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Status assessment and causal factors diagnosis of river system health

Jihong Xia[1,2]*, Junqiang Lin[1] and Lei Ju[1]

[1]College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098 China.
[2]National Center for Computational Hydroscience and Engineering, the University of Mississippi, Oxford, USA.

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A healthy river system means its structures can cooperatively and orderly work together and all functions can be well brought to exert when the external disturbance is under a limit extent. This paper had presented the concept framework, which had included status assessment (SA) and cause diagnosis (CD). On the base of the method of describing entropy, health index (HI) of a river system had been defined via order degrees of indicators, which had been calculated by distance far away from their criteria as well as the health grade had been classified and the main problems had been addressed. Using partial least square (PLS) regression, CD had been conducted to diagnose main factors inducing these problems and to establish the regression equation between external variables and internal variable. Meanwhile, the variable importance projection (VIP) had been quantified. In the case of Anxi River, results of status assessment indicated that this river system was healthy in general. However, abiotic indices were low in S2 and S3 reach. After CD had been conducted, it had been revealed that problems of this river system had been induced by the variable of upstream discharge. It had been suggested helpfully that upstream discharge should be controlled in management. Therefore, river system health diagnosis was very helpful and beneficial to river system management.

Key words: River system health, status assessment, causal factors diagnosis, degree of order entropy, partial least square (PLS).

INTRODUCTION

As society had benefitted immeasurably from rivers (Karr, 1999), the rate and extent to which humans had altered rivers had been surpassing our ability to assimilate and understand the implications of our actions (Kay and Schneider, 1994; Kennard et al., 2006). It has resulted that many rivers have been becoming dramatically degraded (Karr, 1999; Pinto and Maheshwan, 2011). The progressive deterioration has aroused concerns about river health (Xu et al., 2004; Guan et al., 2011) and urgent restoration and maintenance measures of `healthy' river ecosystems have been becoming important objectives of river management (Norris and Thoms, 1999; Palmer and Allan, 2006; Vörösmarty et al., 2010).

Fortunately, increasing attention has been being paid on river health in many countries, such as Australia, the United States and the United Kingdom, South Africa, New Zealand, and China (Australian and New Zealand Environment and Conservation Council, 2000; Hohls, 1996; Norris and Thoms, 1999; Mekong River Commission, 2003; Li, 2004; Yang et al., 2005; Liu and Liu, 2008; Su et al., 2011). The diagnosis of stream and river health has been a vital issue in the field of stream restoration and management (Choi et al., 2011). Thus, bewildering varieties of river health concepts and assessment approaches, providing reliable information on the effect of long-term stressors and serve as the

*Corresponding author. E-mail: syjhxia@hhu.edu.cn, jxia1@olemiss.edu. Tel: +86-13002586871.

foundation for the restoration of disturbed systems, have been reported (Pinto and Maheshwan, 2011). For example, "DEPHI" forecasting and hierarchical model were used to select variables and assess river health (Pinto and Maheswan, 2011). All approaches can be classified into three categories: single perspective studies, ecological function based studies and composite studies (Pinto and Maheshwari, 2011). Composite approaches, using of comprehensive indicators, such as Index of Biotic Integrity (IBI) (Karr, 1981) and Rapid Bioassessment Protocols (RBPs) (Plafkin et al., 1989), Australian River Assessment System (AusRivAS) (Simpson et al., 1997), and River Invertebrate Prediction And Classification Scheme (RIVPACS) (Wright, 1995), etc., have been most common and widely accepted. Through these approaches, it has been easy to find symptoms and problems of river system.

Generally, a river system can be defined by their structures and functions. If its structures and functions are disturbed by external natural factors (e.g. climate, flood, etc.) or anthropogenic factors (e.g. pollution, land use, water resource utilization, etc.), a river system might become disorder or unhealthy. Thus, it is necessary to establish the relationships between the internal variables (indicators) of a river system and external factor. Most past works have paid to only the healthy status assessment of a river system. However, quantitative analyses of causal factors have not been done. The relationships between internal variables and external variables have not been effectively established till now. Therefore, an integrated diagnosing approach should be developed, through which not only symptoms and questions could be known, but also specific sources or mechanisms of causal factors could be quantified and revealed (Bunn et al., 1999; Vörösmarty et al., 2010). The objectives of this study was to: (a) construct the concept framework of river system health diagnosis; (b) figure out internal indicators and present method of status assessment of river system; (c) address the external causal factors and bridge the relationship between external causal factors and health status.

METHODS

Study area

Yunhe County is located in southwest of Zhejiang Province, Eastern China (27°53′ - 28°9′ N, 119°21′ - 119°44′ E) with approximately 10.9 million inhabitants and about land area of 984 km^2. About 90% of lands are characterized by mountains and 5% is used as croplands and 5% is aquatic regions. In Yunhe, there are two main catchments both of which are the branches of Oujiang watershed. One is Wutongken River with the drainage areas of 14.84% of Yunhe's total territory. Another is Longquan River, flowing from southwest to northeast, whose drainage areas account for 85.16% of Yunhe's total territory. In the Longquan River catchment, there exist 13 tributaries such as Fuyun River, Mayangkeng River, Linhaikeng River and so on. Anxi River is the largest tributary of Fuyunxi River, which originates in Dongdai, 1178 m high above sea level. It flows through Shangcun, Chengzai and lastly feeds into Fuyunxi River at Gufang with length of 15.33 km, drainage area of 33.28 km^2, average slope 6.8% (Figure 1). In this watershed, annual rainfall is about 1750 mm and flood events have frequently taken place.

Concept framework

'Health' is short hand for 'good condition' (Karr, 1999). A healthy river system implies good internal and external conditions. Good internal conditions are that all elements of structures can be organized orderly and supply good enough functions. Good external conditions imply that external disturbances do not surpass the self-adjustment capacity of a river system. Meanwhile, these structures and functions are easily disturbed by external factors of a river system. The mechanism is shown in Figure 2. Accordingly, health diagnosis of a river system includes two steps. The first step is assessment of internal condition which is called status assessment (SA). In this step, status of river system can be valued and graded so that some symptoms and problems can be known. Secondly, causal factor diagnosis (CD) is performed, in which the relationship between system status and internal factors is established and the degree to external factors acting on river system can be quantified. It is inferred that main external factors causing degradation can be investigated. The procedure framework is shown in Figure 2.

Status assessment

In order to exactly evaluate the status of a river system, health index should be calculated when comprehensive internal variables or indicators of structures and functions of a river system are selected. First of all, a set of internal indicators should be figured out, among of which there exists one indicator representing the most important function. This kind of indicator is named as controlling indicator while other indicators are grouped as cooperative indicators. If controlling indicator is satisfied with its criterion, a comprehensive assessment integrating controlling indicator into cooperative indicators would be conducted. If not, a comprehensive assessment, only considering cooperative indicators, would be performed. As results of the comprehensive assessment, health index could be quantified and health grade could be evaluated. Depending on health index, it would be inferred what the symptoms and problems of a river system identity would be. The procedure is shown in Figure 3.

Indicators of status assessment

In past few decades, some evaluating index systems such as the index of stream condition (ISC) (Landson and White, 1999; Kennard et al., 2006), Environmental Monitoring and Assessment Programme (EMAP) (Huhges et al., 2000), the Isle of Man a River Habitat Survey (RHS) (Raven et al., 2000) have been developed. In these index systems, all variables related to a river system have been considered as the state variables of a river system. However, status of a river system is denoted only by internal indicators, depending on its structures and functions (Bunn and Davies, 2000; Feio et al., 2010). Its structures include biotic elements and abiotic elements. Biotic elements consist of plants, animals and microorganisms, while abiotic elements include flowing water, sediments, nutrients, riparian, bed, etc. There exist comprehensive interactions and matter exchanges as well as energy flows among these elements. Due to these interactions and exchanges, a river system is dynamic and has self-organizing and self-adjusting capability. In functions, a river system has many essential goods and services as well as aesthetic and cultural values (Meyer, 1997;

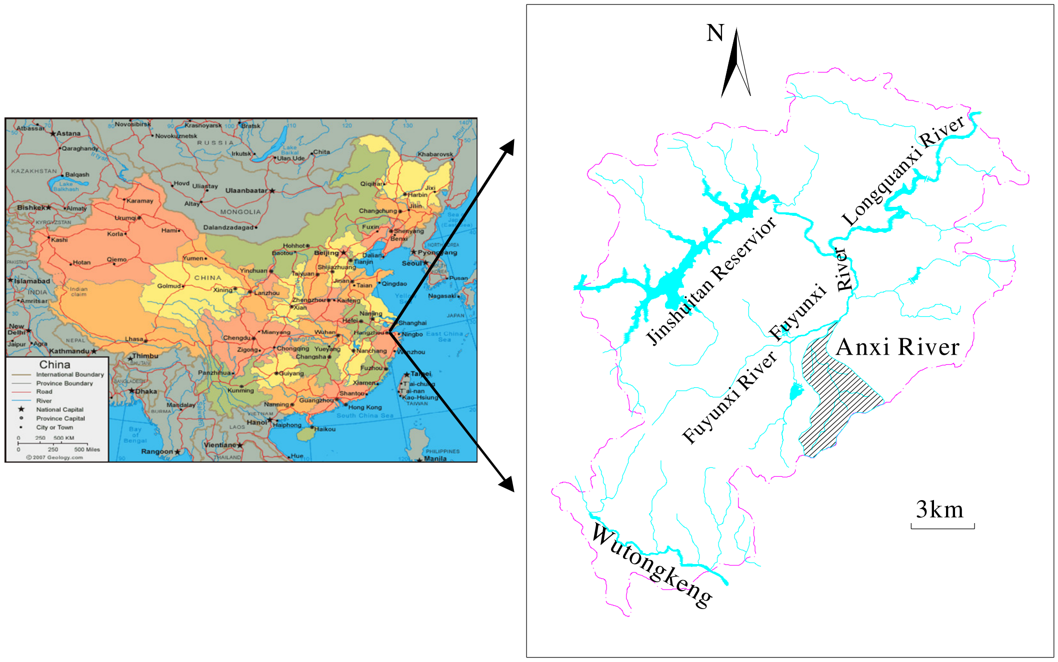

Figure 1. Location of Anxi River.

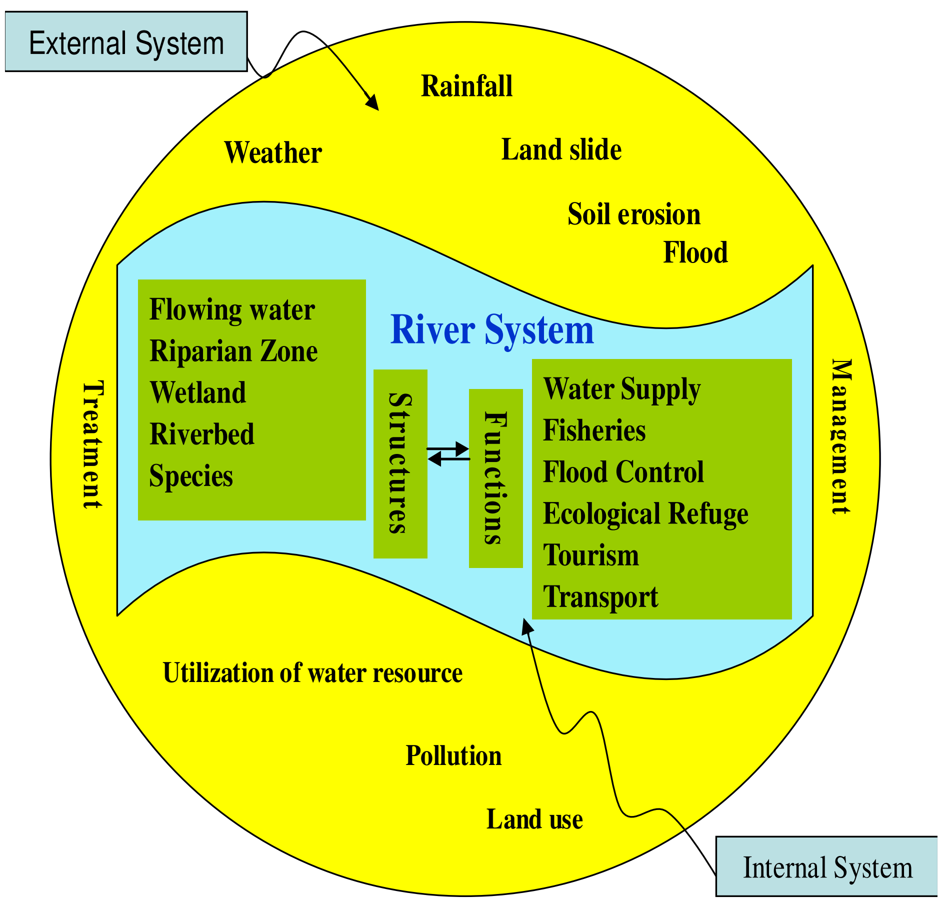

Figure 2. Mechanism of a river system

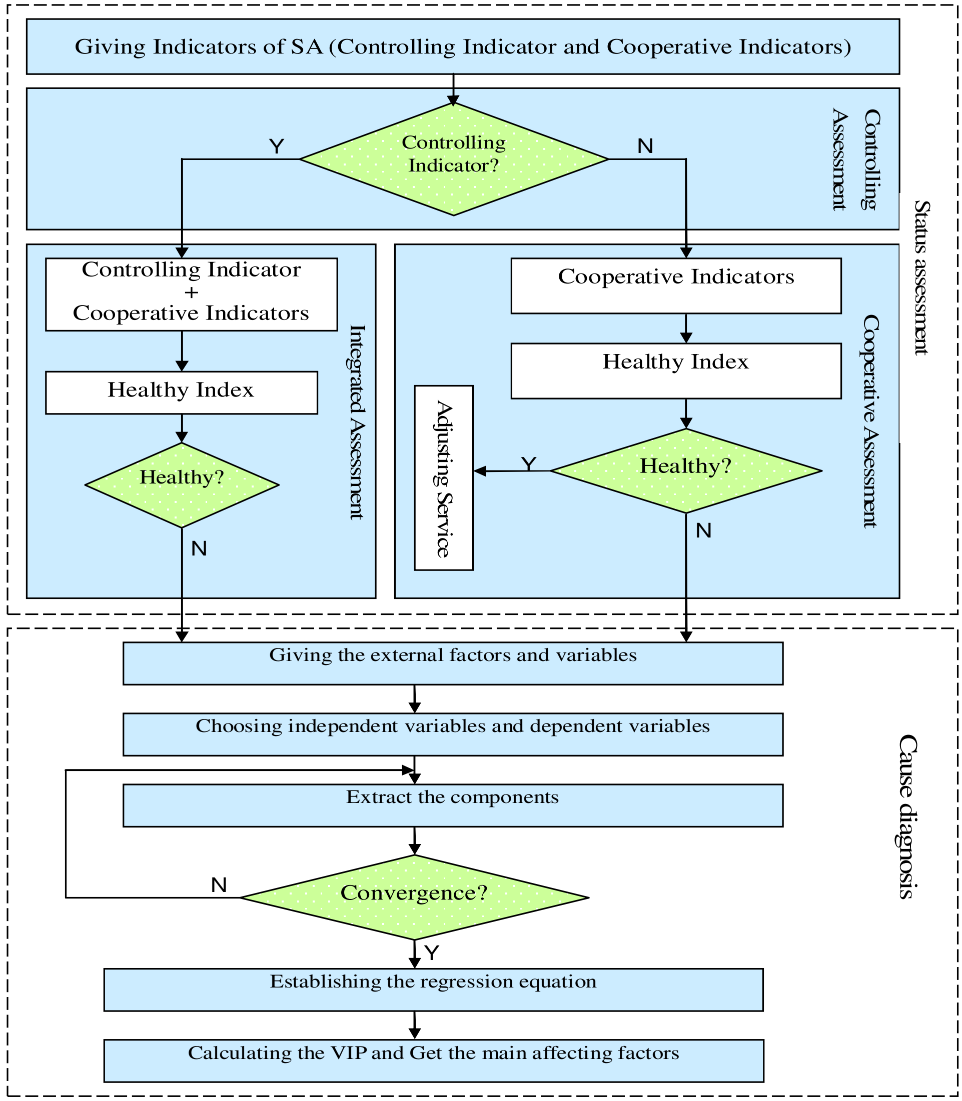

Figure 3. Framework of river system health diagnosis.

Bunn, 2003; Bunn et al., 2010). Commonly, these functions can be classified two types: (a) natural functions which indicate a river system can provide clean drinking water, fisheries production, conservation and biodiversity values, flood management and ecological refuge (Bunn et al., 2010); (b) social functions which mean a river system accommodates communities by providing a medium for transport, recreation, tourism, worship, ecosystem services and a place to experience the serenity of nature (Pinto and Maheshwari, 2011).

Therefore, the indicators of river system health include measures of structures and functions both of the biotic and of the physical components (Norris and Thoms, 1999), which are classified into three sub-indices: abiotic index, biotic index and service index. Abiotic index can be denoted by runoff variation ratio (C_{11}), connectivity (C_{12}), comprehensive stability (C_{13}) and wetland conservation ratio (C_{14}). Biotic index can be comprehensively reflected by biodiversity index (C_{21}), vegetation covering ratio (C_{22}), and ecological discharge insured ratio (C_{23}). Service index can be measured by flood safety index (C_{31}), landscape suitability index (C_{32}), up-to standard rate of water quality (C_{33}), water supply insured ratio (C_{34}) and navigation insured ratio (C_{35}). The hierarchy indicators of SA are shown in Table 1.

Calculation of health index

A river system constitute dissipative systems with many spatial freedom degrees which are reflected by entropy (Jackson, 1968; Rodríguez-Iturbe et al., 1992; Zhao et al., 2009). The more random and chaotic is a system, the higher is entropy. Commonly, entropy of a variable is quantified by its order degree which is determined by the relative distance far away from its ideal value. According to the responding trend of internal variables to order degree, there are three types of variables: increasing-orient variables, decreasing-orient variables and middle-orient variables. The increasing-orient variables are beneficial to river system health with its value increasing. Inversely, those variables are the decreasing-orient variables. Additionally, there are middle-orient variables which have better effect on river system health when its value is more close to a middle fixed value. The order degree ε is defined as Express (1)

Table 1. Indicators of status assessment.

Health Index	Sub-index	Indicators	Denotation
River system health index A	Abiotic index B1	Runoff variation ratio-C_{11}	Variation of annual runoff over average mean annual average runoff
		Continuity -C_{12}	Area of connective water body over total area of water body in water shed
		Comprehensive stability -C_{13}	Length of collapsed river over total river length
		Wetland conservation ratio-C_{14}	Decrease of wetland area over total wetland area
		Riparian width index -C_{15}	Length of riparian satisfied with needs over total riparian length
	Biotic index B2	Biodiversity index -C_{21}	Species numbers in river reach over total numbers in this watershed
		Vegetation covering ratio -C_{22}	Riparian area covering by vegetation over total riparian area
		Ecological flux insured ratio-C_{23}	Days satisfied with leas ecological discharge in one year
	Service index B3	Flood safety index-C_{31}	Flood possibility satisfied with 10-year flood
		Landscape suitability index-C_{32}	Population satisfied with the landscape over total population
		Up-to-standard rate of water quality -C_{33}	Sample numbers satisfied with water quality needs over total sample numbers
		Water supply insured ratio-C_{34}	water requirement over water supply
		Navigation insured ratio-C_{35}	Days satisfied with navigation in one year

and entropy of a variable is defined as Express (2).

$$\varepsilon = \begin{cases} \dfrac{R_{real} - R_{\min}}{R_{\max} - R_{\min}}, & \text{for increasing - orient variables} \\ \dfrac{R_{\max} - R_{real}}{R_{\max} - R_{\min}}, & \text{for decreasing - orient variables} \\ 1 - \left| \dfrac{R_{real} - R_{fix}}{R_{fix}} \right|, & \text{for middle - orient variables} \end{cases} \quad (1)$$

where, ε is order degree of a variable; $R_{\max}$ is the maximum value of a variable; $R_{\min}$ is the minimum value of a variable; $R_{fix_{ij}}$ is the middle fixed value; R_{real} is the real value of a variable.

$$e = -\varepsilon \log \varepsilon \quad (2)$$

where, *e* is the entropy of variable.
When the order degree and entropy of each indicator are obtained, the sub-indices are valued by Express (3).

$$SUBHI_j = -\sum_{i=1}^{n} \omega_{ij} \varepsilon_{ij} \log \varepsilon_{ij} \quad (3)$$

Where, $SUBHI_j$ is the health index of the *j-th* subsystem (*j*=1,2,3); ω_{ij} is the weight coefficient of the *i-th* indicator within the *j-th* subsystem; ε_{ij} is the order degree of the *i-th* indicator in the *j-th* subsystem; *n* is the number of indicators in the *j-th* subsystem.
Health index of a river system or reach is determined by sub-indices which depend on theirs indicators. It can be obtained via Express (4).

$$HI = \sum_{j=1}^{3} w_j SUBHI_j \quad (4)$$

Where, HI is the health index of a river system or reach; w_j is the weight coefficient of the *j-th* subsystem; $SUBHI_j$ is health index of the *j-th* subsystem. ω_{ij} and w_j can be obtained by use of analytic hierarchy process (AHP) (Saaty, 1990).

Causal factors diagnosis

The objective of causal factors diagnosis is to pick up the main causal factors that induce the symptoms and problems of river system health. Firstly, we would select some variables featuring external causal factors as exogenous variables and define the health index or sub-indices as endogenous variables, then we would establish the regression relationship between exogenous variables and endogenous variables by use of partial least square (PLS) regression (Haenlein and Kaplan, 2004).

Causal factors and endogenous variables

Ideally, the factors chosen should assist in the diagnosis of the probable cause of health degradation and inform management actions (Dole´dec et al., 2006; Bailey et al., 2007). A river system is usually affected by natural and human causes. Rainfall is the main natural cause which can result in flood, erosion and pollution. Particularly, runoff from roads and fields containing large amount of litter and other harmful pollutants such as petroleum hydrocarbons, zinc, lead, copper, chromium enters and pollute rivers. Today, storm water pollution is a big problem facing our rivers (http://www.melbournewater.com.au/). Commonly, the influence intensity of rainfall is interpreted by two variables of average rainfall and largest rainfall.

The short-term monetary gains of many past economy-driven management decisions have resulted in harmful long-term healthy consequences (Kay and Schneider, 1994). Many of our rivers and streams have been changed dramatically due to human activities such as deforestation, farming, hydraulic engineering, pumping water, floodplain cultivation, navigation, urbanization and so on. These threats or causes can be grouped as seven categories: rainfall, pollutant, water resource development, illegal occupation activity, unnecessary hydraulic construction, urbanization, and management. Each type of cause can be quantified by its corresponding variables. Rainfall can be interpreted by average rainfall, and largest rainfall, and flood frequency and soil erosion. As there are four types of pollution sources: industry, farming, sewage, fishery, stockbreeding, pollution cause can be quantitatively described by variables of industrial pollutant, farming pollutant, sewage pollutant, fishery pollutant and stockbreeding pollutant. Water resource is the basic resource of industry, agriculture and living. The cause of water resource development depends on upstream discharge, industrial water consumption, agriculture water consumption and living water consumption. Sometimes, river systems may be illegally occupied for enlarging lands or sands from river bed. It results that aquatic area is reduced and river stability is declined. These changes can be measured by variables of water area variation ratio and digging sand ratio. In a river system, crossing constructions and bank protection may be built which have influence on regulating flood ratio and concreting riparian ratio. Urbanization is described via urbanization ratio and management cause can be illustrated by illegal event ratio. The cause variables and their denotations are shown in Table 2.

Establishing regression equation

The PLS was developed by Wold in the late 1960s (Carrascal et al., 2009). Its goal is to predict or analyze a set of dependent variables from a set of independent variables or predictors (Abdi, 2007) and to establish regression relationship between dependent variables and independent variables (Höskuldsson, 1988; Carrascal et al., 2009). Using of PLS, original multidimensionality is declined and intepretation of independent variables is maximized by extracted predictors.(Hubert and Branden, 2003; Maestre, 2004). We consider external variables of river system as independent variable set $[x_1, x_2, x_3, ..., x_{21}]$ and sub-indices as dependent variable set $[y_1, y_2, y_3]$. If there are *n* sample observations, $X_{n\times 21}$ represents the data matrix $[x_1, x_2, ..., x_{21}]_{n\times 21}$ of independent variables and dependent variables matrix $Y_{n\times 3}$ is $[y_1, y_2, y_3]_{n\times 3}$. Supposing t_j as the latent variables of independent variables and u_j as the dependent variables (*j*=1,2,…,*m*), and then a regression model between t_j and u_j is developed. Wold et al. (2001) and Li (2002) presented the procedure through which the regression equation could be established, as follows (Li et al., 2002).

$$u_j = b_j t_j + e_j \quad j = 1,...,m \tag{5}$$

Where, e_j is a vector of errors and b_j is estimated by:

$$b_j = (t_j^T t_j)^{-1} t_j^T u_j .$$

The latent variables are computed by $t_j = X_j w_j \quad u_j = Y_j q_j$, where, w_j and q_j have unit length and are determined by maximizing the covariance between t_j and u_j. Then, $X_{j+1} = X_j - t_j p_j^T$, and $Y_{j+1} = Y_j - t_j q_j^T$,where, $X_1 = X$; $p_j = X_j^T t_j /(t_j^T t_j)$; $Y_1 = Y$; $q_j = Y_j^T t_j /(t_j^T t_j)$. The number of iteration steps is determined by use of cross-validation. Cross-validation is a practical and reliable way to test this predictive significance (Wold et al., 2001). Wold's R criterion, which is based on cross-validation, has been the typical approach used to select the number of latent variables (Li et al., 2002). We suppose the *i*-th group data of *Y* is y_i, and $\hat{y}_{hi}$ is the fitting value of the *i*-th group *Y* when *h* components have been extracted, and $\hat{y}_{h(-i)}$ is the fitting value of Y when the *i*-th group observation is omitted and *h* components have been extracted. Then, the sum of squares of these differences(*SS*) is computed and collected from all the parallel models to form the predictive residual sum of squares (*PRESS*), which estimates the predictive ability of the model (Wold et al., 2001). SS_h and $PESS_h$ and predicted variation Q_h^2 can be obtained as Express (6) to (8).

$$SS_h = \sum_{i=1}^{n} (y_i - \hat{y}_{hi})^2 \tag{6}$$

$$PRESS_h = \sum_{i=1}^{n} (y_i - \hat{y}_{h(-i)})^2 \tag{7}$$

$$Q_h^2 = 1 - \frac{PRESS_h}{SS_h} \tag{8}$$

Usually, when Q_h^2 is larger than 0.095, the prediction and regression is satisfied.

Variable importance projection

The models are interpreted with the help of variable importance in the projection (*VIP*s). The *VIP*s represent the importance of the descriptors for the model, both with respect to correlation to *Y* and with respect to *X* (the projection). Each descriptor is uniquely and independently described by its VIP, which represents a measure of the contribution of the term to the decomposition of *X*, and the correlation with *Y*. Moreover, the *VIP*s are normalized so that they

Table 2. External causal factors and endogenous variables.

External causal factor	Endogenous variables	Denotation
Rainfall	Average rainfall-x1	Average rainfall over past few years
	Flood frequency - x2	Frequency of 10-year flood
	Largest rainfall - x3	The largest rainfall of this year
	Soil erosion- x4	Total soil erosion of this year
Pollution	Industrial pollutant - x5	Mass of pollutant discharging from factories into river this year
	Farming pollutant - x6	Mass of pollutant discharging into river due to farming fields
	Sewage pollutant - x7	Mass of pollutant discharging into river due to resident living sewage
	Fishery pollutant - x8	Mass of pollutant discharging into river due to fishery
	Stockbreeding pollutant - x9	Mass of pollutant discharging into river due to stockbreeding
Water resource utilization	Industrial water consumption - x10	Water resource for industry
	Agriculture water consumption - x11	Water resource for agriculture
	Living water consumption - x12	Water resource for residents living
	Upstream discharge- x13	Water resource discharging from upstream reach
Occupying activity	Water area variation ratio- x14	Variation of water area due to illegally occupying river
	Dug sand ratio- x15	Variation of sand due to illegal human digging
Hydraulic construction	Regulating flood ratio - x16	Storage volume divided by flood volume by use of hydraulic constructions
	Concreting riparian ratio- x17	Riparian area covering by concreting over total riparian area
Urbanization	Population- x18	
	GDP- x19	Total population in watershed
	Urbanization ratio- x20	Gross domestic product in watershed
Management	Illegal event ratio- x21	Average rate of change of the size of the urban population over the given period of time

can be compared. Terms with a large value of *VIP*, larger than 1, are the most relevant for explaining dependent variable. Importance degree of independent variable x_j can be calculated by the next Express (9) and (10).

$$VIP_j = \sqrt{\frac{p}{Rd(y;t_1,t_2,...,t_m)}\sum_{h=1}^{m} Rd(y;t_h)w^2_{hj}} \quad (9)$$

$$Rd(y;t_1,t_2,...,t_m) = \sum_{h=1}^{m} Rd(y;t_h) = \sum_{h=1}^{m} r^2(y,t_h) \quad (10)$$

Where, VIP_j is the variable importance projection of independent variable x_j to dependent variable y; $Rd(y;t_1,t_2,...,t_m)$ is the ability to explain y by $t_1,t_2,...,t_m$; $Rd(y;t_h)$ is the ability to explain y by t_h; $r(y,t_h)$ is the relative coefficient between y and t_h.

Data

As Anxi River lies in mountain region, it has big variation in its geomorphology. Terrain slopes between different reaches vary from 0.75 to 10.69% and the mean slope is 6.8%. The steepest reach is from Dongdai to Shangcun, where the slope is 10.69%. The flattest reach is from Zhifan to Gufang, where the slope is 0.75%. In terms of terrain slope, Anxi River can be divided four reaches as shown in Figure 1. The first reach(R1) is from Dongdai to Shangcun, 4.536 km long; the second reach (R2) is from Shangcun to Dongkeng, 2.864 km long, whose slope is 2.31%; the third reach (R3) is from Dongkeng to Zhifan, 1.689 km long, whose slope is 7.98%; the fourth reach is from Zhifan to Gufang, 6.241 km long, whose slope is 0.75%. Based on statistic data in 2007, the values of these indices have obtained as shown in Table 3. To

Table 3. Values of indicators of Status Assessment (in 2007).

C_{35}	0	0	0	0
C_{34}	0.541	0.562	0.569	0.547
C_{33}	1.000	1.000	1.000	0.980
C_{32}	0.891	0.879	0.883	0.880
C_{31}	0.724	0.748	0.732	0.765
C_{23}	0.846	0.863	0.874	0.941
C_{22}	0.962	0.502	1.000	0.227
C_{21}	0.301	0.301	0.301	0.419
C_{15}	1.000	1.000	1.000	1.000
C_{14}	1.000	1.000	1.000	0.987
C_{13}	0.845	0.821	0.809	0.823
C_{12}	0.984	0.992	0.978	0.982
C_{11}	-0.060	-0.079	-0.072	-0.074

Table 4. Values of independent variables.

Year	*X1*(t)	*X2* (m^3)	*X3* (t)	*X4* (%)
2007	8760	90687	5320	61.28
2006	8910	108274	3630	61.25
2005	9040	105410	2230	54.24
2004	8860	85187	1230	54.21
2003	8670	72011	1230	54.20
2002	8500	101056	1220	52.17
2001	8530	102145	1210	52.16
2000	8590	108217	1200	52.13
1999	8630	100941	1190	52.12
1998	8670	108102	2580	47.09
1997	8710	98822	3760	39.58
1996	8760	80547	3750	30.55
1995	8810	106728	3740	18.54
1994	8850	101285	2250	13.01
1993	8760	88338	1410	11.50

mountain rivers, the worst health problem is its safety degradation. Generally, factors causing the health problems of soil erosion (*X1*), upstream discharge (*X2*), Digging sand mass (*X3*) and concreting riparian ratio (*X4*) are selected as independent variables. Values of independent variables and from 1993 to 2007 are shown in Table 4.

RESULTS

Health index of Anxi River

As Anxi River belongs to a typical mountain river, there are frequent flood disasters in this catchment. It would be harmful to river stability or ecological safety or resident safety. For instance, the most serious flood event happened in 2005. It results that some reaches, about 5 km long, were collapsed, and about 20 houses were broken out and approximate 10 km^2 crops were submerged. In terms of this, it is very important to keep Anxi River safety from flood disasters. Therefore, safety of flood control can be used as the controlling indicator. Basically, controlling assessment can be conducted on the base of data in 2007. As results, it is inferred that controlling indicator satisfied its healthy criterion. Then the integrated assessment can be executed. Firstly, the order degree of each internal indicator can be obtained by use of Express (1) and weights of internal indicators can be valued through AHP. Secondly, sub-indices can be determined in terms of Express (3) and the weights of sub-systems can be calculated in AHP. When compounding sub-indices and their weights, we can get the health index (Table 5), in terms of which grade of

Table 5. Health Index and Sub-index(in 2007).

	Abiotic index	Biotic index	Service index	Health index
S1	0.603	0.935	0.645	0.718
S2	0.599	0.854	0.665	0.699
S3	0.585	0.943	0.663	0.720
S4	0.660	0.807	0.693	0.716
Average	0.612	0.885	0.667	0.713

health status can be inferred.

Regressive equation

According to result of SA, we set the abiotic index as dependent variable (*Y*). Applied method of PLS, regressive equation between the dependent variable and the independent variables can be established as Express (11) (R^2=0.95, *Q2*=0.45).

$$y=-0.0024X1+X2+0.0025X3-0.0018X4 \quad (11)$$

Express (11) denotes the regression relationship between abiotic index and all these independent variables. However, different factors have different influence degree on dependent variable.

Conclusion

How can we know whether the outside effects overrun limitation of river system and what factors play main function on a river health? Quantitative diagnosis on a river system can help to solve these issues. In the case of Anxi River, its health status was assessed and its causal factors were diagnosed. In terms of value of health index (*HI*), we classified health status into three grades: Health, subhealth and disease. When *HI* is less than 0.50, a river system is disease; When *HI* lies in between 0.5 and 0.65, a river system is subhealty; When *HI* is larger than 0.65, river system is healthy (Suo et al., 2008; Liu and Liu, 2009).

As the general *HI* of Anxi River is 0.713, it is inferred that health status of this river belongs to healthy grade. But the sub-indices have large difference. For instance, the average value of biotic index is the largest, 0.885 which illustrates Anxi Stream has rich species components and fine ecological integrity. But in different reaches, health index of each reach varied greatly each other. Health index of S3, 0.720, is the highest. It means that S3 is best. Inversely, health index of S2, 0.699, is the least. It shows that S2 is not better than other reaches although S2 belongs to health grade. Moreover, the average abiotic index of Anxi River is only, 0.612, which implies that there exist some problems in abiotic structures of river system. According to the assessment of each reach, respectively, abiotic indices of S2 and S3 are 0.599 and 0.585, which is less than 0.6. It shows that structure statuses in S2 and S3 are the most serious. Thus, much more focus should be paid on this segment.

It is necessary to analyze what factors cause this problem. So, abiotic index has been considered as the dependent variable. The significance of each factor is illustrated by variable importance projection (*VIP*). Basically, the *VIP* can be obtained by the use of Equation (12) and (13). Respectively, the *VIP*s of *X*1, *X2*, *X3* and *X4* are 0.114, 3.851, 0.291 and 0.276 as shown in Figures 4 and 5. The *VIP* of *X*2 is the largest, which illustrates the upstream discharge plays the most significant role in abiotic index. In fact, because there is a sudden turn and the terrain slope in the third reach varies dramatically, flow, flow regime has dramatic variation and carries large hydraulic energy when water flows through this reach. Intensive flow turbulence can result in potential risk of bank or bed damage. So as to keep healthy status of this river, it is importance to control the upstream and improve flow condition through suitable mending. It is helpful to manager to make good decisions to improve the health index. Therefore, the results of diagnosis can help decision makers to take ecological restoration treatments to reduce the intense variation of upstream discharge. Therefore, river system health diagnosis is a useful tool for river management.

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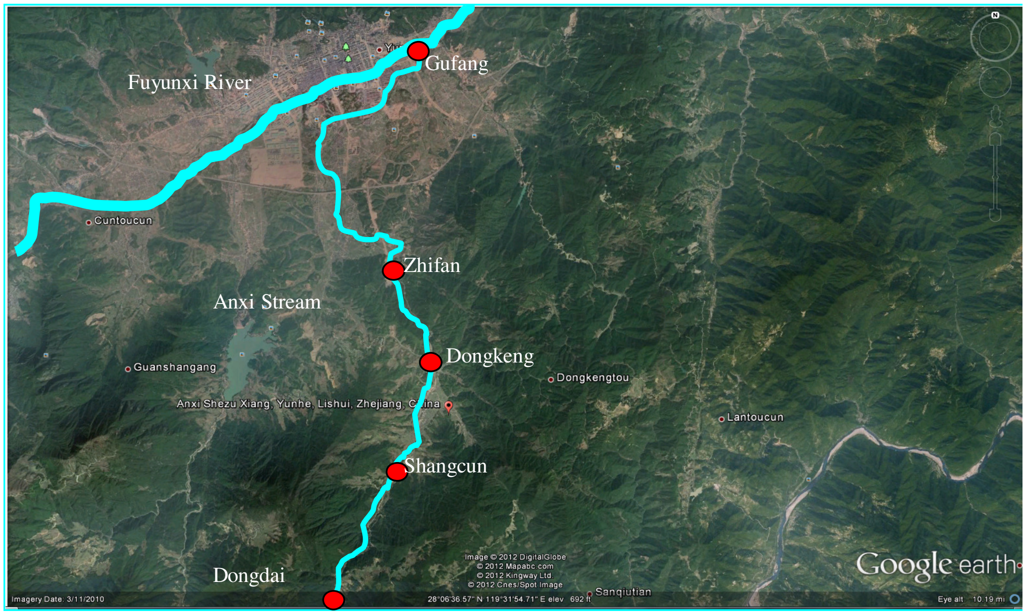

Figure 4. Four reaches of Anxi River.

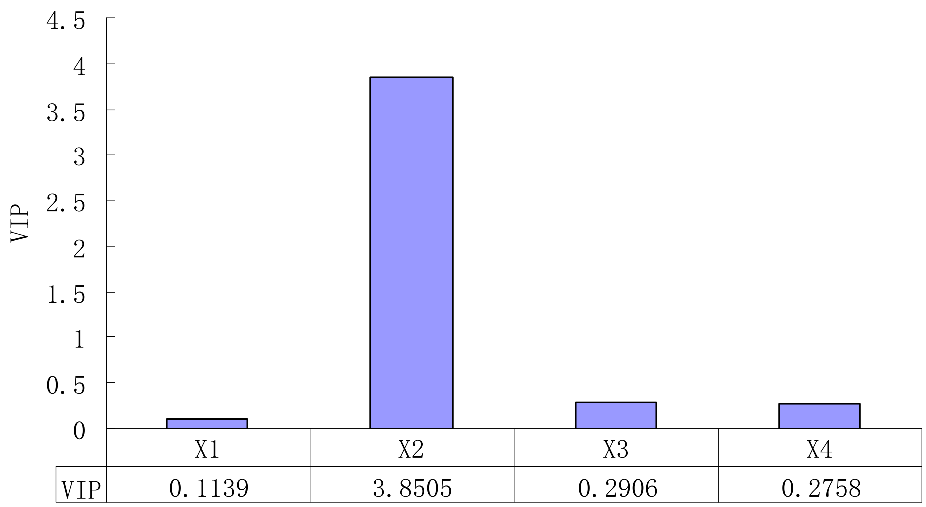

Figure 5. Independent variables' *VIP* to dependent variables variable *y*.

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