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Assessment of the fused image of multi-spectral and panchromatic images of SPOT5 in the investigation of geological hazards

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The investigated area in this paper is located on the northern mountain in Guangzhou City. It is characterized by high relief and inaccessibility. Multispectral and pan Images of SPOT5 were used as the remote sensing data source, and high-pass filtering (HPF), Brovery transform (BT), intensity-hue-saturation (IHS), principal component analysis (PCA) and the modified IHS (MIHS) methods were adopted for image fusion. Here, a comparison has been made between the entire fused images and the original multispectral images. Subjective evaluation and objective evaluation (entropy, average gradient, correlation coefficient, distribution of gray) have been adopted to assess the quality of the fused images. Also regional geological survey has been taken to find the interpretation veracity. Results show that the MIHS is the best image fusion method for geological hazards interpretation, and the fused image can provide abundant textural and spectral information for easy interpretation of such geological hazards as collapse, landslip, and debris flow.

geological hazard, remote sensing, image fusion, SPOT5

1 Introduction

Because of the scope and bad natural conditions, the conventional regional geological survey of geological hazard is very difficult. Remote sensing technology can efficiently get the surface information, thus it plays an important role in the investigation of geological hazard[1]. In order to fully reflect the difference between surrounding environment and geological hazard, investigation of geological hazard usually requires high-resolution images. At present, high-resolution remote sensing satellites (such as QuickBird and IKONOS) and airborne remote sensing can meet the request of high spatial resolution. however, high costs and large volume of data are their problems. The TM/ETM+ images have high spectral resolution, but the spatial resolution is too low to meet

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the needs of geological hazard survey. SPOT5 images have high spatial resolution and spectral resolution, and the spatial resolution of multispectral images can be improved by remote sensing data fusion technique too, so SPOT5 images are ideal data source for survey of geological hazard.

Many fusion methods have been proposed for combining a high-resolution panchromatic image (HRPI) with low-resolution multispectral images (LRMIs). Pohl and van Genderen have given detailed review on this issue[2]. Some methods, such as intensity-hue-saturation (IHS)[3−8], Brovey transform (BT)[9,10], principal component analysis (PCA)[10,11], and wavelet transform[9] all have advantages and disadvantages. And high-quality synthesis of spectral information is very important for most remote sensing applications based on spectral signatures, such as lithology and soil analysis[7].

Taking SPOT5 images of the mountain located in the north part of Guangzhou for example, the paper introduces the resultant images of different fusion methods of the regional geological survey, and ultimately determines the fusion method for regional geological survey.

2 Physical principles of SPOT 5 image and fusion methods

2.1 Data source and preprocessing

SPOT5 HRG has five bands, the spatial resolution of panchromatic band is 2.5 m, and its wavelength ranges from 490 nm to 690 nm; multispectral model using four-band images, i.e. near-infrared (NIR), red (R), green (G), short-wave infrared (SIR), respectively, their spatial resolution is 10 m (The original spatial resolution of short-wave infrared band is 20 m, it has been resampled to 10 m in 1A-level data)[12].

Band combination is a key step of remote sensing image fusion, choosing the best band combination can make full use of fusion technology to achieve the best results, in particular certain fusion model, such as IHS, can only use a three-band fusion, so it is of great significance to make band combination. Band combination should follow this principle: The relevance of the bands is as far as possible to the smallest and the content of information is the largest. Correlation coefficient matrix reflects the degree between two variables of the multi-dimensional random variables; its main diagonal elements are all one and other elements are the correlation between each two variables[13]. Chavez (1984) first proposed an optimum index factor (*OIF*) to calculate the amount of information of any three-band combination. We select band combination by these two parameters (correlation coefficient and *OIF* index). Table 1 gives the correlation coefficients (*CC*s), which shows that all *CC*s between the two bands are small except the *CC* between band 2 and band 3.

Table 1 Correlation coefficients

	Band 1(NIR)	Band 2 (R)	Band 3 (G)	Band 4 (SIR)
Band 1	1.000			
Band 2	0.215	1.000		
Band 3	0.32	0.953	1.000	
Band 4	0.711	0.712	0.716	1.000

The red band of SPOT5 can be used for geological interpretation, identification with the oil, rocks and minerals[14], because this study is to make survey for the regional geological hazard, band 2 (red) must be chosen. All the possible band combinations are as follows: ① Bands 1, 2, 3; ② bands 1, 2, 4; ③ bands 2, 3, 4. Table 2 gives the *OIF*, which shows that the combination of bands 1,

Table 2 *OIF* of three combinations

Combination	Band 1, 2, 3	Band 1, 2, 4	Band 2, 3, 4
OIF	42.256	50.907	25.259

2, 4 has the largest *OIF*, and from Table 1 we can see that the *CC*s of these three bands are small, so the combination of bands 1, 2, and 4 is the best.

2.2 Principle of fusion method

In this part, we will introduce some fusion methods. The methods dealt with here are high-pass filtering (HPF), IHS, BT, PCA. For all the methods, it is assumed that the images are geometrically registered, and the LRMIs are upsampled to the pixel size of HRPI.

2.2.1 HPF method. The principle of HPF is to add the high-frequency information from the HPPI to the LRMIs to get the high resolution multispectral images (HRMIs)[15]. Research shows that of all the traditional image fusion methods HPF can greatly increase the information[16]. The mathematical model is as follows:

$$DN_{\mathrm{MS}}^{\mathrm{h}} = DN_{\mathrm{MS}}^{1} + DN_{\mathrm{PAN}}^{\mathrm{h}}, \tag{1}$$

where $DN_{\mathrm{MS}}^{\mathrm{h}}$ is the digital number (*DN*) of HRMIs, $DN_{\mathrm{PAN}}^{\mathrm{h}}$ means the high-frequency information of HRPI.

2.2.2 BT method. BT is a widely used algebra fusion method, which is famous for the promotion by Brovery. Image will be decomposed into color and brightness by this algorithm. The mathematical model is as follows:

$$DN_{\mathrm{MS}}^{\mathrm{h}} = \frac{DN_{\mathrm{MS}}^{\mathrm{h}} \cdot DN_{\mathrm{PAN}}}{\sum_{i=1}^{3} DN_{\mathrm{MS}}^{1}}, \tag{2}$$

where DN_{PAN} is the digital number (*DN*) of HRPI.

2.2.3 IHS method. The IHS technique is a standard procedure in image fusion, with the limitation that only three bands are involved[2−5]. The IHS technique comprises four steps: i) To transform the red, green, and blue (RGB) channels (corresponding to three multispectral bands) into IHS components; ii) to match the histogram of the panchromatic image with the intensity component; iii) to replace the intensity component with the stretched panchromatic image; iv) transform IHS channels to RGB channels. The resultant images have a higher spatial resolution in terms of topographic texture information[15]. The IHS transform has four kinds of algorithm: sphere transform, cylinder transform, triangle transform and pyramid transform, and we chose cylinder transform as the fusion method to make the IHS transform. The forward transform model is

$$\begin{bmatrix} I \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \tag{3}$$

$$H = \tan^{-1}\left[V_1/V_2\right],\ S = \sqrt{V_1^2 + V_2^2}. \tag{4}$$

The backward transform model is

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & -\frac{2}{\sqrt{6}} & 0 \end{bmatrix} \cdot \begin{bmatrix} I \\ V_1 \\ V_2 \end{bmatrix}. \tag{5}$$

V_1 and V_2 from eq. (3) were replaced by V_1 and V_2 in eq. (5).

2.2.4 PCA transform method. The PCA method is to make K-L (Karhunen-Loeve) transform for the LRMIs, the mean and variance of HRPI will match the first component by gray stretch, and then the HRPI that has been stretched will replace the first component, and the fused images will be obtained by inverse K-L transform. The fused HRMIs contain both the texture information of the original HRPI and the spectral information of the original LRMIs. The detailed feature of the objective on the fused HRMIs is clearer, the PCA transform overcomes the limitation of the IHS fusion method which can only make fusion with three bands at the same time, and it can make fusion for two bands at least. The limitations of the PCA method are: i) The first component of the PCA transform is the expression of the same information of LRMIs. It is different from the HRPI, although the stretched HRPI has high similarity with the first component, the spatial information and spectral information of the fused LRMIs will change. ii) There are still changes in spectral information, and the fused LRMIs are inconvenient for identification. The mathematical models of the forward and backward processes are represented by eqs. (6) and (7). The transformation matrix contains the eigenvectors, ordered with respect to their eigenvalues. It is orthogonal and determined either from the covariance matrix or the correlation matrix of the input LRMIs. PCA performed using the covariance matrix is referred to as un-standardized PCA, while PCA performed using the correlation matrix is referred to as standardized PCA[15].

$$\begin{bmatrix} PC1 \\ PC2 \\ \cdots \\ PCn \end{bmatrix} = \begin{bmatrix} V11 & V21 & \cdots & Vn1 \\ V12 & V22 & \cdots & Vn2 \\ \cdots & \cdots & \cdots & \cdots \\ V1n & V2n & \cdots & Vnn \end{bmatrix} \cdot \begin{bmatrix} DN_{\mathrm{MS1}}^{\mathrm{l}} \\ DN_{\mathrm{MS2}}^{\mathrm{l}} \\ \cdots \\ DN_{\mathrm{MS}n}^{\mathrm{l}} \end{bmatrix}. \tag{6}$$

The transformation matrix is

$$V = \begin{bmatrix} V11 & V12 & \cdots & V1n \\ V21 & V22 & \cdots & V2n \\ \cdots & \cdots & \cdots & \cdots \\ Vn1 & Vn2 & \cdots & Vnn \end{bmatrix}, \begin{bmatrix} DN_{\mathrm{MS1}}^{\mathrm{h}} \\ DN_{\mathrm{MS2}}^{\mathrm{h}} \\ \cdots \\ DN_{\mathrm{MSn}}^{\mathrm{h}} \end{bmatrix} = \begin{bmatrix} V11 & V12 & \cdots & V1n \\ V21 & V22 & \cdots & V2n \\ \cdots & \cdots & \cdots & \cdots \\ Vn1 & Vn2 & \cdots & Vnn \end{bmatrix} \cdot \begin{bmatrix} DN_{\mathrm{PAN}}^{\mathrm{h}'} \\ PC2 \\ \cdots \\ PCn \end{bmatrix}, \tag{7}$$

where $DN_{\mathrm{PAN}}^{\mathrm{h}'}$ is stretched to have the same mean and variance as $PC1$.

2.2.5 The modified intensity-hue-saturation (MIHS). As the I (Intensity) component was replaced by the HRPI in the IHS transform, the fused HRMIs have large spectral distortion. The first component of the PCA forward transform contains most of the information (usually more than 80%), equivalent to the sum weight of the original LRMI bands, so the PCA transform is conducive to the enhancement of the detailed feature and analysis. Combining the advantages of the IHS transform and PCA transform, we propose a MIHS fusion method, and the process of MIHS to make fusion is shown as Figure 1.

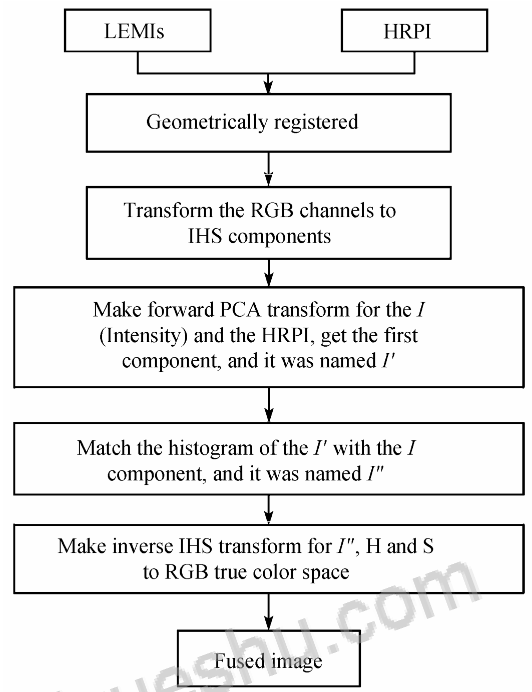

Figure 1 Flowing chart of the MIHS fusion method.

The original images and the fused images of all fusion methods are shown in Figure 2.

3 Quality evaluation of the fused images

Quality evaluation of the fused images is an important part of image fusion[17−19]. The reasons are as follows: 1) The evaluation of the fused images can provide a theoretical basis for the application scope; 2) through the evaluation of the fused images, it can be targeted to improve the methods and process of fusion methods so as to improve the quality of fused images.

At present, there are two ways to evaluate the quality of the fused images, that is, the objective evaluation and the subjective evaluation.

3.1 Subjective evaluation

Subjective evaluation is to evaluate the quality of the images with the naked eyes, and make judgments according to the subjective feelings of image quality. Subjective evaluation method is simple and intuitive, and it can make quick and convenient evaluation of the images.

Figures 2(a)—(f) are the fused and original images. In the aspects of spectrum, all the fused images have large changes in the color of water and rock except MIHS fusion image, the worst is PCA method, the MIHS method is the best which has little change in spectrum. In the aspects of the

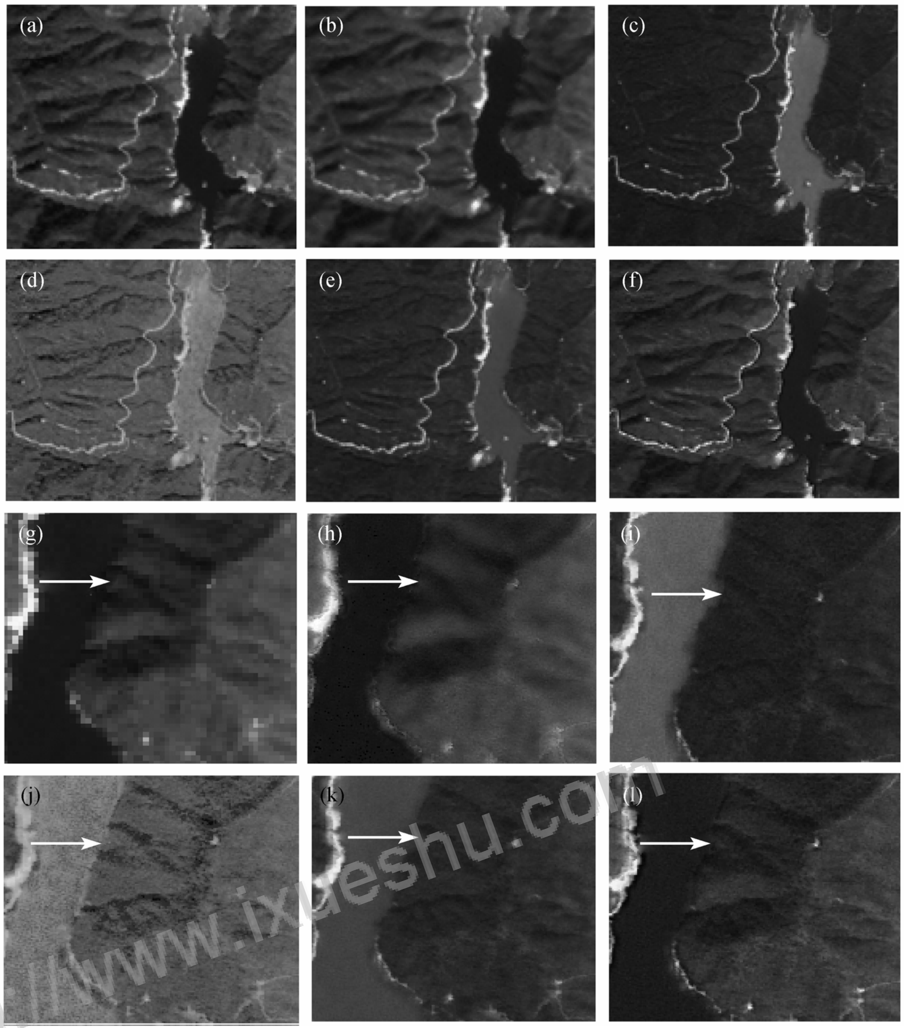

Figure 2 The original images and the fused images of all fusion methods. (a) Original LRMIs; (b) HPF fused images; (c) BT fused images; (d) IHS fused images; (e) PCA fused images; (f) MIHS fused images; (g) collapse of original LRMIs; (h) collapse of HPF fused images; (i) collapse of BT fused images; (j) collapse of IHS fused images; (k) collapse of PCA fused images; (l) collapse of MIHS fused images.

texture, all the fused images are clearer than the original LRMIs, and contain more texture information. The fused images of HPF and IHS have relatively poor texture information, and the texture information of PCA method is rich, but the spectrum distortion of PCA is serious and affects the overall effect. The MIHS fused images (Figure 2(f)) are much clearer than the others and have higher contrast, and the surface information is much more prominent. The MIHS fused images are clearer than other images, have high contrast and more texture information. From Figures 2(g)—(l) we can see the collapse marked by arrow, and the collapse in the MIHS fused images is clearer than others. So the MIHS fused images are more suitable for the interpretation of regional geological hazard.

3.2 Objective evaluation

Subjective evaluation will be impacted by man-made subjective factors and objective evaluation can overcome the impacts of subjective factors, it can make scientific and objective evaluation for fusion methods. In order to make an objective and reliable assessment of the fused images, some parameters of evaluation should be adopted. The main evaluation parameters are as follows.

① Entropy. Image entropy is an important indicator for image information content. The bigger the entropy is, the greater the information content.

② Average gradient. The average gradient is sensitive to the tiny details of the image. It can be used to evaluate the clarity of image, and the image can also be reflected in the tiny details of texture and the contrast between the characters of transformation.

③ Correlation coefficient. Correlation coefficient reflects the related degree between two images. The correlation coefficients between the fused images and the original LRMIs mean the level that multispectral information has changed. The bigger the correlation coefficient is, the smaller the change of spectrum.

④ Distribution of gray. Image histogram is usually used to express the distribution of gray, and it describes the statistical distribution of image brightness of each pixel value number; it is the probability distribution of all the gray value. Histogram abscissa means gray change of image and the longitudinal coordinate means the pixel number of each image pixel grayscale value. Overall, the histogram is a visual description of image gray distribution in order to reflect the amount of information and distribution character.

Entropy, average gradient and *CC*s of all images are summarized in Tables 3－5.

The histograms of the fused images and the LRMIs are shown in Figure 3.

Table 3 Entropy of all images

	Band 1	Band 2	Band 4
Original LRMIs	6.0952	6.0627	6.0598
BT	5.6371	6.2393	5.1429
HPF	6.9469	6.9428	5.9238
IHS	5.9055	6.4812	5.8278
PCA	6.0089	6.3624	5.9485
MIHS	6.3509	6.2881	6.2971

Table 4 Average gradient of all images

	Band 1	Band 2	Band 4
Original LRMIs	4.0176	2.8171	3.2773
BT	9.9214	9.1894	9.266
HPF	6.6193	6.5239	5.6477
IHS	6.5412	6.8252	6.5109
PCA	10.3735	9.396	9.6198
MIHS	7.3693	7.9691	6.2375

Table 5 Correlation coefficient for the fused image and the original LRMIs

	Band 1	Band 2	Band 4
BT	0.7847	0.9732	0.7844
HPF	0.6441	0.9546	0.2372
IHS	0.8231	0.8786	0.8157
PCA	0.928	0.9616	0.9263
MIHS	0.9455	0.9636	0.9843

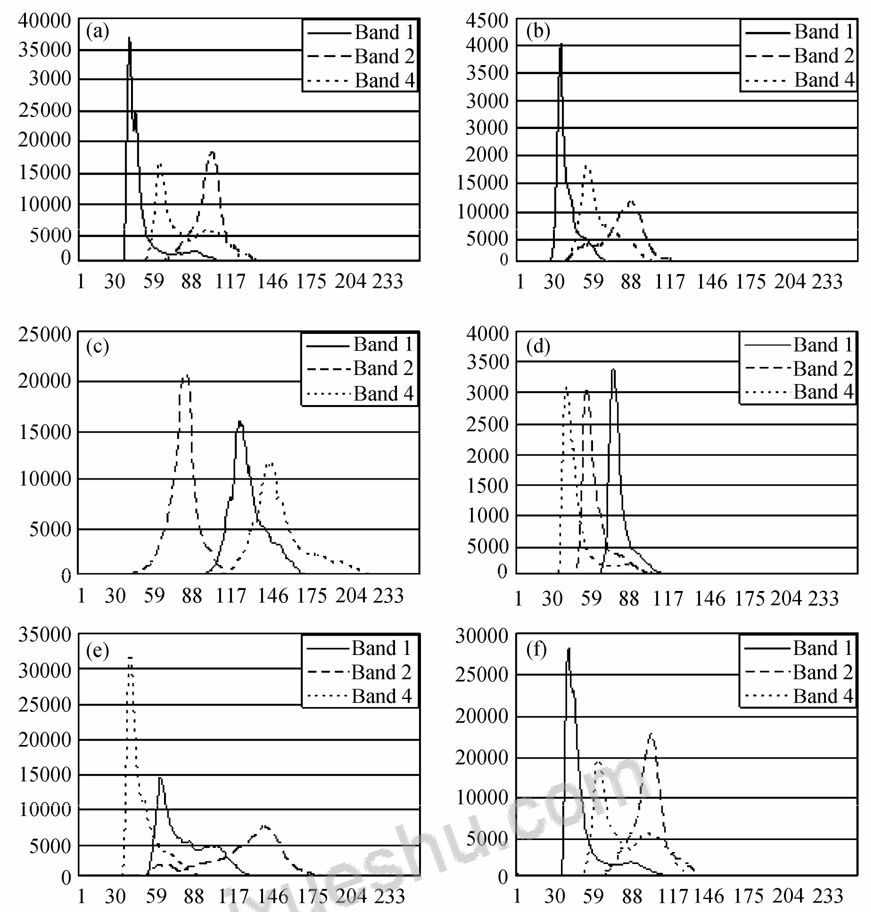

Figure 3 The histograms of the fused images and the LRMIs. (a) The distribution of gray of the original LRMIs; (b) the distribution of gray of the BT fused images; (c) the distribution of gray of the HPF fused images; (d) the distribution of gray of the IHS fused images; (e) the distribution of gray of the PCA fused images; (f) the distribution of gray of the MIHS fused images.

From Table 3 to Table 5 we can see that: ① All the fused images have much more information than the original LRMIs except the BT and IHS fused images, PCA and HPF are especially better than others; ② all the fusion methods can enrich the texture information, but MIHS and PCA are better than the others; ③ the MIHS fused images have the largest *CC*s with the original LRMIs, which means that the MIHS method has maintained the spectral information largely. From the image histograms (Figure 3), we can see that: ① The histograms of the BT and MIHS fused images are similar to the histogram of the original LRMIs, but the three bands of the BT fused images all have moved left to the original LRMIs, so the brightness of the BT fused images is lower than the original LRMIs; ② the histograms of all the other three fused images have large difference from the histogram of the original LRMIs.

From the subjective and objective evaluations we can draw the following conclusion: MIHS method can not only maintain spectral information, but also improve the texture information. Therefore, MIHS method is suitable for survey of geological hazards.

4 Test of interpretation

Remote sensing interpretation of geological hazard is characterized by professional, pertinence and empirical. At present, human-computer interaction is still the primary means for evaluation and identification of geological hazard. Based on the past survey results and the geological environment characters of the study area, remote sensing interpretation methods for study area are shown in Table 6.

Table 6 Remote sensing interpretation of geological hazards[20]

Geological hazards	Interpretation method
Collapse	The collapse has steep chair-shaped back wall and more micro geomorphologic features, it has significant difference from the surrounding geological body in texture etc.
Landslip	Landslip has significant geomorphologic features, most developed in the valley or river on both sides of the steep cliff, scarp, or broken rock zone, the back wall of the landslip is steep and rough. Landslip forms cone accumulation at the foot of the slope, and the color is shallower than surrounding environment.
Debris flow	Gully debris may generally be divided into three parts: source area, circulation area and the accumulation area. Interpretation of the debris flow is mainly the identification of accumulation area, if the image could show clear accumulation of debris flow fan, it can determine the debris flow.

Make MIHS fusion with HRPI and LRMIs of SPOT5 of the geological hazard area, at the same time make a field survey of geological hazard to test the accuracy of remote sensing interpretation, and select 32 geological hazard points for surveying, the accuracy is show in Table 7, which is greater than 90%.

Table 7 Comparison of field survey with geological hazards interpretation

Geological hazard	Collapse	Landslip	Debris flow	Sum
Interpretation result	11	7	14	32
Survey	10	7	13	30
Accuracy	90.9%	100%	92.8%	93.7%

5 Conclusion and discussion

On the regional geological surveys, remote sensing images need to have both high spatial resolution and high spectral resolution; it is a hard task for image fusion[21]. The paper analyzed various fusion methods and evaluation methods; combined the advantages of PCA and IHS, and then proposed a MIHS fusion method. Make subjective evaluation and objective evaluation for all fused images, and the MIHS fused images are the best. Making interpretation and field survey of geological hazard to test the accuracy of interpretation, we can draw the conclusions below.

1) SPOT5 images are the ideal data source for the survey of geological hazards. Yao et al. made interpretation for geological hazard using the fused image of ETM+, the accuracy is merely 59.2%, which is because the low spatial resolution (The spatial resolution of the ETM+ panchromatic image is 15 m) can't meet the request of interpretation (e.g. A 60-m wide alluvial fan of debris only has 4 pixels, and it is hard to make interpretation)[1]. The panchromatic image of SPOT5 is 2.5 m, and the fused image of SPOT5 can find small geological hazard easily, so SPOT5 images are the ideal data source for the survey of geological hazards.

2) All the fusion methods can improve spatial quality and produce color distortion more or less via the fusion process. From the subjective and objective evaluations of all the fused images, we

can see that, the MIHS fusion method can not only maintain spectral information well, but can also improve the texture information largely. Therefore, MIHS is a good fusion method, suitable for the survey of geological hazards. Field investigation shows that interpretation accuracy of the MIHS fused image is 93%, and it can meet the requirements.

Through the comparison analysis of all the fused images of the investigated area, we choose the MIHS fused image as the ideal data source for survey of geological hazards at last. The interpretation accuracy of the MIHS fused images can meet the requirements of geological survey.

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