data structures of hydrological models following Object-oriented Programming (OOP), a Microsoft Component Object Model (COM)-based general HydroFeature was introduced at first, which can be merged into the ArcGIS framework by a custom ArcGIS layer (hereafter referred to as HydroLayer) as an add-on. In the construction and computation of the hydrological model, it is essential to incorporate not just the fundamental geographic data but also to establish seamless links among the basic elements of the hydrological model. This ensures that operators can view the model holistically, rather than merely from point, line, and surface perspectives. Consequently, integrating object-oriented approaches from computer science into complex hydrological models has proven invaluable. In this way, the HMS can take advantage of ArcGIS and, at the same time, keep it easy to be understood by hydrologists. Furthermore, HMSs either were or can be easily developed by COM compatible computer languages, which warrants the easy transfer of the coupling method developed in this study to any other hydrological modelling system. Compared to other coupling strategies, the one introduced in this research has the following characteristics: (1) the COM technology is employed so that it is not limited to specific computer language; and (2) a general idea to couple HMS with commercial ArcGIS is presented, which is not designed for specific models and can be extended easily. As an example, the Xin'anjiang model was selected as a real application to illustrate how to build a real model feature and establish the entire modelling process.

The rest of the paper is organised as follows: Section 2 gives details about the COM interfaces and implementing procedures of general HydroFeature, HydroLayer and HydroRenderer; Section 3 shows the real application of the introduced method by tightly coupling the Xin'anjiang model with ArcGIS; and finally, Section 4 discusses the merits and further development directions of this new coupling method.

2. Methods

2.1. ArcGIS and COM Technology

ArcGIS, as a powerful GIS platform, provides different products, such as Arc Hydro tools to support hydrologic modelling (e.g., [24]). ArcGIS 10.2 (ESRI, Redlands, CA, USA) was used in this research. The tool packages contained in Arc Hydro can delineate catchments and analyse hydro-geometric networks, which facilitate the representation of HydroFeature within the ArcGIS environment (e.g., [24,25]). The excellent work of Arc Hydro tools is useful for hydrological studies (e.g., [26]) and will be used as a pre-processing tool in this research. Arc Hydro tools were developed using COM technology and plugged into ArcGIS as an add-on. COM is a standard that enhances software interoperability using the binary unit of reusable code (e.g., [27]) and allows for different software coded in different programming languages to communicate with each other directly (e.g., [28]). Furthermore, COM encapsulates all properties and methods internally and can only be exposed to the outside by several well-defined interfaces. The high encapsulation of COM essentially allows the components to become self-contained building blocks that can be assembled into larger systems (e.g., [23]) and be reused at the binary level; thus, third-party developers do not require source codes or object libraries in order to extend the system (e.g., [29]). As the core technology of ArcGIS platform, COM has been applied to nearly all aspects of the software, such as graphical user interface (GUI), display module, and geometry module, making it extendible. Having benefited from the COM standard and open architecture of ArcGIS platform, hydrological data structures designed in this study can be easily integrated into the ArcGIS platform.

To enable the tight coupling between ArcGIS and hydrological models, we first extended the feature classes of ArcGIS by developing a new custom and extendible feature that is suitable for a hydrological model. Because HydroFeature is not accepted by any existing layer in ArcGIS, including FeatureLayer, TinLayer, and RasterLayer (e.g., [30]), a HydroLayer is therefore constructed as the container of the HydroFeatures. Then, an all-purpose HydroFeature that can hold arbitrary data structures is designed and added to the HydroLayer. Meanwhile, the visibility and aesthetics of HydroFeature and HydroLayer were implemented by introducing a HydroRenderer. As an example, a feature consistent with the Xin'anjiang model (e.g., [31]) was set up by extending the introduced HydroFeature, and the model ran and displayed results in ArcGIS. It is noted that the principle of the Xin'anjiang model itself is not the focus of this paper. The model results shown in this research were neither calibrated nor validated against field observations and were just used to explain how to realise the coupling between HMS and ArcGIS through the new approach developed in this research. The method exhibited here can be used in other types of modelling systems, e.g., hydrodynamics modelling systems and water quality modelling systems, as long as appropriate disciplinary feature data structures are defined using the same method shown in this study.

2.2. Coupling Method

2.2.1. Defining HydroFeature and HydroLayer

The data in hydrological models cannot be simply expressed as points, polylines, polygons, or other fundamental vector elements in ArcGIS. From the state-of-the-art concepts of OOP, the whole watershed can be regarded as a single entity, which includes basin boundaries, sub-basins, channels, and others. Even by treating sub-basins as polygons and channels as polylines, a watershed entity is still a complex feature. According to this analysis, there are two kinds of features in hydrological models. The first one is a simple feature, which is a basic entity and cannot be divided any more. For example, a sub-basin can be treated as one polygon, while a river channel can be regarded as one polyline. The second feature is a combined feature and contains several simple features. For instance, the watershed feature is of this kind and comprises several simple features.

Since COM solely interacts with external objects through interfaces, designing interfaces for HMS is imperative for integrating HMS and ArcGIS. The interfaces design should

be a thoughtful and visionary work, which should be able to handle unforeseen situations. In order to meet the requirements, the abstract design of interfaces for custom hydrological feature must follow several rules: (1) it must be consistent with Microsoft's COM specification; (2) it need to contain the common properties of different model data structures; and (3) it cannot be specially designed for any specific model. Following these rules, two interfaces are designed first for simple features and combined features, respectively. A simple feature interface only contains a simple geometry (one type of point, polyline, polygon, etc.), which should at least include a unique ID for differentiating various HydroFeatures in a HydroLayer, a name for labelling a HydroFeature, and a geometry for identifying its geographical type. Since parameters of hydrological models are associated with features, these parameters are also managed by related simple features. Therefore, a simple feature interface should also include methods for getting and setting model parameter values. Due to the fact that a combined feature is the representation of the whole data in the hydrological models, it is obvious that it also includes the characteristics of a simple feature. Besides those, one collection interface needs to be presented for the sake of assembling different kinds of simple features into a combined feature. This interface should include some methods for manipulating contained simple features, such as adding features, removing features, getting feature count, etc. After interfaces are designed, the architectures of a simple feature and a combined feature are easy to understand with the help of OOP. An instance of a simple feature must inherit from the simple feature interface and implement all functions defined in that interface. In a similar manner, an instance of a combined feature must inherit from both the simple feature interface and the collection interface simultaneously and implement them all. The implementation detail of the two instances is associated with the specific computer language, but the ideas and methods are the same. All design templates in this research follow the Unified Modelling Language (UML) specification (e.g., [32]), through which the interfaces and instances of HydroFeature and their interrelations are shown in Figure 1.

The parameters of hydrological models in the "ISimpleHydroFeature" interface are managed by two functions ("GetParameter" and "SetParameter") using key-value pairs, which is different from the way used in embedded the ArcGIS feature (managed by table) and is easy to understand for model developers. The instance of "SimpleHydroFeature" implements both the "ISimpleHydroFeature" interface and "IPersistStream" interface, with the latter having been designed by Microsoft for persisting objects to disk. For the sake of simplicity, the functions in "IPersistStream" interface are not listed. The geography of HydroFeature takes advantage of "IGeometry" interface design by ESRI, which is compatible with the ArcGIS platform and is the bridge between HydroFeatures and the platform.

As a feature of hydrological model itself, the instance of "CombinedHydroFeature" not only inherits from "ISimpleHydroFeature" and "IPersistStream", but also implements the collection type "IFeatureCollection" interface. It is worth noting that the functions for management in this interface are designed explicitly due to it consisting of many simple features of different categories. Taking the Xin'anjiang model as an example, the sub-basins can be categorised as a string "sub-basin", and channels can be categorised as a string "channel"; in this way, one can easily and effectively manage all sub-features. This is the reason for the parameter named "strCate: string" in some functions of the "IFeatureCollection" interface.

Though HydroFeatures have been designed following the COM standard, ArcGIS cannot accept them directly. The best solution for this challenge is to create a HydroLayer for these features. According to ESRI specification (e.g., [33]), a layer is a basic element in ArcGIS and can be customised if specific rules are obeyed. Here, we show how a HydroLayer can be specially designed for HydroFeatures. The main role of the HydroLayer is to plug these newly defined features into the ArcGIS platform and control their lifespans in the platform. Designing the HydroLayer interface is the first step. The interface is a collection style, in which there are functions for adding, removing, and operating features. Different from the simple instances of HydroFeatures, the implementation of a HydroLayer

is more difficult and challenging. ESRI specification has established many rules for creating a valid HydroLayer. A HydroLayer must inherit from some specific interfaces designed by ESRI in order to become an acceptable layer in the ArcGIS platform. Fortunately, there are exhaustively detailed samples and documents in ESRI specifications on creating a HydroLayer (e.g., [33]). In addition to these necessary interfaces, the HydroLayer interface and the persisting purpose interface “IPersistStream” are also essential in the implementation. When the instance of a HydroLayer is completed, it can control the all-purpose HydroFeatures in the layer, which are unrelated to specific hydrological models.

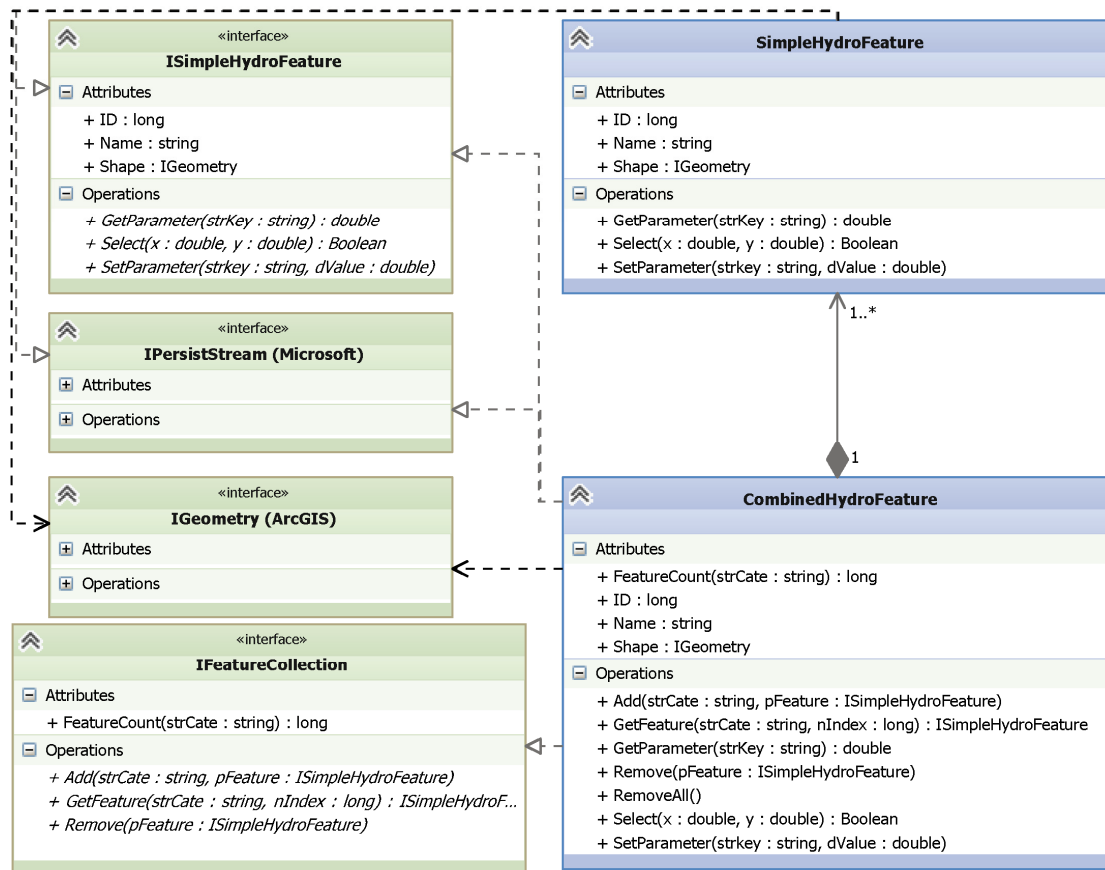


Figure 1. Class diagram of the simple HydroFeature and combined HydroFeature. * is a number greater than or equal to one, so 1..* means from one to many objects.

Another problem is how to show and operate the HydroLayer with features after it is added to the ArcGIS platform. Since our HydroFeatures are not the embedded features of ArcGIS, the platform cannot render and operate them using the existing technology. The solution for rendering HydroFeatures is to build a HydroRenderer for all kinds of HydroFeatures based on the ArcGIS rendering architecture. The sole objective of the HydroRenderer is to render different types of geometries in the HydroLayer at the same time. This is different from the existing renderer architecture in the ArcGIS that can only render one type of simple geometry (e.g., point, multipoint, polyline, or polygon) in a feature layer. In order to comply with the ESRI specification, the HydroRenderer mainly implements the “ILegendInfo” interface defined in ArcGIS (e.g., [34]) and “IPersistStream” for persisting. The main task now is to control the “LegendGroup” count (e.g., [35]) in the HydroRenderer, in which one “LegendGroup” represents the renderer for one HydroFeature type. For example, the feature of the Xin’anjiang model consists of one basin boundary with the polygon geometry type, a series of sub-basins with the polygon geometry type, and river channels with the polyline geometry type, and then the HydroRenderer should include three “LegendGroup”, one for each category. In the real application, the

“LegendGroup” count can be determined in accordance with the categories of complex features referred in the “IFeatureCollection” interface in Figure 1. The instances of both the HydroLayer and HydroRenderer are shown in Figure 2, and the relationship between them and HydroFeatures is also illustrated.

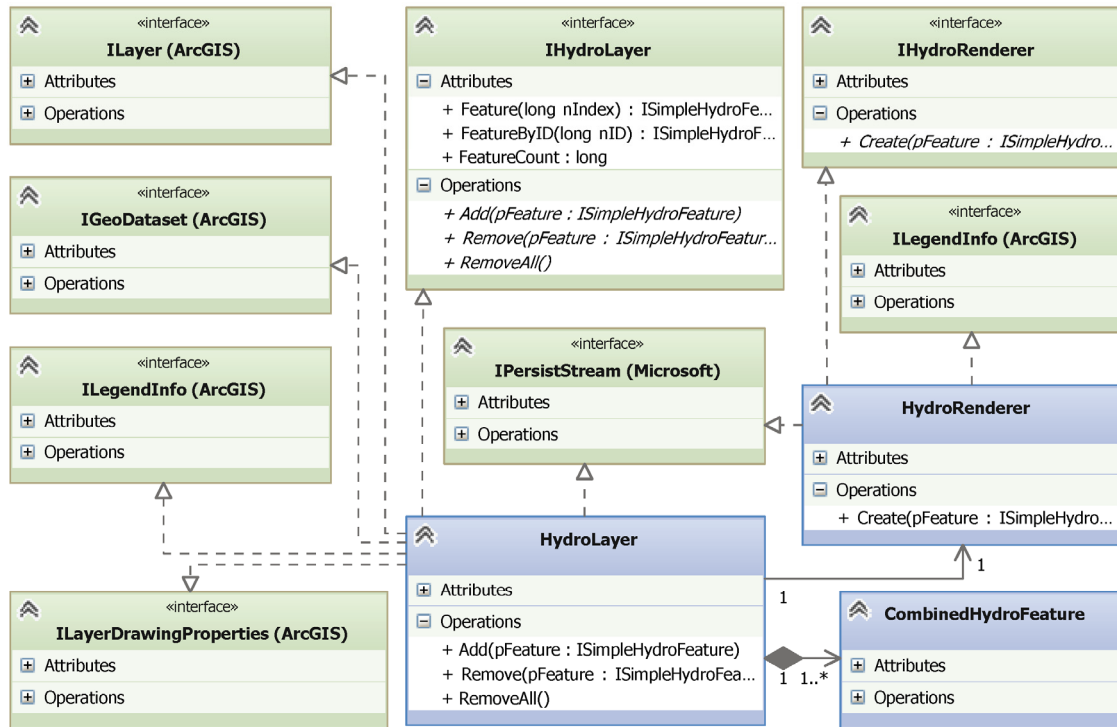


Figure 2. Class diagram of the HydroLayer and HydroRenderer. * is a number greater than or equal to one, so 1..* means from one to many objects.

The details of ArcGIS interfaces such as “ILayer” and “IGeoDatabase” and their implementation requirements can be found from the ESRI specification (e.g., [33]). The custom interface “IHydroLayer” only includes a few functions for aggregating the “Cumbined-HydroFeature” collection (Figure 2), and the arguments of these functions is the “ISimpleHydroFeature” interface. The reason for this design is that even though a “CumbinedHydroFeature” consists of several “SimpleHydroFeature” interfaces, it is still a derivative of the “ISimpleHydroFeature” interface according to the architecture of Figure 1 and can be represented by the interface in OOP. An additional benefit of this design is that if a feature is not a complex one, i.e., a “SimpleHydroFeature” object (Figure 1), it can also be held by a HydroLayer due to its relationship with the “ISimpleHydroFeature” interface. Meanwhile, a disadvantage is also obvious that any objects implementing the “ISimpleHydroFeature” interface can be added to a HydroLayer, even if they are different types. For example, two combined features designed for different hydrological models can exist in one HydroLayer simultaneously, which will drastically increase the difficulties for managing and rendering this layer. To avoid this problem, we recommend just to add the same type of HydroFeatures to one HydroLayer, though there is no mandatory requirement in the architecture of Figure 2. A HydroRenderer is accompanied by a HydroLayer, whose main function is to render the features in that layer. Therefore, a “HydroRenderer” object in Figure 2 is set up immediately when a HydroLayer is created, and then the “LegendGroup” interfaces in it are determined by the “Create” function in the “IHydroRenderer” interface (Figure 2) as long as the first feature is added to the related HydroLayer.

In the ArcGIS platform, all operations about the layers and features are performed with the support of the GUI, e.g., toolbars, commands, tools, and other interactive windows. Here, we will use the same approach to operate the HydroFeatures and HydroLayers

by developing some commands, tools, and dialogue windows as add-ons in the ArcGIS platform, similar to Arc Hydro. This skill is common in ArcGIS extensions (e.g., [35]).

2.2.2. Plugging the HydroFeatures and HydroLayer into ArcGIS

The designs of the HydroFeatures, HydroLayer, and HydroRenderer have been introduced in the above sub-sections. Next, we will introduce how to connect these objects to the ArcGIS platform. Since layers are the only object that can directly connect with the ArcGIS platform, a layer must be created first and plugged into the ArcGIS through the ArcGIS-provided functions. HydroFeatures can then be created and added into the HydroLayer by the layer functions, while a corresponding HydroRenderer for the HydroLayer is also created simultaneously. Up to now, only HydroFeature data management in ArcGIS platform has been performed. When the ArcGIS platform automatically renders all layers, the HydroLayers will render all features with their corresponding HydroRenderers. During the process, the HydroLayers and HydroFeatures that we created for hydrological models work as well as the embedded ones in ArcGIS. The hydrological model is originally developed with its own data structures that are consistent with HydroFeatures, so it can be directly used in ArcGIS. The model parameters and other settings can be handled by self-developed GUI, such as commands and tools, etc. The workflow for plugging HydroFeatures into the ArcGIS platform and rendering processes is shown in Figure 3, in which the numbers in the comments are the sequence.

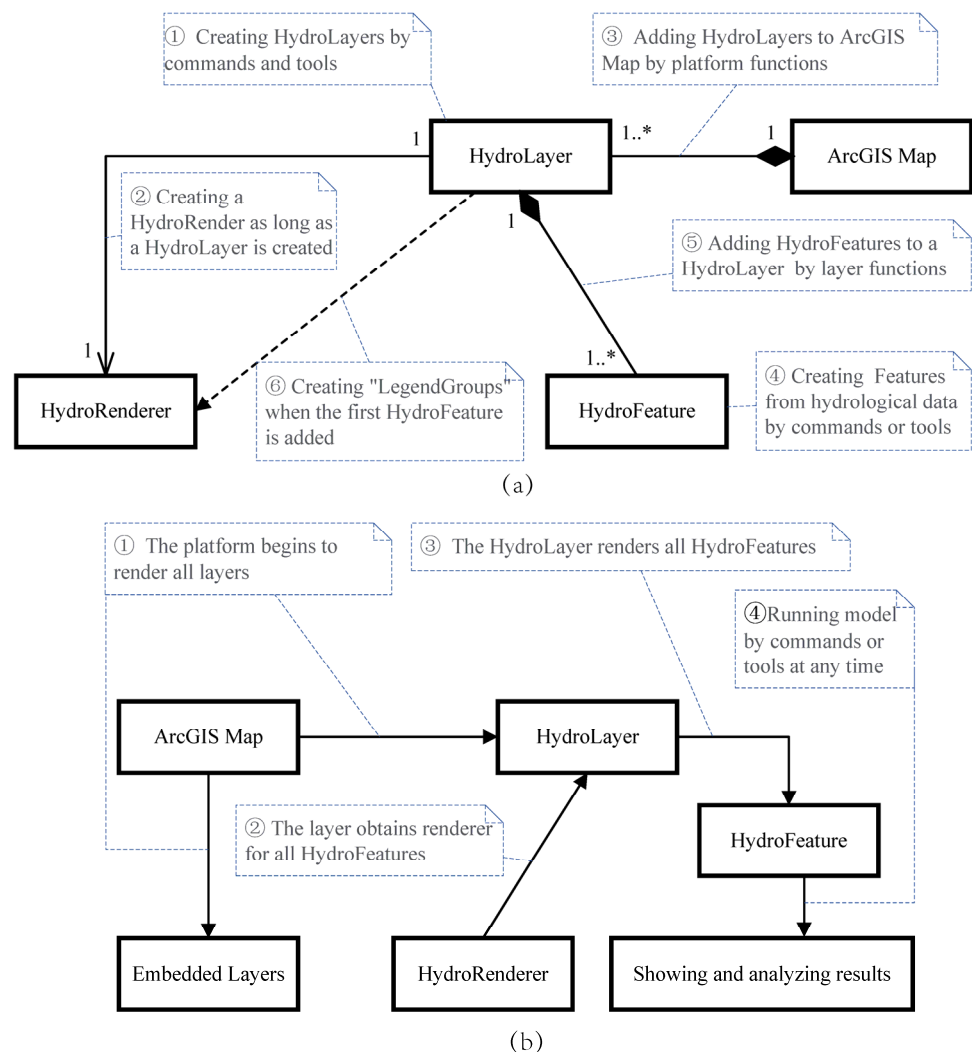


Figure 3. The workflow of plugging HydroFeatures into the ArcGIS platform (a) and rendering processes (b). * is a number greater than or equal to one, so 1..* means from one to many objects.

More details about this software can be found in Supplementary Materials.

3. Research Area

3.1. Study Area

To evaluate the ArcGIS-Xin'anjiang modelling system, we selected the Shaying basin as our case study (Figure 4). This helped us conduct simulations and demonstrate the effectiveness of this coupling work. The Shaying basin oversees a contributing area of approximately 1800 km², 75% of which comprises mountainous terrain. The main stream stretches for about 100 km, with an average altitude of around 820 m. The basin's topography slopes from the southwest to the northeast. It experiences a warm temperate semi-arid continental climate characterised by four distinct seasons. Historical data indicates that the average annual rainfall between 1980 and 1996 was about 900 mm. Notably, rainfall distribution is quite uneven throughout the year, with the bulk of it—between 60% to 70%—occurring from June to August.

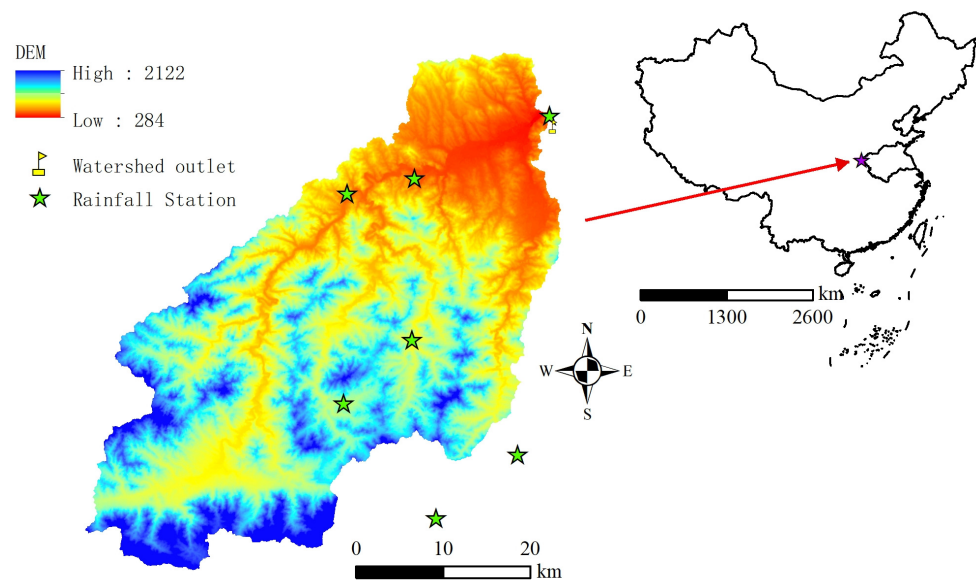


Figure 4. Location and topography of study area.

Within the basin, there is one hydrology station, one evaporation station, and seven rainfall stations. The Ziluoshan Hydrology Station, established in 1951, boasts an extensive series of hydrological observation data. With no large- or medium-sized water conservancy projects present and minimal influence from human activities, the basin largely retains its natural state.

The topographic data utilised for the model calculations is sourced from the publicly available ASTGTM dataset with an inherent resolution of 30 m. Soil information was derived from the 1:100,000 soil database published by the Institute of Soil Science, Chinese Academy of Sciences. Within the Ziluoshan Basin, predominant soil textures comprise sandy soil, loam, and clay. Between depths of 0–1 m, the percentages of sand and clay are 5.3–83% and 1.7–31.6%, respectively, with the remainder being loam. The primary land cover categories in the basin are deciduous broadleaf forest and mixed forest. The average vegetation cover exceeds 75%, and the average annual normalised difference vegetation index (NDVI) is above 0.6.

3.2. Establishment of Coupling Hydrological Modelling Systems

Digital Elevation Model (DEM) data, with a 30 m grid resolution, has been employed to elucidate the spatial variations in topography. According to the geographical map, the terrain of the catchment slopes from the southwest towards the northeast. The catchments were delineated using the Arc Hydro Tools (e.g., [26]), resulting in the watershed being subdivided into 110 sub-basins. Each of these sub-basins encompasses one river channel.

Within or in close proximity to the watershed, there are seven rainfall measurement sites. The Thiessen polygons represent the spatial variability of rainfall across the watershed. Rainfall within each of these polygons correlates to its respective rainfall measurement site. Notably, the sub-basins do not always align perfectly with the Thiessen polygons. Consequently, to determine rainfall rates for each sub-basin, the area-weighted average method was employed. The weights for this calculation are determined by the areas of overlap between the Thiessen polygons and the respective sub-basins. Following the preprocessing of both the sub-watershed data and rainfall time series, a hydrological model object has been constructed to facilitate the integration of GIS with the hydrological model.

4. Results

4.1. HydroFeature Extension for Xin'anjiang Model

In this study, we used the Xin'anjiang model as an example to illustrate the coupling of ArcGIS and hydrological models. The Xin'anjiang model, initially developed by Zhao et al. [31], is a conceptual hydrological model that simulates the outlet flow process of watersheds. Several improvements have been made from the original version of this model to become a distributed model (e.g., [36,37]), making it increasingly popular and widely used in various applications (e.g., [38]). Since the theoretical basis of the Xin'anjiang model has been clearly reported elsewhere (e.g., [31]), a brief description of the model is introduced here. A critical concept of this model is that watershed heterogeneity is expressed in an empirical distribution curve of soil moisture storage capacity, e.g., a single parabolic curve. The geographical information, such as DEM and soil characteristics, is considered in an implicit way. Generally, this curve can be directly derived from TOPMODEL's topographic index (e.g., [39–41]) or the empirical shape parameter B was estimated in terms of the characteristic land surface slope (e.g., [42]). Once the curve is determined, a simple comparison between the sum of net rainfall and soil water content (directly obtained from the curve) can determine and separate the runoff based on the saturation excess runoff generation theory. The runoff flows to the channel of sub-basins through the "lag-and-route" method and is routed along the river channel using the Muskingum method. Small tributaries of sub-basins merge to form larger streams that ultimately lead to the outlet of the watershed. Arc Hydro Tools were employed here to delineate catchments for the generation of sub-basins and channels together with their topological relationship, which meets the needs of the Xin'anjiang model.

The strategy introduced in the above sub-sections is a standard method to manage geographic information for different hydrological models. However, besides the geographic data, there are still some special operations for any specific model. For the Xin'anjiang model, the operations should at least include: (1) the method to create the Thiessen polygons using the provided rainfall sites to assign rainfall values for each sub-basin; (2) the method to import hydrological data such as rainfall data, evaporation data, and flow data; and (3) the method to execute the model.

According to the above description, an instance of the Xin'anjiang model should be designed, and the "CombinedHydroFeature" in Figure 1 is aggregated as geographical component by following the COM aggregation strategy (e.g., [43]). The diagram of the group of models and HydroFeatures and its relationship with HydroLayer is shown in Figure 5.

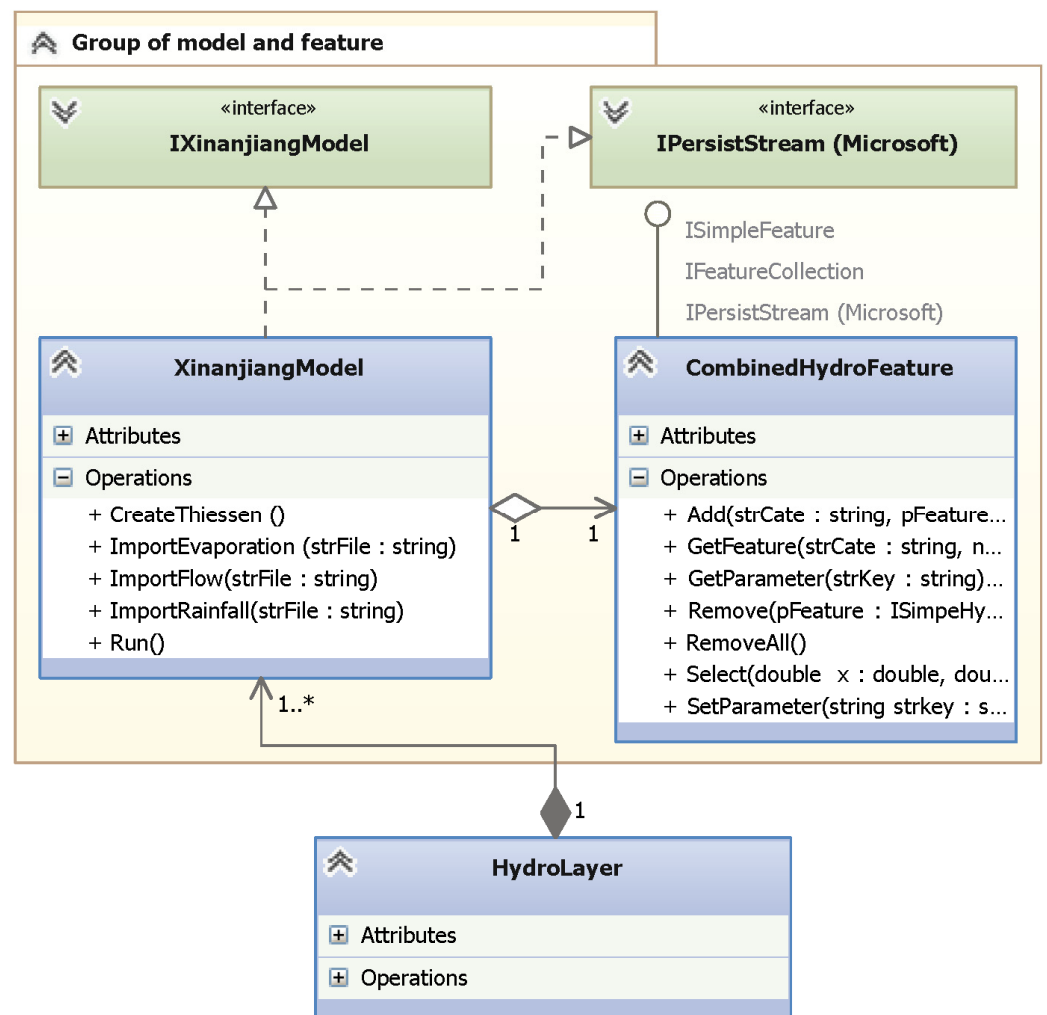


Figure 5. The relationship between Xin’anjiang model and HydroLayer. * is a number greater than or equal to one, so 1..* means from one to many objects.

An “IXinanjiaModel” interface with some necessary functions is designed at first, and then an instance of the Xin’anjiang model inherits from this interface and the “IPersistStream” interface. The whole structure is prepared for the model itself, and in order to obtain the geographic information during the modelling process, the “CombinedHydroFeature” introduced in Figure 1 is aggregated. The sub-basins and channels contained by the Xin’anjiang model are also instances of HydroFeature, and here, they are created as “SimpleHydroFeature” interfaces (Figure 1) and added to “CombinedHydroFeature”. From the specification of the aggregation strategy (e.g., [43]), the group of model and features in Figure 5 has the same behaviour as “CombinedHydroFeature” due to it having four exposed outward interfaces (e.g., “ISimpleHydroFeature”, “IFeatureCollection”, “IPersistStream”, and “IXinanjiaModel”). Among the aggregation process, the “IPersistStream” interface of “CombinedHydroFeature” is excluded so that it will not conflict with the same interface of the “Xin’anjiang Model”. With the above group strategy, the model can also be added to a HydroLayer, even though the layer has no extra preparation for this. Therefore, when the Xin’anjiang model was plugged into the ArcGIS platform, the real feature contained by a HydroLayer in Figures 2 and 3a is the group object in Figure 5.

The architecture of the coupled ArcGIS–Xin’anjiang modelling system has been introduced completely. The remaining work involves coding the designed structures using appropriate programming languages. Since the COM specification is independent of the specific computer language, any kind of COM compatible and ArcGIS compatible programming language can be used (e.g., VC++, c#, VB, and Java).

4.2. Establishment of Hydrological Objects

4.2.1. Importing Sub-Basins and Channels

A command for parsing catchments delineated by Arc Hydro Tools is first created in the ArcGIS platform. The execution of this command includes two steps: (1) create a HydroLayer and a “CombinedHydroFeature” and name them; and (2) parse geometries of each sub-basin and channel, then add them as “SimpleHydroFeature” interfaces to “CombinedHydroFeature” by the functions of the “IFeatureCollection” interface. Meanwhile, each sub-basin and channel must keep the topological relationship of the original catchments.

Among these functions, creating a HydroLayer and HydroFeatures are the new functions developed in this research, while the parsing process can be fulfilled by the available functionality of ArcGIS. After the command is executed, the HydroLayer and HydroFeatures have been plugged into ArcGIS platform. For aesthetic reasons, sub-basins and channels need to be rendered by different colours and symbols, which is the speciality of HydroRenderer developed in this research. The graph after rendering is shown in Figure 6.

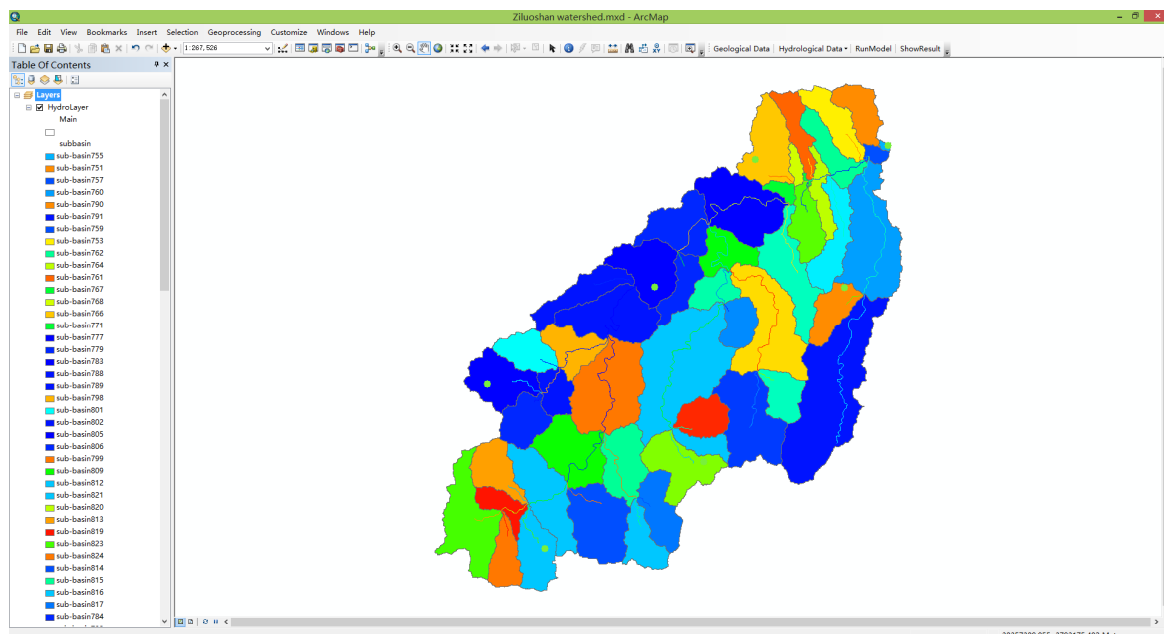


Figure 6. Sub-basins and channels in a HydroFeature. Note: The list of sub-basins on the left is incomplete due to space limitations.

4.2.2. Adding Sites and Hydrological Data

A tool for creating rainfall sites and adding hydrological data was also created in ArcGIS platform. This tool has three functions: (1) create rainfall sites by mouse-click in the ArcGIS map and name it, and then add them as “SimpleHydroFeature” interfaces to the “CombinedHydroFeature” by the functions of the “IFeatureCollection” interface; (2) assign rainfall data from an ASCII file; and (3) add evaporation data and outlet data from ASCII files.

Different from commands, a tool interacts with the ArcGIS map. The creation of Thiessen polygons is a simple job by calling ArcGIS functions, while hydrological data management is handled by the HydroFeature. The rainfall Thiessen polygons and hydrological data management GUI are shown in Figure 7. The whole model has been completed now, and the HydroLayer, HydroFeatures, HydroRenderer, and hydrological data can be persisted into the ArcGIS document for reuse next time.

4.3. Accuracy Analyses of Hydrological Model

4.3.1. Analysis of Xin'anjiang Model Calculation

The Xin'anjiang model was developed for the Ziluoshan basin using the described method. To verify the model's effectiveness, six sets of runoff data from 1989 to 1995 were selected. Further references to applications in various fields can be found in another study that employs the same object-oriented hydrological modelling approach (e.g., [44]). The flow process at the Ziluoshan hydrological station was chosen as the evaluation target. For each flood event, the flood peak, flood volume, and certainty coefficient were statistically analysed. The findings are presented in Table 1 and Figure 9. From the results, the maximum relative error in absolute terms was found to be 21.02%. The flood peak's maximum relative error in absolute terms is 0.88%. The root mean square error of the flood process flow is 15.62–85 m³s⁻¹. The certainty coefficients for the three evaluated fields exceed 0.8, with an average value of 0.81.

Table 1. Results of model calibration.

Flood No.	P (mm)	E (mm)	Flood Volume (10 ⁶ m ³)			Peak Discharge (m ³ /s)			RMSE (m ³ /s)	NSC
			Vobs	Vsim	RE (%)	Qobs	Qsim	RE (%)		
1989081122	11.1	1.3	13.8	15.5	12.32	242.0	229.1	-5.33	31.91	0.80
1990061915	33.2	10.7	50.9	40.2	-21.02	524.0	517.6	-1.22	41.62	0.95
1991053120	45.8	28.8	41.5	46.8	12.77	266.0	269.7	1.39	24.62	0.89
1991061412	18.5	11.4	16.9	19.5	15.38	155.0	155.9	0.58	23.40	0.72
1993051220	19.8	5.9	18.7	17.6	-5.88	103.0	99.0	-3.88	15.62	0.78
1995072422	52.7	3.5	36.1	38.2	5.82	775.0	706.2	-8.88	85.00	0.74
Mean	30.2	10.3	29.7	29.6	3.23	344.2	329.6	-2.89	37.03	0.81

Note: P is the rainfall, E is the evaporation, Vobs is the measured total water volume, Vsim is the simulated total water volume, RE is the relative error, Qobs is the measured discharge, Qsim the simulated discharge, RMSE is the Root Mean Squared Error of discharge, and NSC is the Nash-Sutcliffe coefficient.

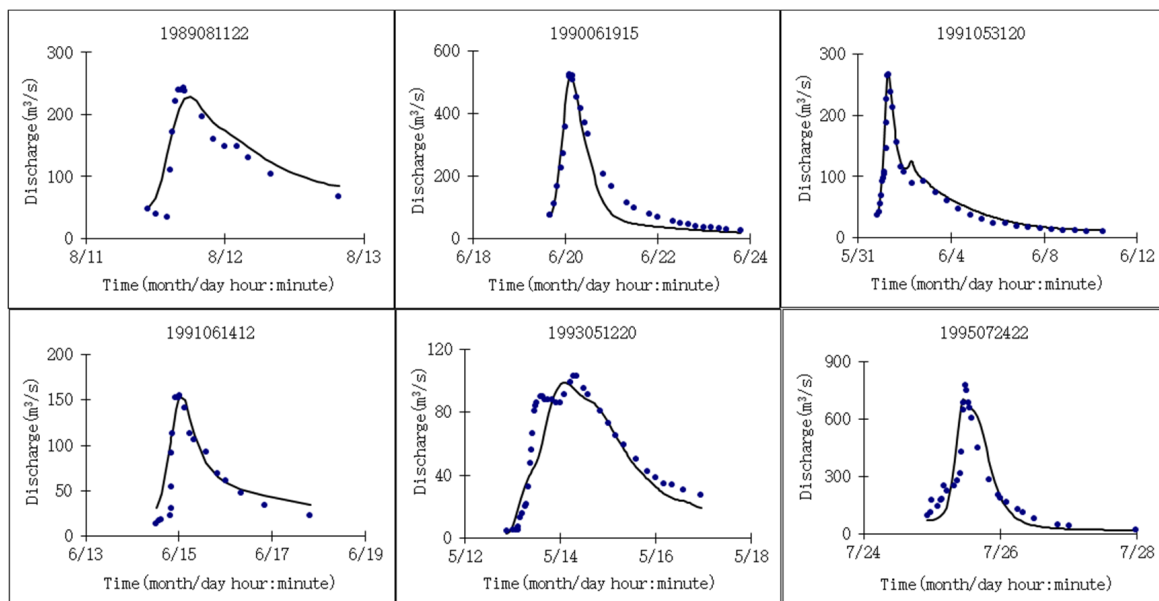


Figure 9. Hourly simulated (black line) and observed (blue dot) runoff values in the watershed during the selected flooding events.

The primary cause of the observed phenomenon is the limited number of rainfall stations, coupled with their uneven spatial distribution. Notably, in the upstream regions of the basin, there are hardly any rainfall stations. This results in a deviation in precipitation data collection and subsequent inaccuracies in runoff simulations. From the application, it is evident that the hydrological modelling system (HMS) based on Object-oriented

Programming (OOP) and integrating Microsoft's Component Object Model (COM) with GIS can be effectively employed in hydrological research.

4.3.2. Analysis of Construction of Object-Oriented Hydrological Model

This paper introduces a novel approach to seamlessly integrate ArcGIS and HMS by directly incorporating model data structures into the ArcGIS platform as HydroFeatures. We utilise Microsoft's COM standard to design these HydroFeatures and HydroLayer, which offers significant advantages:

(1) The COM specification is agnostic to specific programming languages. Many contemporary programming languages (e.g., VC++, C#, VB, Java, and Python) are directly compatible with both COM and ESRI standards. This allows hydrological scientists to employ familiar programming languages when developing models with the support of ArcGIS, circumventing the need for specialised coding skills. Consequently, this increases research efficiency and considerably diminishes the challenges associated with implementing the integrations.

(2) COM technology is recognised as a software industry standard that defines interoperability among various software modules. HMS systems developed using COM can effortlessly leverage other COM resources, allowing others to utilise these models even in the absence of the original source codes. After all, deciphering source codes authored by others can be daunting. Models adhering to the COM standard facilitate easier reuse of these modelling systems.

The essence of our approach is to design a unique hydrological feature, which allows for the creation of complex data structures in ArcGIS and represents hydrologic model objects using an Object-oriented Programming (OOP) approach. This OOP representation aligns with our understanding of hydrological phenomena, eliminating the need to abstract hydrological features into numerous components. To integrate these custom hydrological features with the ArcGIS platform, we designed the "HydroLayer" to house them. Central to the HydroLayer's function is managing the lifespan of these "HydroFeatures" by adding or removing them both from the HydroLayer and the platform. Furthermore, the HydroLayer serves as a bridge between the HydroFeatures and the platform, enabling the HydroFeatures to leverage the advanced functionalities of ArcGIS.

Visualisation is another key element introduced in our study. As ArcGIS cannot inherently recognise the HydroFeature, it fails to render it appropriately. We present a method to design a "HydroRenderer" suitable for all HydroFeatures, extending ArcGIS's rendering architecture to simultaneously depict various geometric types within a single layer. This is achieved by establishing distinct "LegendGroups" tailored to each HydroFeature, rendering specific components of that feature. This adaptation is crucial for ensuring visibility and aesthetic coherence in our proposed concept.

After managing and rendering the HydroFeatures in the ArcGIS platform, the subsequent step involves operating models associated with these features. This is achieved by developing specific commands and tools tailored to our model, in accordance with ESRI specifications (e.g., [35]). For the Xin'anjiang model, commands have been formulated to import Arc Hydro catchments, along with tools to incorporate rainfall sites and hydrological data. Ultimately, the model is run using a specific command, with the results displayed via a user-friendly interface. Given that the Xin'anjiang model is relatively simple, the number of commands and tools is limited. Nevertheless, additional commands can be seamlessly created for more intricate models using the same methodology.

As HydroFeatures preserve the data structures of their corresponding models, other hydrological, hydrodynamic, and environmental modelling systems can also be integrated with the ArcGIS platform. This can be achieved using the methodology introduced in this study with minimal modifications to the original source codes. Nonetheless, implementing this approach in practical applications requires extra effort. For instance, in our case study, model developers needed to design data structures for the features of the Xin'anjiang model, necessitating the creation of a unique interface for that particular model—a task that

is far from straightforward. Furthermore, the hydrological data is currently stored in ASCII files and accessed directly by models. This format is suboptimal for large-scale models for several reasons: (1) managing extensive data with ASCII files is highly challenging; and (2) if the modelling time step alters frequently, the hydrological data must be reorganised each time—a task that can sometimes be insurmountable with ASCII files.

5. Discussion

In this study, we have explored the application of hydrological models through a three-step process: pre-processing, model calculation, and post-processing. Our approach is juxtaposed with traditional hydrological modelling techniques, which typically involve a separate calculation program, the manual organisation of input files, and external analysis operations to output results (e.g., [45]).

The conventional methodology, as applied to the Xin’anjiang model, begins with the extraction of the topological structure of the basin, a process that is mirrored in our proposed method. Utilising ArcHydro Tools in ArcGIS, both approaches extract sub-basins and sub-channels from DEM data, establishing a unique identification system (HydroID) and constructing a topology attribute table (Figure 10). The subsequent steps involve identifying downstream units and recording topological relationships using the NextDownID, with the DrainID field indicating the corresponding relationships between sub-channels and sub-basins. This foundational work sets the stage for the divergent methodologies that follow.

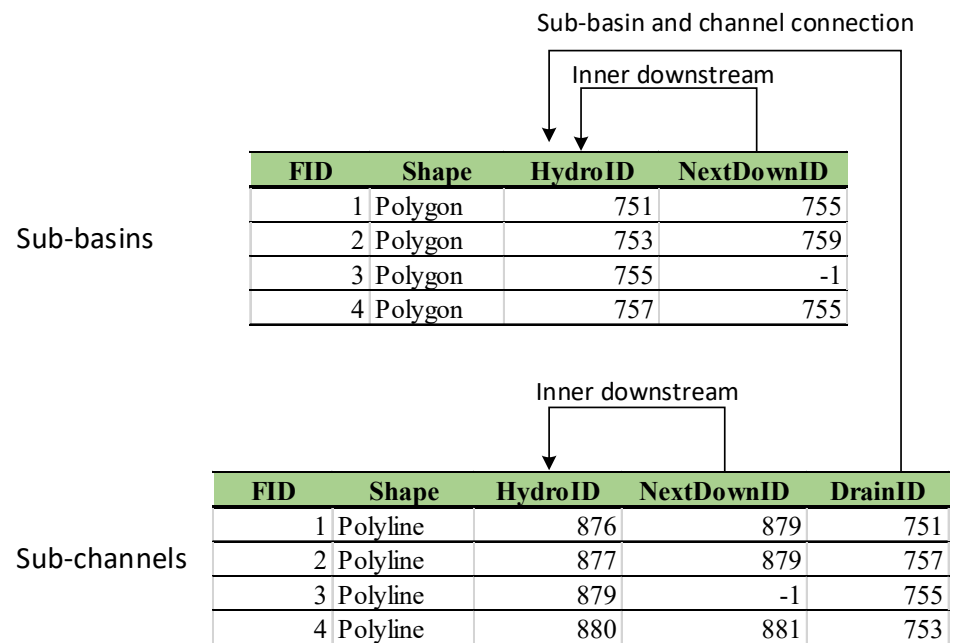


Figure 10. The watershed logical topology diagram for model input files.

Our method deviates from the traditional approach in the subsequent stages of pre-processing, model calculation, and post-processing. The novel tool introduced in this paper streamlines these steps, eliminating the need for external software. For instance, the Tyson polygon is employed to assign rainfall weight to sub-watersheds directly within the tool, a significant departure from the conventional method that requires external tools for such assignments (Table 2).

The establishment of the hydrologic model integrates the processed layer information of sub-basins and sub-channels, facilitating a more seamless transition into the model calculation phase. This phase includes parameter adjustments and the creation of diagrams to assess accuracy, tasks that are traditionally outsourced to additional software. Our

integrated tool simplifies these operations, enhancing the user experience and reducing the potential for error.

Table 2. Comparison between the proposed tool referred in this paper and the General model tool.

	Pre-Treatment	Modelling	Post-Treatment
The proposed tool	<ol style="list-style-type: none"> 1. ArcHydro Tools 2. This tool creates rain weight 3. This tool creates model directly 	The model run by a tool button-click	<ol style="list-style-type: none"> 1. The results are saved by a binary file for efficiency 2. The precision evaluation between observation and calculation can be handled by inner UI tool 3. The model parameters can be modified by inner UI tool
General model tool	<ol style="list-style-type: none"> 1. ArcHydro Tools 2. ArcGIS for Thiessen polygon 3. ArcGIS for rain weight 4. User create model input files manually 5. The model is created by reading these files 	The model run automatically	<ol style="list-style-type: none"> 1. The results are generally saved by ASCII files 2. The precision evaluation between observation and calculation usually can be handled by external tools 3. The model parameters can be modified by reorganising input files

The implications of our findings are multifaceted. Notably, the proposed tool demonstrates a significant improvement in the efficiency and accuracy of hydrological modelling. By consolidating the entire modelling process into a single tool, we mitigate the complexity and error-prone nature of multi-software interactions. This has profound implications for the field of hydrological modelling, suggesting that a move towards more integrated software solutions could streamline research and applications in this domain (e.g., [46,47]).

Furthermore, the increased accuracy and simplified process have the potential to make hydrological modelling more accessible to a broader range of users, including those who may not have extensive experience with the traditional suite of software typically required. This democratisation of modelling tools could accelerate innovation and applications in water resource management, disaster preparedness, and environmental conservation (e.g., [48]).

In comparison with the existing literature, our results underscore the need for a paradigm shift in hydrological modelling practices. While previous studies have acknowledged the challenges associated with conventional modelling techniques (e.g., [49]), our study provides a tangible solution that addresses these issues head-on. The enhanced efficiency and accuracy of our tool not only corroborate the findings from earlier research but also offer a practical advancement that could be adopted by the field at large.

6. Conclusions

To achieve object-oriented hydrological modelling, a unified HydroFeatures framework is essential for integrating diverse models within the ArcGIS platform. This paper delves into the construction of professional hydrological models, evaluates the accuracy of their computational results, and assesses their usability. The study underscores the utility of the coupled hydrological modelling system (HMS) that leverages Object-oriented Programming (OOP) and integrates Microsoft’s Component Object Model (COM) technology with GIS in the hydrological domain. This approach ensures that GIS data support aligns adequately with the object-oriented demands of hydrological models. In this research, the introduced method of seamless integration between ArcGIS and HMS successfully incorporates model data structures into the ArcGIS environment as HydroFeatures. This methodology’s efficacy is demonstrated through its application to the new Xin’anjiang model, highlighting its potential for broad applicability in aquatic environment, including coasts.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse11112140/s1>, Supplementary Materials: 1. Software availability; 2. Simple user manual.

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