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An interface of drainage division for modeling wetlands and riparian buffers in agricultural watersheds

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Abstract

In a complex watershed, isolated wetlands, riparian wetlands and riparian buffers provide important functions such as flood attenuation and water quality improvement. For conservation purposes, it is critical to properly delineate drainage areas for these features such that their impacts on runoff, sediment and pollutant transport can be reasonably simulated. However, traditional methods for watershed delineation typically fill depressions or ignore riparian features in order to maintain the continuity of surface flow pattern. In this study we develop an ArcView geographic information system (GIS) interface for watershed delineation that accounts for wetlands and riparian buffers. Based on digital elevation model (DEM), wetland distribution, and stream network GIS data, a subwatershed is further divided into isolated wetland drainage, concentrated flow drainage, riparian wetland drainage, and direct stream drainage. Outflow from isolated wetlands forms a source of concentrated flow that may contribute to riparian wetlands or bypass riparian buffers depending on its outlet location. This approach of drainage division makes a contribution in linking watershed models and field-based models through divided drainage areas. The developed interface provides a tool for simulating hydrologic processes of these features and assessing different restoration scenarios. The drainage division interface is applied to the Fairchild Creek watershed of southern Ontario in Canada where numerous isolated wetlands, riparian wetlands and riparian buffers exist. A comparison of runoff and sediment simulation results before and after drainage delineation shows the importance of the interface in facilitating watershed modeling.

Keywords: Drainage division, DEM, GIS, wetlands, riparian buffers, concentrated flow

Introduction

In the field of soil and water conservation, there is a growing awareness of riparian buffers and wetlands for their importance in providing hydrologic control, water quality protection, and wildlife habitat (Viaud et al. 2004). These landscape features slow down storm flows, trap sediment and associated contaminants, and recharge groundwater. Over the past decades, hydrologic modeling of these landscape features has been conducted extensively at field or small watershed scales (Toner and Keddy 1997, Lowrance et al. 2000, Ducros and Joyce 2003). However, modeling these processes at a watershed scale still challenges hydrologists due to complex hydrologic features within a watershed (Viaud et al. 2004).

Riparian buffers are vegetated areas located immediately adjacent to streams, lakes, or other surface water bodies (Lowrance et al. 2000). These areas differ from uplands because of high levels of soil moisture, frequent flooding, and unique assemblage of plant and animal communities. The hydrology of riparian buffers is influenced mainly by local geology, topography, soil, and in particular, upland drainage characteristics. In areas where slope is minimal and surface water flows are slow and uniform, riparian areas can be highly effective in slowing down storm flows and reducing sediment, crop debris, and other particulate materials that reach streams. However, when surface runoff becomes concentrated and bypasses riparian buffers in defined channels, the function of buffers in sequestering runoff is limited. Wetlands, including isolated wetlands and riparian wetlands, are areas of land that are intermittently or permanently inundated by shallow water. Water budget of a wetland involves precipitation, evapotranspiration, runoff, and groundwater discharge or recharge. The hydrology of wetlands is rather complex, depending on not only climate but also site-specific

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parameters such as landscape position, soil, vegetation, and drainage characteristics. The outflow from a filled isolated wetland often forms the source of streams or concentrated flows that run through riparian buffers of the main stream. Due to complexity of hydrologic processes in these landscape features, proper drainage delineation for riparian buffers and wetlands is critical for evaluating their impacts on runoff, sediment yield, and water quality improvement at a watershed scale.

Watershed delineation with digital elevation model (DEM) data is one of the most common methods for characterizing a watershed (Garbrecht et al. 2001). The DEM consists of a square grid matrix with an elevation value specified at each grid cell, while the cell location is defined by the row and column with known coordinates of the matrix boundaries. With advancement of GIS software products, automatic processing techniques have been developed for extracting surface drainage, channel network, drainage division, and other hydrographic data from DEMs (Olivera 2001, Garbrecht et al. 2001). However, these methods fill depressions (e.g. isolated wetlands) or ignore riparian features (e.g. riparian wetlands or buffers) when applied in watershed modeling in order to maintain the continuity of surface flow pattern, and therefore, are not suitable for examining the hydrologic processes of wetlands and riparian buffers.

The purpose of this study is to develop an ArcView geographic information system (GIS) interface for delineating different drainage areas including isolated wetland drainage, concentrated flow drainage, riparian wetland drainage, and direct stream drainage in agricultural watersheds. An application of the interface to the Fairchild Creek watershed of Southern Ontario in Canada demonstrates the importance of the interface in facilitating watershed modeling. Using the Soil and Water Assessment Tool (SWAT), distinct results are obtained for simulated runoff and sediment yields before and after drainage delineation.

Methodology

Study area and data availability

The 366-km^2 Fairchild Creek watershed is selected as the study area for applying the drainage division interface. The elevation in the watershed ranges from 188 to 361 meters and about 90% of the area has a slope less than five degrees (Figure 1a). The watershed is comprised predominantly of agricultural land, which makes up approximately 64% of the area. Other landuses are forest (21%), pasture (9%), urban (5%) and open water (1%) as shown in Figure 1b. Most natural areas are small, fragmented and narrowly sinuous along streams and have steep slopes. The agricultural areas of the watershed commonly feature crop rotations of corn, soybean, and winter wheat, which is typical of farming in the area (Bonnycastle 2006). There are 48 soils present in the watershed and the seven major ones are Beverly, Brantford, Dumfires, Grimsby, Guelph, Farmington, and Toledo (Yang et al. 2005). Due to intensive agricultural production, this watershed has been experiencing water quality problems suspected from non-point source pollutions. Restoration of riparian buffers and wetlands has been considered as one of the effective measures to control sediment yield and to improve stream water quality in the watershed (Grand River Conservation Authority 2004).

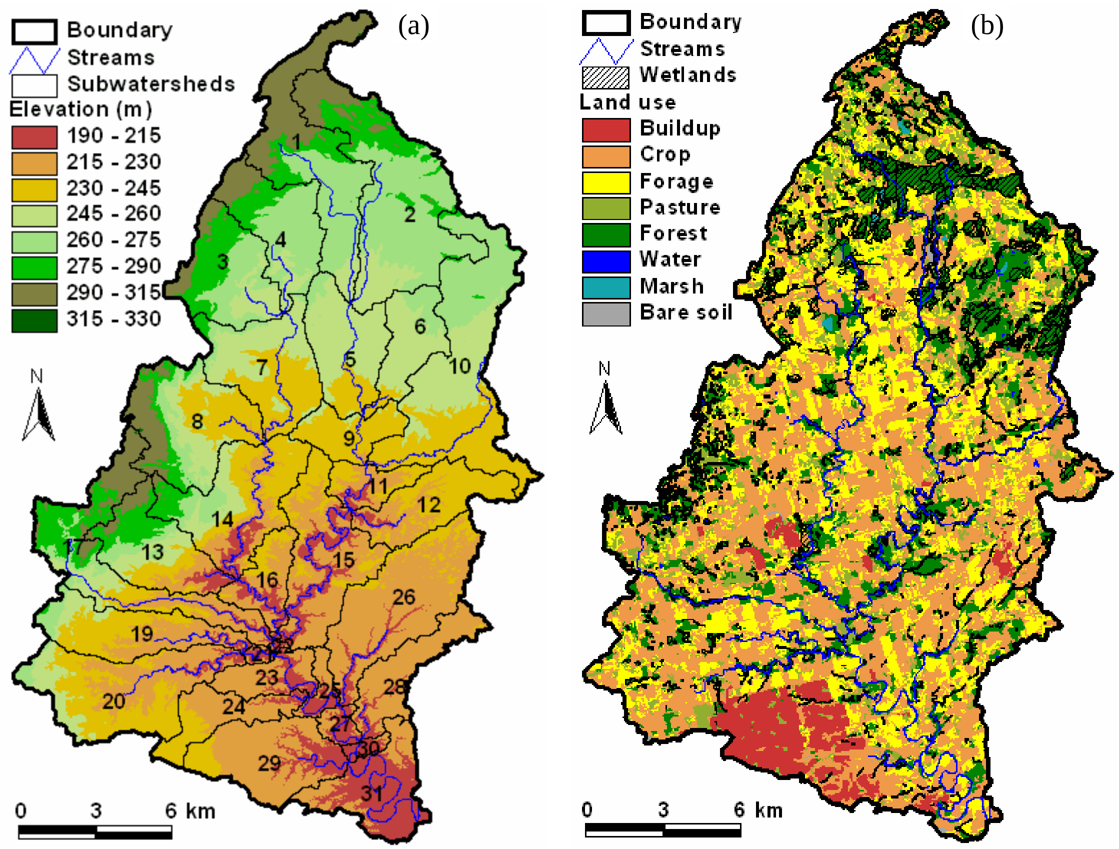

Figure 1: (a) DEM and subwatersheds and (b) wetlands and landuse of the study watershed

The watershed contains numerous wetlands in the history. However, these wetlands have lost more than 60% of their areas over last two centuries mainly due to drainage for agricultural purpose. According to their connectivity to the streams, wetlands can be classified into isolated wetlands and riparian wetlands. In the study area, isolated wetlands are usually bogs and fens that have no significant inflows or outflows and support marshlike vegetation, while riparian wetlands are usually swamps and bottomlands that are dominated by trees and shrubs. These areas are periodically inundated by water over the year and waterlogged conditions are dominant in their ecosystem. At present, the total wetland area is about 39.2 km^2 being 10.7% of the watershed area. Among them, riparian wetlands have 10.2 km^2 and isolated wetlands have 26.4 km^2, which are 27.8% and 72.2% respectively of the wetland area in the watershed (Table 1). Several large swamps exist in the upper part of the watershed (Figure 1b). The largest one has an area of 2.1 km^2. Riparian buffer width in the watershed varies generally from 10 to 50 meters for the main stream, and 3 to 10 meters for the small tributaries.

The geospatial data of 10×10 m DEM, stream network, and wetland coverage were provided by the Grand River Conservation Authority, Ontario. These dada are used as inputs to the interface to delineate different drainage areas in the watershed. The landuse and riparian buffer data was classified from SPOT and Landsat imageries acquired in August of 2004 and 2005 respectively (Bonnycastle 2006). The soil type data was obtained from the Canadian Soil Information System (CANSIS) database of Agriculture and Agri-Food Canada. The digital data of DEM, soil type and landuse are combined together to derive spatial model parameters for estimating runoff and sediment input into wetlands and riparian buffers.

Drainage division

The watershed is firstly delineated into subwatersheds for model simulation purpose. Within each subwatershed, those wetlands that interact directly with streams are considered as riparian wetlands. Others that do not interact directly with streams are considered as isolated wetlands. The riparian wetlands are considered as a special type of buffers in the stream buffer system. Secondly, the subwatershed is further divided into isolated wetland drainage area, concentrated flow drainage area, riparian wetland drainage area, and direct stream drainage area based on a high resolution DEM, a stream network and a wetland distribution dataset. The outflow of isolated wetlands forms the source of concentrated flow. The sum of riparian wetland drainage area and direct stream drainage area forms the riparian buffer drainage area used for riparian buffer simulations.

Isolated wetlands receive surface runoff, sediment and particulate pollutant from their surface drainage areas. The contributing area above a specific cell can be determined by the flow accumulation function available in ArcView Spatial Analyst based on DEM-derived flow direction data. Because a flow direction cannot be determined for cells that are lower than their neighboring cells, a process of filling the terrain depressions is necessary before determining flow directions (ESRI 1992). Isolated wetlands are true terrain depressions, and therefore, should not be filled and be kept as part of the landscape features so as to find out their surface runoff contributing areas. To avoid filling these depressions, drainage to the depression pour point can be allowed by defining a NODATA cell at its lowest point (Olivera 2001). The pour point of an isolated wetland is the lowest point along its boundary at which water flows out of the wetland when its water level is higher than the normal storage level. The pour point can be identified by comparing the cell elevations along the wetland boundary, or appointed as the intersection cell between wetland boundary and the delineated stream network if the elevation difference is very small. After assigning NODATA to pour points of isolated wetlands, the DEM can be filled to produce the filled DEM grid for which the flow directions can be determined. Based on the flow direction grid, the contributing cells of the wetlands can be identified. The drainage area of each cell can be obtained by the cell area multiplied by the number of contributing cells. The watershed Avenue request is then used to delineate the areas draining to the pour point of each isolated wetland. This method requires accurate determination of the wetland pour point cell, which is somewhat difficult to realize due to limitation in DEM quality and resolution.

An alternative approach to delineate isolated wetland surface contributing areas is to assign NODATA value in the DEM for all isolated wetland cells that are converted from the wetland coverage. Water from surrounding cells can flow to these NODATA cells. However, these NODATA cells do not have flow direction, and therefore do not allow water flow though them. The modified DEM after assigning NODATA values is then filled using the fill sink request, from which the flow direction grid is determined excluding the isolated wetland cells. Next, the contributing areas to the wetlands are obtained by using the watershed Avenue request of Spatial Analyst based on the flow direction grid and the isolated wetland grid. The identification numbers for isolated wetlands need to be unique in order to delineate contributing areas for each of them. The identification numbers for a specific subwatershed may also be kept as the same and the derived contributing areas for isolated wetlands are lumped for semi-distributed watershed modeling on a subwatershed scale. This approach is simpler in comparing to the first one and is adopted in the developed interface in the study, which will be presented in the next section.

The watershed drainage area after subtracting surface contributing area for isolated wetland is considered as the direct contributing area that have direct surface flow connections to streams. This remaining area is composed of riparian buffer drainage area and concentrated flow drainage area, from which the surface flow bypasses the riparian buffers with minimal runoff reduction and sediment abatement. To differentiate concentrated flow drainage areas from the riparian buffer contributing area, two grids of stream network are generated based on the original filled DEM, namely stream network and ditch network. The stream network grid is derived using the flow accumulation grid with a user defined threshold value. This value sets a limit to include only those streams in which each grid cell drains more than the threshold number of cells upstream of it. This value can be determined by comparing the derived stream network with digitized stream network or the information collected from field survey. The stream network grid is used to create stream link grid and subwatershed grid by incorporating flow direction information. Similarly, by setting a small threshold value, a much dense stream network can be created, which includes the stream and small tributaries or ditches flowing into it. These small tributaries or ditches are considered as water courses of concentrated flow running through the riparian buffers. This user defined threshold value is a key parameter for delineating concentrated flow drainage areas and must be determined based on terrain characteristics and hydrologic pattern of the watershed.

The grid for small tributaries or ditches in the direct contributing area is obtained by multiplying the dense stream network with its mask grid (watershed mask grid subtracts isolated wetland drainage mask grid) and by assigning NODATA values to the stream cells. These small tributaries or ditches are disconnected links contributing flow into the stream, and can be assigned to unique identification numbers using the stream link Avenue request in Spatial Analyst. Accordingly, the flow direction and subwatershed grids in the direct contributing area can be computed. Next, the contributing areas to the small tributaries or ditches are obtained by using the watershed Avenue request based on the flow direction grid and the grid for small tributaries or ditches. If the identification numbers for small tributaries or ditches are different from each other, the delineated contributing areas will be spatially differentiable. This information can be used for simulating concentrated flow of the stream ditches with a fully distributed hydrologic model. The identification numbers may also be assigned to the same value within a specific subwatershed, for which the derived concentrated flow drainage areas are lumped, and can be used for simulating concentrated flow using a semi-distributed hydrologic model.

The watershed drainage area after subtracting isolated wetland drainage area and concentrated flow drainage area is considered as the riparian buffer contributing area. This area is adjacent to the stream and is composed of riparian wetland drainage areas and direct stream drainage areas. Riparian wetland may be continuously distributed along the stream reach within a subwatershed. But in most cases, they are discontinued with non-wetland buffers in between. Concentrated flow may run through non-wetland buffers or enter into riparian wetlands depending on the location of its outlet.

To differentiate riparian wetland drainage areas from non-wetland buffer drainage areas, a similar approach for delineating isolated wetland drainage areas is applied. Firstly, a mask grid of riparian buffer drainage areas is created by subtracting concentrated flow areas from the direct contributing areas. Next, the DEM is modified by assigning NODATA values for all riparian wetland cells converted from the wetland coverage, from which filled DEM and flow direction grids can be obtained. In order to exclude the upstream drainage areas for riparian wetlands, the flow direction cell values along the stream are assigned to NODATA. This leads to lateral flows into the stream and no-flow through the stream. The grid of riparian wetland drainage areas is then computed using the watershed Avenue request based on the flow direction, riparian wetland, and mask grids. The identification numbers of riparian wetlands can be different from each other in the delineating processes, which result in a grid of spatially distributed riparian wetland drainage areas. This information can be incorporated into fully distributed models to simulate hydrologic processes within each riparian wetland. If the riparian wetland identification numbers are the same within a subwatershed, a grid of lumped riparian wetland drainage areas is obtained, which can be used in a semi-distributed model for simulating riparian wetland hydrologic processes at a subwatershed scale.

The rest of the watershed drainage areas after subtracting drainage areas for isolated wetlands, concentrated flows and riparian wetlands are considered as direct stream drainage areas, from which the surface runoff entering riparian buffers can be assumed in a relatively uniform sheet-like form. For a stream segment without riparian wetlands, this information can be used for hydrologic simulation, evaluation and restoration design of the riparian buffers. Finally, the watershed drainage grid can be obtained by overlapping the grids of isolated wetland drainage areas, concentrated flow drainage areas, riparian wetland drainage areas and direct stream drainage areas.

The GIS interface

The GIS interface is developed using ArcView GIS software and is designed as a pre-processing tool for watershed hydrologic models. ArcView is selected because it provides an easy-to-use interface and can solve specific problems by using an object-oriented and event-driven Avenue programming language. In addition, many of the hydrologic models use ArcView to develop their interface, such as SWAT (Di Luzio 2002), AnnAGNPS (Wang et al. 2003) and WetSpa (Liu 2004). The developed interface can serve as an ArcView extension providing all the tools for drainage division and can plug into any ArcView project linking GIS with hydrologic models. A screenshot of the interface loaded into a SWAT ArcView project is presented in Figure 2.

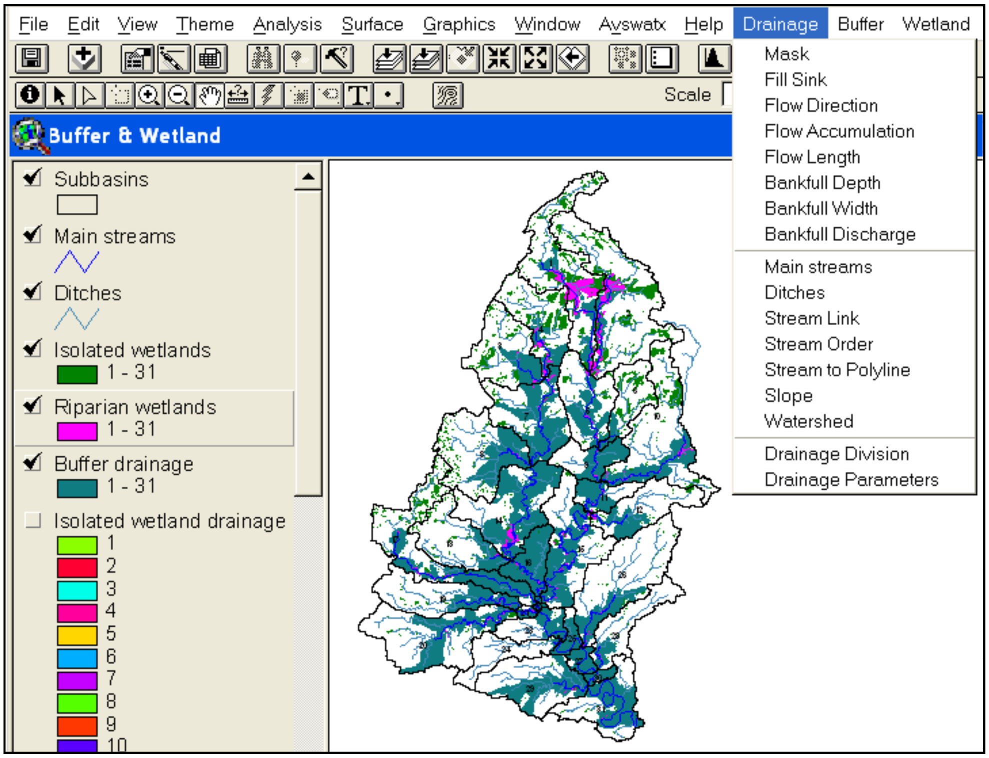

Figure 2. A screenshot of the ArcView interface for drainage division

The input files consist of a DEM, a stream network, and a wetland distribution GIS datasets. The digitized stream network can be burned into the DEM, which is an effective technique in areas of low relief or where the elevation data is not detailed enough for accurately predicting the stream network. It also helps to determine connections between streams and wetlands, and differentiate isolated wetlands from riparian wetlands. If the digitized stream network is not available, the stream network derived from a high resolution DEM can be used. However, this virtual network needs to be validated by incorporating information of landuse, soil type and field investigations. The geospatial data of landuse and soil type can be used to determine possible wetland locations and boundaries in the DEM, if the wetland distribution data is not available. Additionally, these data are also used to extract model parameters associated with soil and landuse for different drainage areas after drainage division.

After loading the drainage division extension into an ArcView project, a new view is created, and the user is asked to provide necessary base data into the new view including a DEM grid, and coverages of digitized stream network and wetland distribution. From the view's menu, user can perform individual tasks such as filling sinks, determining flow direction and accumulation, delineating streams and tributaries, defining stream links, orders and subwatersheds. The major tasks are undertaken using the drainage division request, by which different drainage areas are divided using the approaches described above.

The outputs of the ArcView project are grids of drainage areas for isolated wetlands, concentrated flow, riparian wetlands and non-wetland riparian buffers. Intermediate outputs of the project include grids of isolated wetlands, riparian wetlands, streams, small tributaries or ditches, stream links, stream orders, and subwatersheds. These datasets can be used for additional spatial analysis, model parameter derivation and layout visualization. Characteristics of different drainage areas within each subwatershed can be computed after the request of drainage division including area, perimeter, maximum flow length, average slope and elevation, major soil type and landuse. These output parameters are stored in ArcView attribute tables and text files for use in the hydrologic modeling. The interface also has functions for characterizing wetlands, channels and riparian buffer geometric parameters, such as normal and maximum volume and surface area of wetlands; bankfull width, depth and discharge; width, slope, soil and landuse of riparian buffers. These parameters together with parameters of different drainage areas are used for hydrologic simulations of wetlands and riparian buffers. The ArcView Interface allows for the results to be displayed graphically and in map form. These results can then be modified and exported using corresponding functions in ArcView.

Results and Discussion

Division of drainage areas

To demonstrate the applicability of the drainage division tools, the developed ArcView extension is loaded into the SWAT project of the Fairchild Creek watershed, and the derived grids of different drainage areas are used for further analysis of the SWAT runoff output. Using the ArcView interface, the digitized stream network is burned into the 10×10 m DEM of the watershed. The stream network is delineated using a threshold area value of 700 ha, which means a visible stream channel is initiated when the cell's drained area becomes greater than 700 ha. The same threshold value is used in the SWAT stream network delineation for modeling purpose. A threshold area value of 50 ha is chosen to delineate ditch network in the study watershed. These ditches are assumed to be small tributaries to the streams during a flood event and dried up during non-flood season (Figure 2). As a result, 31 subwatersheds are divided based on the stream links (Figure 1a).

By incorporating the grids of wetland distribution, stream and ditch network, flow direction, and the subwatershed, the drainage areas of isolated wetlands, concentrated flows, riparian wetlands and non-wetland buffers are obtained using the developed ArcView interface. In order to be compatible with the SWAT simulation results, the contributing areas draining to isolated wetlands, concentrated flows, riparian wetlands, and riparian buffers are lumped within each subwatershed. To do so, the identification numbers of these areas are assigned the same number as their corresponding subwatershed and reach segment. The drainage division results of subwatershed 3 and 7 are presented in Figure 3 and Figure 4.

Subwatershed 3 is a headwater subwatershed situated in the upper left part of the study area (Figure 1a). The subwatershed covers an area of 13.7 km^2 with an average slope of 2.3% and an average elevation of 274 m. The lengths of streams and ditches are 2.4 km and 11.2 km respectively. Isolated wetlands have cover surface areas of 1.7 km^2 and are distributed mostly in the upper and middle parts of the subwatershed (Figure 3). These wetlands are assumed to have no surface flow connection to the streams under low flow condition, and form three major concentrated flow tributaries when water storage in the isolated wetlands exceed their normal storage during flood events. The concentrated flow contributing areas are situated between isolated wetlands and streams while surface runoff generated from upper isolated wetlands are assumed to be captured firstly by the wetlands and be released after the wetland normal storages are filled. Riparian wetlands have surface areas of 0.2 km^2 and cover almost all the stream segment with widths ranging from 30 m to 200 m. The estimated contributing areas to isolated wetlands, concentrated flows, riparian wetlands and non-wetland riparian buffers are 10.8, 0.9, 1.6 and 0.4 km^2, representing 79%, 7%, 12% and 3% respectively of the subwatershed area (Figure 3). Most areas contribute surface runoff to the isolated wetlands, while runoffs contributing to concentrated flows and non-wetland riparian buffers are less important in this subwatershed.

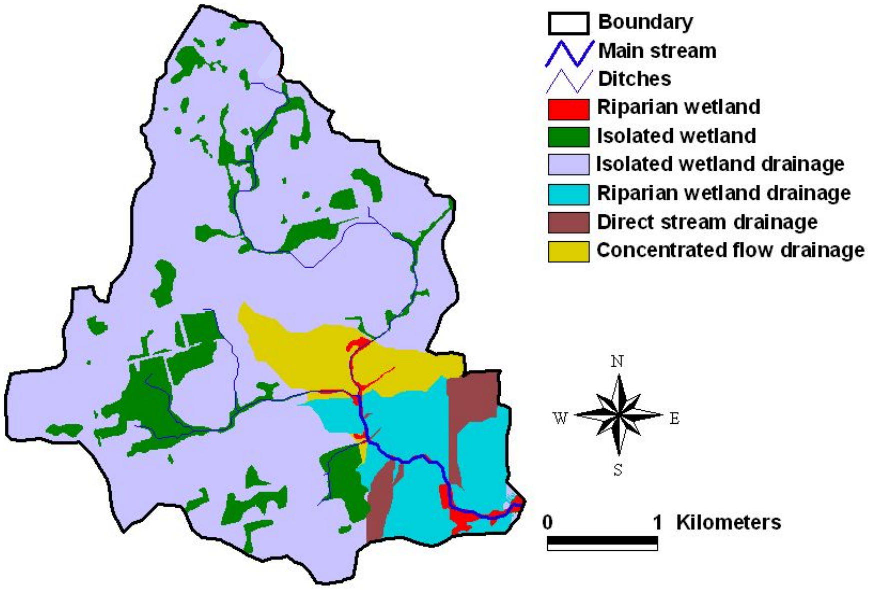

Figure 3. Drainage division of subwatershed 3

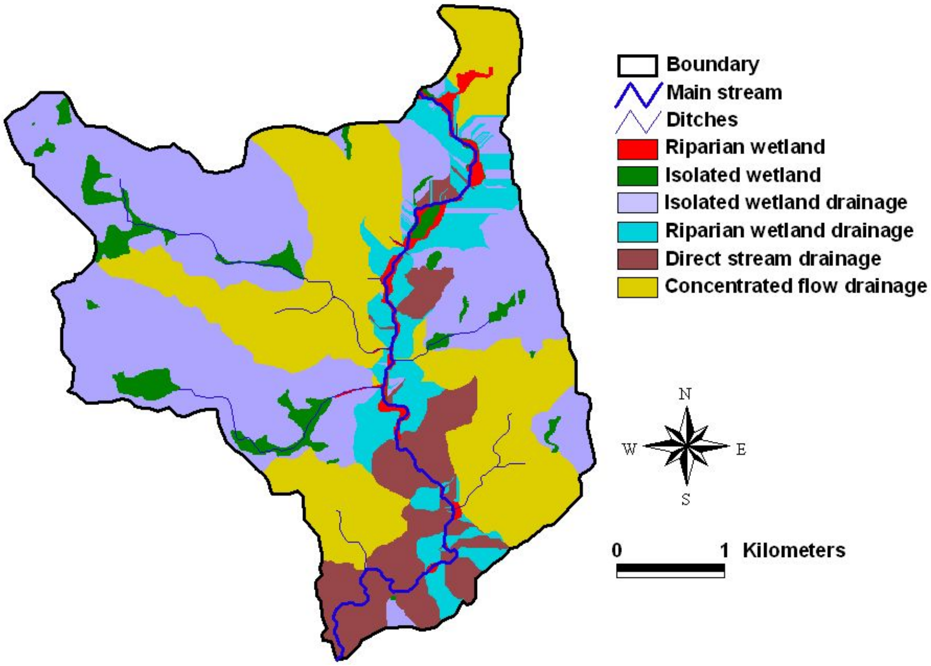

Figure 4. Drainage division of subwatershed 7

Subwatershed 7 is located downstream of subwatershed 3 in the middle left of the study watershed (Figure 1a). The subwatershed covers an area of 15.3 km^2 with an average slope of 1.7% and an average elevation of 248 m. The stream is 8.0 km running through the subwatershed, while the tributary ditches have a total length of 10.4 km obtained by setting a ditch initiating threshold area of 50 ha. Isolated wetlands cover surface areas of 0.7 km^2 and are distributed both sides of the stream along the delineated tributary ditches (Figure 4). Seven major concentrated flow contributing areas are identified with sources from the upland isolated wetlands. Riparian wetlands have surface areas of 0.3 km^2 and cover about half of the stream segment with width ranging from 30 m to 150 m. The estimated contributing areas to isolated wetlands, concentrated flows, riparian wetlands and non-wetland riparian buffers are 6.8, 5.2, 1.5 and 1.8 km^2, representing 45%, 34%, 9% and 12% respectively of the subwatershed area (Figure 4). Concentrated flows and runoff contributing non-wetland riparian buffers become more important compared to that in subwatershed 3.

Table 1. Drainage parameters for subwatersheds in the Fairchild Creek watershed

ID	A (km^2)	SL (km)	IWSA (km^2)	RWSA (km^2)	IWDA (km^2)	RWDA (km^2)	CFDA (km^2)	DSDA (km^2)
1	21.4	9.38	3.58	2.48	17.1	2.97	0.87	0.43
2	30.4	6.90	5.50	2.00	25.7	2.48	1.70	0.53
3	13.7	2.44	1.74	0.19	10.8	1.60	0.92	0.38
4	13.0	3.74	2.41	0.62	10.5	1.23	0.62	0.65
5	12.3	5.66	0.70	0.36	7.98	3.16	0.83	0.30
6	8.01	1.51	1.78	0.01	7.06	0.12	0.39	0.44
7	15.3	8.02	0.72	0.31	6.82	1.45	5.21	1.83
8	18.1	3.06	1.11	0.08	12.5	1.36	2.58	1.64
9	6.49	2.91	0.03	0.13	2.81	0.78	1.76	1.14
10	30.2	9.88	2.67	0.57	17.3	5.23	6.36	1.34
11	4.75	4.17	0.09	0.19	1.93	1.83	0.32	0.67
12	10.8	3.12	0.31	0.16	7.93	0.78	0.70	1.35
13	12.5	1.44	0.70	0.03	10.2	0.08	1.36	0.91
14	18.2	11.6	0.31	0.61	7.17	1.28	6.23	3.48
15	17.3	16.6	0.58	0.72	9.58	2.79	3.30	1.65
16	6.35	5.84	0.04	0.16	0.52	1.65	3.12	1.06
17	18.5	12.1	1.89	0.44	11.3	3.03	1.42	2.82
18	0.13	0.60	0.00	0.01	0.00	0.00	0.00	0.13
19	12.8	6.15	0.43	0.14	9.13	1.03	0.86	1.74
20	20.6	8.43	0.52	0.48	13.8	2.42	3.05	1.35
21	0.71	2.33	0.02	0.09	0.16	0.35	0.13	0.07
22	0.26	0.74	0.00	0.02	0.00	0.11	0.00	0.15
23	5.48	3.96	0.06	0.01	3.26	0.08	0.25	1.89
24	7.40	1.01	0.11	0.01	7.00	0.07	0.18	0.15
25	2.25	2.92	0.01	0.00	0.36	0.00	0.74	1.15
26	20.4	5.07	0.52	0.17	16.5	1.22	1.13	1.59
27	2.02	3.19	0.00	0.01	0.00	0.15	0.05	1.82
28	8.99	1.91	0.16	0.06	7.72	0.38	0.54	0.35
29	14.6	3.34	0.17	0.13	8.45	0.89	4.00	1.22
30	1.12	1.40	0.00	0.00	0.00	0.00	0.02	1.10
31	12.1	12.4	0.22	0.02	6.38	1.15	0.98	3.62
Total	366	162	26.4	10.2	240	39.7	49.6	37.0

The division results of different contributing areas for each subwatershed are presented in Table 1. Variables listed in the table include subwatershed number (ID), area (A), stream length (SL), isolated wetland surface area (IWSA), riparian wetland surface area (RWSA), isolated wetland drainage area (IWDA), riparian wetland drainage area (RWDA), concentrated flow drainage area (CFDA) and direct stream drainage area (DSDA). It is found that wetlands are more densely distributed in the headwater areas, and become sparse in downstream areas. Accordingly, the contributing areas to the isolated and riparian wetlands decrease from headwater subwatersheds to downstream subwatersheds. The total estimated contributing areas to isolated wetlands, concentrated flows, riparian wetlands and non-wetland riparian buffers are 240, 49.6, 39.7 and 37.0 km^2 respectively, representing 66%, 14%, 11% and 10% of the study watershed.

Application of drainage division in modeling of watershed hydrology

As a demonstration of the developed interface, the drainage division results are incorporated into SWAT and REMM (Riparian Ecosystem Management Model, Lowrance et al. 2000) to estimate the impacts of isolated wetlands and riparian buffers on runoff and sediment reduction. The SWAT, developed by the Agricultural Research Service of the United States Department of Agriculture (Arnold et al., 1998), has been widely used to assess the impact of land management on water, nutrient and pesticide flows (Arnold and Fohrer, 2005). The model is applied in a semi-distributed manner supported by an ArcView GIS interface (Diluzio et al., 2002). The watershed is divided into subwatersheds defined by topography and stream network. Each subwatershed is further subdivided into hydrologic response units (HRUs) having a uniform soil and landuse combinations. SWAT has an isolated wetland component in the model for which each subwatershed may contain one wetland, and the hydrologic processes are based on a simple mass balance method. Inputs to the wetland module include the faction of the subwatershed area draining into the wetland, wetland surface area at the maximum and the normal water level (ha), volume of water held in the wetland when filled to the maximum and the normal water level (m^3), effective saturated hydraulic conductivity of the wetland bottom (mm/hr), and other initial and boundary parameter controlling sediment and water quality. These parameters are usually difficult to collect in the field, and are adjusted during model calibration.

As shown in previous section, the developed interface computes contributing areas to isolated wetlands and other wetland associated parameters within each subwatershed. The maximum wetland surface area is read from the wetland distribution coverage. Assuming the normal wetland surface area is 30% of the maximum surface area, and the normal and maximum wetland water depth are 0.1 and 0.3 meters, the normal and maximum water volume can be estimated by the request of Drainage Parameters from the Drainage menu on the interface. Parameter values are stored in attribute tables and SWAT input text files that can be used in SWAT simulation. Using the computed wetland parameters along with default values for other wetland parameters in SWAT, the model is run and calibrated against the observed data at the watershed outlet. Figure 5 shows the simulated monthly discharges for the year 1999 and 2000 with and without wetland simulation in the model.

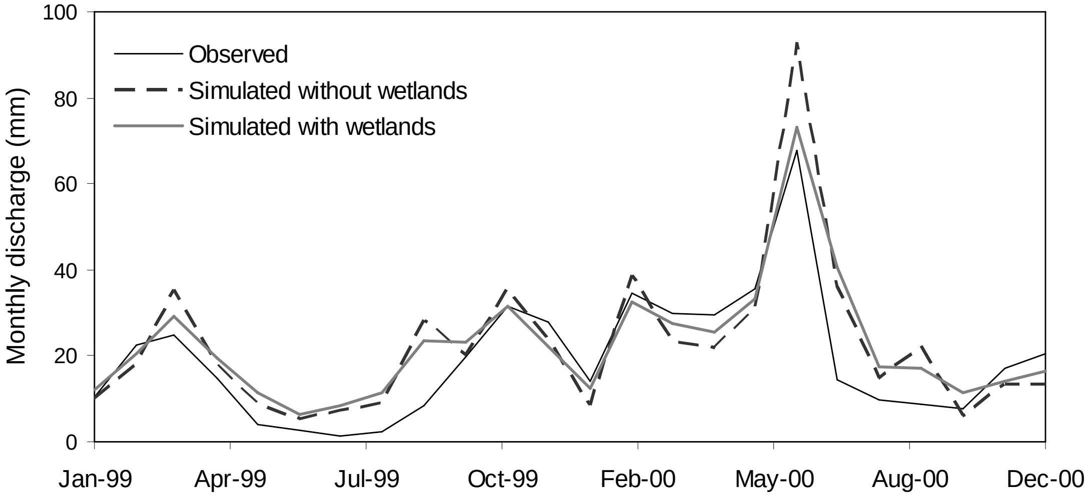

Figure 5. Observed and simulated monthly discharge at the watershed outlet

For the case of simulation without considering the effects of wetlands, wetlands are treated as natural forest or grass cover in the SWAT landuse classification. After model calibration, a reasonable match can be achieved between simulated and observed discharges at the watershed outlet. However, most of the peak discharges are overestimated. For example, the simulated monthly discharge in June 2000 is 92.9 m^3/s, which is a 37% overestimation of the measured discharge (67.8 m^3/s). Simulation considering the effects of wetlands behaves much better, and results in more moderate flows than the case without considering wetlands (Figure 5). The simulated discharge in June 2000 becomes 73.3 m^3/s, being 8% overestimated of the measured discharge. The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) calculated for daily flow over the simulation period, 1999-2003, without and with wetlands are 0.57 and 0.68, which indicates the simulation with wetlands gives a better representation of the flow processes for the study watershed. The evaluation of sediment yield simulation is not performed because of data scarcity. In addition to better modeling performance, the model can also provide simulated wetland status at each time step such as surface area, volume, inflow and outflow. However, these outputs are lumped at a subwatershed scale due to semi-distributed approach of the watershed model.

The second example of the use of the interface is to integrate SWAT and REMM for assessing the impacts of riparian buffers on sediment abatement. REMM is a field-based comprehensive model that simulates the effectiveness of riparian buffers in reducing non-point source pollutants flowing from upland fields (Lowrance et al. 2000). It divides riparian buffers spatially into three zones, and vertically into three layers plus a litter layer at the top of the ground surface. A mass balance and rate controlling approach is used for the storage of water in all the three zones and for the movement of water between zones and layers. The model requires inputs of climate and upland input data, and gives outputs of runoff, sediments, and nutrient loads coming from all the three zones on daily basis. Since monitoring upland inputs to the riparian buffers is not feasible at a watershed scale, a preferable alternative would be to develop these input datasets from the output of watershed models.

For demonstration purpose, riparian wetlands are considered part of the riparian buffers that can be modeled by REMM. The landuse, soil type and geometric parameters of riparian buffers are calculated based on available geospatial data using the developed interface. Upland inputs of runoff and sediment load are computed using SWAT assuming a uniform rate distribution over the subwatershed. The volume of runoff and sediment load from upland fields are then estimated by the rate multiplied by the contributing areas. This approach is applied for each subwatershed over the simulation period, and the total sediment reduction due to stream riparian buffers can be estimated. Three scenarios are designed to analyze the importance of differentiating various contributing areas in the study watershed. They are: (1) neglecting the effect of riparian buffers, (2) considering upland contribution areas to the riparian buffers and (3) assuming all subwatershed area drains to riparian buffers. The simulated annual sediment yields at the watershed outlet for these three scenarios are shown in Figure 6.

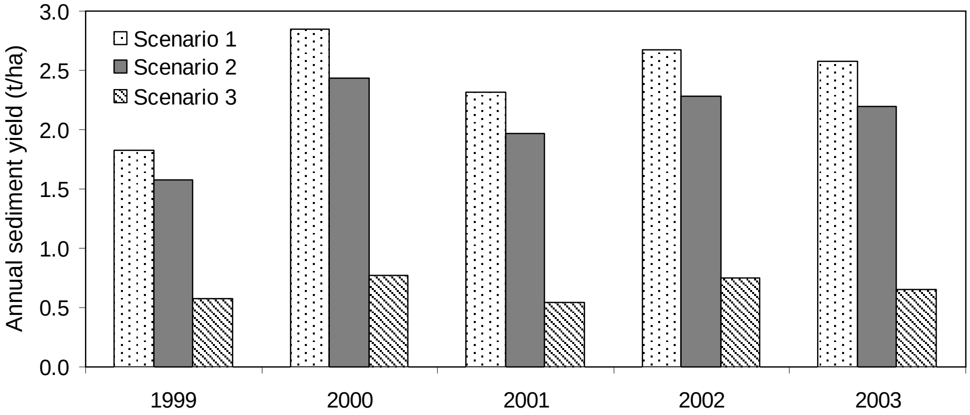

Figure 6. Simulated annual sediment yield at the watershed outlet for various scenarios (1) neglecting the effect of riparian buffers, (2) considering upland contribution areas to the riparian buffers and (3) assuming all subwatershed area drains to riparian buffers

Obviously, simulation without considering the effects of stream riparian buffers gives the highest sediment yield from the watershed, which is about 2.5 t/ha per year over the period 1999 - 2003. A good match can be achieved between simulated and observed sediment yield by adjusting model parameters during calibration. However, this may lead to less estimation of soil erosion or over estimation of in-stream sediment deposition because the effects of riparian buffers are not taken into account. The second scenario simulates the effects of riparian buffers with upland input from the divided riparian buffer contributing areas, while sediment from outflow of isolated wetlands and from concentrated flow is assumed to bypass riparian buffers without deposition. The simulated sediment yield in this case is about 2.1 t/ha per year from the watershed, which reduces 14.6% of the sediment yield compared to the first scenario. The third scenario assumes all surface runoff generated from the subwatershed contributes to the stream riparian buffers. The simulated sediment yield in this case is about 0.7 t/h per year from the watershed, which reduces 73.1% of the sediment yield compared to the first scenario. Obviously, the function of riparian buffers to reduce sediment and nutrient loads is over estimated because the effects of concentrated flow are not accounted for. This result is in agreement with the statements of Dosskey et al. (2002) and Verstraeten et al. (2006) that riparian buffers are highly effective at a field scale to reduce sediment load, but are less effective at a watershed scale due to (1) overland flow convergence, which reduces the sediment trapping efficiency, and (2) part of the sediment bypasses riparian buffers through ditches, sewers and road surfaces. Because concentrated flow of surface runoff from agricultural fields limits the capability of stream riparian buffers to remove sediment and pollutants considerably, division of their contributing areas from the subwatershed may help the model to give a reasonable evaluation result.

Discussion

The division of different contributing areas within a complex watershed is accomplished using the geospatial data of DEM, stream network and wetland distribution. Therefore, the quality and resolution of the DEM data have important influence on the drainage division result. Quality refers to the accuracy of the elevation data, and resolution refers to the horizontal grid spacing and vertical elevation increment. High quality and resolution of the DEM results in more accurate division of the different contributing areas, and low DEM quality and resolution leads to poor drainage division. In practice, the selection of DEM quality and resolution should be consistent with the watershed scale, the major physical processes under consideration in the coupled model and the study objectives.

In this study, the stream network is used to distinguish isolated wetlands and riparian wetlands. The ditch network is an extension to the stream network, and is assumed to be no-flow under normal condition. This ditch network forms the basis for the delineation of concentrated flow contributing areas using GIS. Therefore, determination of the stream and ditch network is the key factor in the GIS drainage division process, and the threshold values for delineating streams and ditches become the most sensitive parameter in differentiating different contributing areas within a watershed. If a small threshold value is used to delineate streams from the DEM, a denser stream network will be obtained, and consequently, more wetlands are categorized as riparian and less as isolated. This will result in more contributing areas to the riparian wetlands and less contributing areas to the isolated wetlands. Similarly, a small threshold value in delineating ditches and tributary streams from the DEM will lead to a denser ditch network. As a result, more areas are categorized as concentrated flow contributing areas, and less as direct riparian buffer contributing areas, which will alter the modeling simulation results considerably. In addition, a constant threshold value is usually applied to delineate stream networks in hydrologic models for simplicity. However, the occurrence of flow in headwater streams and in tributary ditches varies with flood frequency, which results in variable concentrated flow and direct riparian buffer contributing areas. Delineation of stream networks in such a way can be used for evaluation and management purposes, but may not predict real flow condition in stream ditches precisely. Due to the importance of these two networks, the threshold values used in the network delineating process must be defined cautiously based on local hydrologic conditions, terrain characteristics and field investigations.

An application of SWAT in this study watershed demonstrates the importance of isolated wetland simulation in the modeling process. As shown in Figure 1a, numerous isolated wetlands exist in each of the subwatershed. Dividing the subwatershed further into additional small subwatersheds is not efficient and may cause computing and memory problems during model simulation. To meet the requirement of SWAT, contributing areas to isolated wetlands are lumped within each subwatershed, which are realized by assigning the same identification number for all isolated wetlands within the subwatershed in the dividing process. The model takes all isolated wetlands within the subwatershed as a whole into simulation and gives outputs at a subwatershed scale. Simulation of wetlands in such a way has advantages of efficient parameterization and model calibration. However, this approach can not simulate isolated wetland individually. The developed GIS interface has the ability to delineate contributing areas to each individual isolated wetland, riparian wetland and stream and ditch segment. By coupling with a fully distributed model, the hydrologic processes of these individual landscape features can be simulated.

In applying the developed interface, the impacts of riparian buffers on sediment abatement are evaluated by integrating SWAT and REMM. The SWAT rate outputs are used to estimate upland runoff and sediment load to the riparian buffers assuming a uniform distribution over the contributing areas. Using average rates to estimate upland inputs for riparian buffers simplify the data preparation. However, cautions need to be taken when applying this approach to a subwatershed with large drainage area and complex landuse and land cover systems. For example, for a subwatershed with hills and forest cover in headwater areas and floodplain and crop cover in the valley, the distribution of runoff and sediment yield will be highly heterogeneous. The inputs to the riparian buffers computed from the average rate will be quite different from the actual situation, which may lead to an inaccurate estimation of the hydrologic responses of riparian buffers. Therefore, a fully distributed watershed model should be used to simulate upland runoff and sediment load to the riparian buffers in a complex watershed. The hydrologic processes in riparian wetlands differ significantly from those in non-wetland buffers. Modeling of these processes requires a coupling of a riparian wetland model, which is not discussed in this paper.

Conclusions

In this study an ArcView GIS interface is developed for watershed delineation taking account of isolated wetlands, concentrated flow, riparian wetlands and non-wetland riparian buffers. The different surface contributing areas to these landscape features are delineated based on geospatial data of DEM, wetland distribution and stream network. An approach of assigning NODATA to the cells of isolated wetlands, tributary ditches and riparian wetlands is used to determine flow direction grids and their contributing areas within a watershed. The drainage delineation can be implemented for each individual wetland, tributary ditch and stream segment, and also can be lumped into the four groups of drainage areas within each subwatershed. The drainage division map of the watershed is obtained by overlapping the grids of the four contributing areas. The interface can be loaded into any ArcView based hydrologic models as an extension for site specific characterization of surface contributing areas and preparation of spatial parameters for modeling purpose.

The use of the developed interface is demonstrated by coupling a watershed hydrologic model, SWAT, and a riparian ecosystem management model, REMM, to evaluate the impacts of isolated wetlands and riparian buffers on runoff attenuation and on sediment reduction at a watershed scale. The interface is used to provide drainage and site characteristic parameters in the SWAT and REMM modeling process. Simulation results from SWAT indicate that accounting for isolated wetland processes in the model gives a better representation of the outflow dynamics at the watershed outlet. More reasonable results from REMM are obtained by computing upland inputs from the delineated contributing areas to the riparian buffers. However, uncertainties may arise from the threshold values for delineating stream and ditch networks. The choice of these threshold values for delineation of different contributing areas within a watershed needs to be carefully justified for varies topographic and hydrologic conditions.

The proposed approach takes advantages of spatially distributed data and GIS for watershed analysis, and provides a tool for drainage division and parameter characterization of isolated wetlands, riparian wetlands and riparian buffers. Coupled with a spatially distributed hydrologic model, the developed interface can benefit the model potentially to (1) better simulate hydrologic processes in a watershed containing a large numbers wetlands, (2) evaluate the performance of wetlands and riparian buffers in reducing runoff, sediment and nutrient load, and (3) assess the impacts of alternative wetland and riparian buffer restoration scenarios on flow and water quality improvement. In addition, the approach makes a contribution in linking watershed models and field-based models through divided contributing areas, and has a potential to be used for evaluating various conservation practices in agricultural watersheds.

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