DEM-based Feature Information Index of Runoff Nodes

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Abstract

Runoff nodes, located where stream segments merge to form a larger one, carry important structural geographic information. Extensive research has been done on runoff nodes, but there is still a lack of work on measuring the information content of runoff nodes across watersheds. This paper develops a novel index, called the "Feature Information Index of Runoff Nodes" (FIIRN), to assess the feature information content according to the Theory of Rough Sets (TRS). Firstly, this paper establishes the conception of, and the algorithm behind, FIIRN. Then, by exploring seven typical landforms of the Loess Plateau of China as case studies, values of FIIRN are calculated after extracting all the runoff nodes. Our experiment shows that FIIRN can effectively represent the feature information of watersheds, such as runoff order or evolutionary status. In summary, FIIRN will play a significant role in future watershed analysis.

Keywords:

digital elevation models, watershed analysis, runoff nodes

1   Indroduction

Runoff nodes, located where streams merge to form a larger one (Yi et al., 2003; Li, J. F. et al., 2005a), are a physical geographical entity on the earth's surface. Runoff nodes play a pivotal role in capturing the watershed characteristics, thanks to their extensive morphological information content (Zhu et al., 2012). Recently, multiple publications have documented the extraction methods for crucial properties, watershed partitioning algorithms, identification feature points (e.g. the head of channels), and their topological relationships (Jiang et al., 2013; Qian et al., 2013; Liu T. et al, 2013; Xie et al., 2013; Sun & Tang, 2013; Li, Y. S., 2013; Lin et al., 2008; Wilson, 2012; Iwahashi & Pike, 2007). The existing literature, however, mainly focuses on geomorphologic structures in watersheds, on hydraulic information (Xie et al., 2013; Sun & Tang, 2013; Li, Y. S., 2013; Lin et al., 2008; Wilson 2012; Iwahashi & Pike, 2007; Li, J. F. et al., 2005b; Wang 2012; Zhou & Liu, 2006; Liu, X. et al., 2011; Li, D. R. et al., 2008), and on energetic features (Liu, T. et al., 2013). Nevertheless, there is substantial interest in the information content of runoff nodes. In fact, runoff nodes are considered to represent the evolutionary processes of watersheds prominently, as they

reflect the stream order, represent drainage density (Vogt et al., 2003), and describe different evolutionary stages of runoff network development. Furthermore, we can more fully assess watersheds by considering runoff nodes. To date, there has been insufficient research on quantitatively extracting the feature information of runoff nodes from digital elevation models (DEM). Aiming to address this lack, this paper focuses on calculating the information content of runoff nodes in watershed analysis, defines a Feature Information Index of Runoff Nodes (FIIRN) by using the Theory of Rough Sets (TRS), and tests the performance of FIIRN with a case study.

2   Data preparation

The Loess Plateau of China is the most typical loess landform in the world due to its intact geomorphological sequences, and as such it has received increasing attention (Xiong et al., 2014). The present study uses the Sheng mu, Sui de, Yan chuan, Gan quan, Yi jun, Chun hua and Chang wu for case studies (Figure 1a), for the following reasons: (1) the study areas should cover both intact sequences and morphological diversity; (2) the landform types of case areas should closely approach the sequence from "Huang Tu Mao" to "Huang Tu Liang", and to "Huang Tu Yuan".

By using ArcGIS, MATLAB and Excel, the workflow illustrated in Figure 1b was designed: (1) extracting the runoff nodes from DEM, and (2) calculating the FIIRN. The data used in this study are projected using a Gauss-Krüger projection, and referenced in the Chinese XI'AN 1980 coordinate system. A 5-metre grid resolution for the DEM was used.
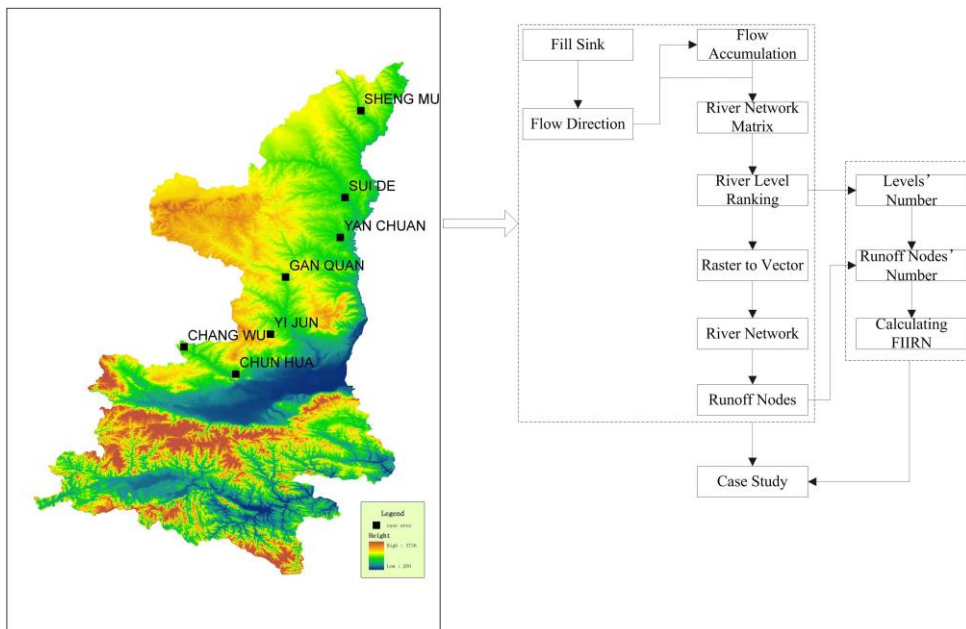
Figure 1: Experiment outline: 1(a) overview map of the case study area; 1(b) the analysis sequence performed using ArcGIS software.

For a given region, we can easily derive the stream (gully) density from the DEM by: (1) extracting the gullies from the DEM; (2) calculating the total length of the gullies; (3) calculating the total area of the study area; (4) establishing the gully density according to the definition of gully/drainage density (Melton, 1957). Table 1 shows the results obtained.

Table 1: The gully density of the case study area

Unit	Case area						
	Sheng mu	Sui de	Yan chuan	Gan quan	Yi jun	Chang wu	Chun hua
km/km²	3.4	5.34	6.78	5.60	5.20	3.13	3.15

3 Methods

Feature Information of Runoff Nodes

Different geomorphological states and the changes in evolutionary processes of watersheds exhibit ample geospatial information, with some important distinctions. From the perspective of geomorphologic structural features (Zhu et al., 2012), runoff nodes are linked to information such as hydraulic dynamics, the status of evolutionary landscape processes, stream order, morphological features, and flow accumulation (Table 2). Various watershed parameters are closely related to runoff nodes, such as river network density, average relief of watershed, and flow routing through watershed. Thus, runoff nodes are considered important information resources for watersheds.

Table 2: Information attached to runoff nodes

Information types	Information details
Hydraulic relief information	The hydraulic relief between origins and outlets
Evolutionary status information	Indicating different evolutionary status/stage of sub-watershed
Ranking information of rivers	Runoffs at different volume merge themselves into the same trunk
Morphological features	Distribution pattern of runoff nodes maps the morphological features of the watershed as a whole
Flow accumulation	Collecting all the flows of the catchment

Representation of runoff nodes using Theory of Rough Set (TRS)

The physical characterization of a watershed has to deal with vagueness and uncertainties, such as calculating the azimuthal direction of a slope (Kenny et al., 2008). Nevertheless, TRS, which is derived from set theory in mathematics (Pawlak, 1982), can help to deal with this

problem as it provides a new mathematical toolkit for extracting useful information from data without requiring any prior knowledge and experience. In fact, it is commonly accepted that TRS is effective in dealing with imprecision, vagueness and uncertainty (Pawlak, 1997).

First, let us shed light on the feature information of runoff nodes if we use TRS. Considering R as a limited domain and $P(x) = 2^R \rightarrow [0,1]$ as a probability density function, the potential probabilities of R can be described by Formula 1:

$$p_i = P(x_i) \text{ per } x_i \quad \text{(Formula 1)}$$

Here, p_i is a probability distribution of R.

A watershed can also be treated as a geometric network (Liu, X. et al., 2011). If likened to an information network, runoff nodes can be considered as the switches of the geographical information, and streams can be considered as the geographical information pipelines.

Considering L as the stream-level set of all the runoffs of R, N is the number of runoff nodes at each level. According to TRS, every level represents an equivalent class of R. So, we obtain a cluster of equivalent classes: $L_i = \{l_1, l_2, \cdots, l_n\}$, here, $L_i \subset R, L_i \neq \phi$. Hence, L_i is a subset of R:

$$R/_{L_i} = \{x_1, x_2, \cdots\} \quad \text{(Formula 2)}$$

According to Formulas 1 and 2, within the domain R, the cluster of equivalent classes L_i can reflect the information content of runoff nodes in a watershed. Note that differences among all the physical states of watersheds are neglected in this study on the basis of mathematical rules of TRS. For example, relief, flow accumulation and flow power are different states in a watershed, but this study views them as fluvial geographical information without their own physical properties.

Definition of Feature Information Index of Runoff Nodes

In order to measure the information content of runoff nodes within watersheds, we employ TRS. Considering (as in section 3.2) L as the overall level of runoff of R, L_i as the specific levels of the runoff in R, and $m(m \in N)$ as the corresponding number of runoff nodes, we can assess the values of FIIRN for level L_i as follows:

$$FIIRN_{L_i} = log_2 m \quad \text{(Formula 3)}$$

To determine the total information content of runoff nodes across the entire watershed, we can add up the values of FIIRN for each level.

4   Results and Analysis

Table 3 presents the results from extracting runoff nodes within the study areas introduced in Figure 1; Table 4 shows the computation results of FIIRN.

For a given region, a runoff node can present some crucial geomorphologic features. As seen in Figure 2, there is obviously a linear correlation between stream order rank and the number of nodes. From this case study, we can confirm the following: (1) values of FIIRN show a positive correlation with stream order; (2) the FIIRN value is in line with the gully density; and (3) from north to south across the Loess Plateau, with the landforms changing from hilly to plane, the FIIRN values show a decreasing trend. Hence, FIIRN depicts a macro-scale trend of landforms.

The above results show that the definition and characteristics of FIIRN can be verified well by the results of experiments. Undoubtedly, FIIRN as introduced here can be employed as a useful tool to evaluate the information content of runoff nodes for a given watershed.

Table 3: Extraction results of the runoff nodes of each case

Rank	Extraction results						
	Sheng mu	Sui de	Yan chuan	Gan quan	Yi jun	Chang wu	Chun hua
I	217	275	262	231	181	208	160
II	133	170	172	118	143	61	109
III	47	59	106	59	62	69	78
IV	33	47	12	16	-	23	4
Total	430	551	552	424	386	361	351

Table 4: FIIRN values of each case

Rank	FIIRN's value (bit)						
	Sheng mu	Sui de	Yan chuan	Gan quan	Yi jun	Chang wu	Chun hua
I	7.761	8.1033	8.033	7.851	7.498	7.700	7.321
II	14.816	15.512	15.459	14.734	14.658	13.631	14.090
III	20.371	21.395	22.187	20.616	20.612	19.739	20.375
IV	25.875	26.949	25.772	24.616	-	24.263	22.375
Watershed	25.415	26.949	25.772	24.617	20.613	24.263	22.375
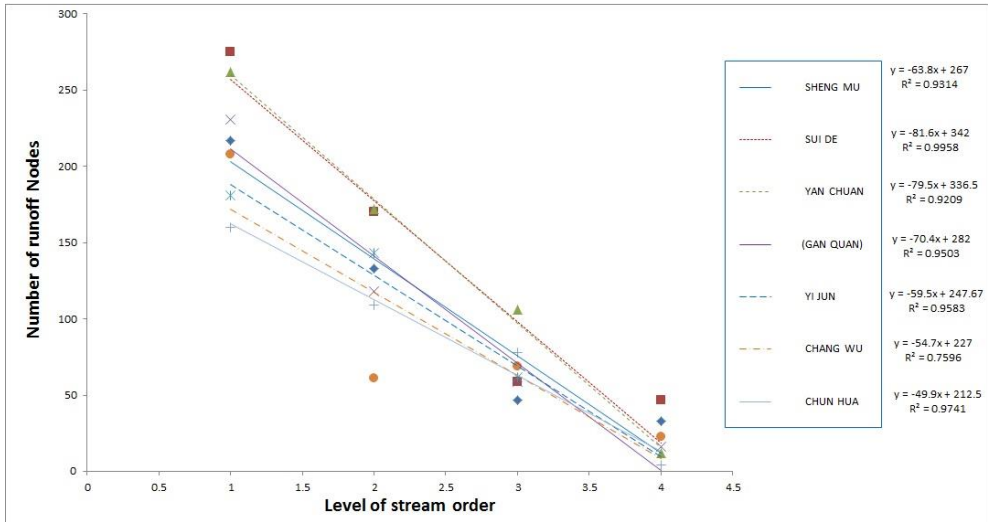
Figure 2: Linear correlation between rank of runoff and number of nodes.

5   Conclusions

In this study, the Feature Information Index of Runoff Nodes (FIIRN) was developed as an index for measuring the feature information content of runoff nodes in a given watershed by introducing the Theory of Rough Sets. FIIRN can work well when used to extract the information features throughout sample areas. This experiment shows that FIIRN can represent succinctly the features of watersheds, such as stream order or stage of evolution. Hence, FIIRN has the potential to play a pivotal role in watershed analysis in the future.

Acknowledgements

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