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Methodological Guidelines for Vulnerability Assessment of Freshwater Resources is to support assessment at different scales (regional, national, basin and sub-basin), with the primary goal of generating timely and credible information for informed decision making on Integrated Water Resources Management (IWRM) and the achievement of the Millennium Development Goals (MDGs). The guidelines prioritize the key IWRM issues – namely the development and use of water resources, ecosystem health and management challenges – and have developed MDG-relevant indicators for quantifying the vulnerability of freshwater resources to environmental change.

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METHODOLOGIES GUIDELINES

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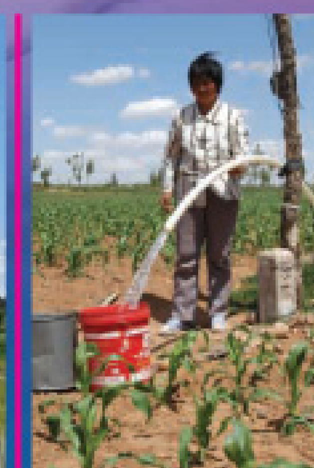
Vulnerability Assessment of Freshwater Resources to Environmental Change



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Inside Front Cover

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METHODOLOGIES GUIDELINES

Vulnerability Assessment of Freshwater Resources to Environmental Change

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Acronyms

DPSIR	Driver, pressure, state, impact and response
EH	Ecological health
GDP	Gross Domestic Product
GEO	Global Environment Outlook
IDWS	Improved Drinking Water Supply
IS	Improved sanitation
MC	Management challenges
MDGs	Millennium Development Goals
R&D	Research and Development
RS	Resource stresses
UNEP	United Nations Environment Programme
US	United States
USD	United States dollar
VI	Vulnerability Index

Abbreviations and Symbols

km	Kilometres
km^2	Square kilometres
km^3	Cubic kilometres
MCM	Million cubic metres
m	Metres
m^3	Cubic metres
mm	Millimetres

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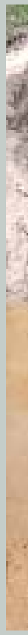

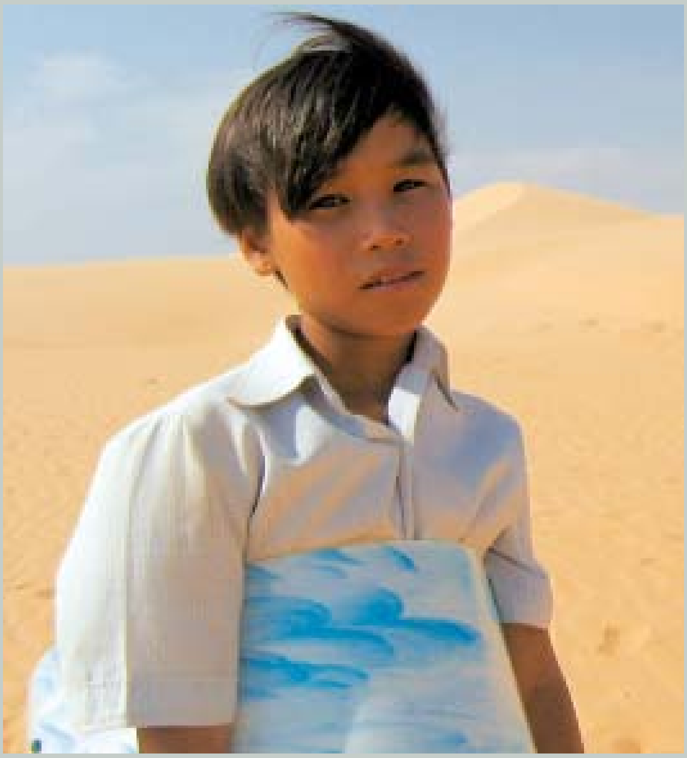

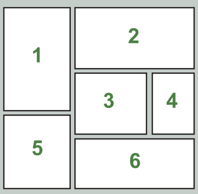

1. Indus river
Source: www.sxc.hu/Vinish K Saini

2. Helping hand, India
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Source: www.sxc.hu/Vlado Sestan

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5. Vietnamese boy, White sand dune, Muine
Source: Nadhika Mendhaka

6. Sirindhorn Dam, Ubon Rachatani, Thailand
Source: Keerati Tantasuwat

FOREWORD

Since 2000, the United Nations Environment Programme (UNEP) and its partners in the UN system, along with a number of universities and research institutes in Africa and Asia, have collaborated to assess the vulnerability of freshwater resources to environmental change, with the primary goal of generating timely and credible information for informed decision making on Integrated Water Resources Management (IWRM) and the achievement of the Millennium Development Goals (MDGs).

Based on the experience gained in Africa and Asia, Peking University of China and UNEP, with contribution of other partners, compiled these *Methodological Guidelines for Vulnerability Assessment of Freshwater Resources* to support assessment at different scales (regional, national, basin and sub-basin). The guidelines prioritize the key IWRM issues – namely the development and use of water resources, ecosystem health and management challenges – and have developed MDG-relevant indicators for quantifying the vulnerability of freshwater resources to environmental change. Using these methodological guidelines, comprehensive assessments have been conducted for nine major river basins in Northeast Asia, South Asia and Southeast Asia, with the findings presented in separate reports.

These guidelines are an excellent example of UNEP's role in promoting South-South cooperation in protecting water resources. It is very encouraging to know that several countries in Asia are now preparing national comprehensive assessments using these guidelines, and that regional and subregional water vulnerability assessments are planned in East Europe, Latin America and the Caribbean and West Asia using the same approach.

Achim Steiner

United Nations Under-Secretary General and Executive Director

United Nations Environment Programme

October 2008

1 Introduction

Agricuture near Mekong River, Thailand
Source: Keerati Tantasuwat

This document aims to provide a general framework to partners under UNEP's project on "Vulnerability Assessment of Freshwater Resources to Environmental Change". The framework is developed on the basis of available knowledge of the field, with full consideration of data availability and other constraints, and is intended to be a common platform for partners to adopt their studies, and produce comparable results for regional and inter-basin synthesis at later stage of this joint effort. However, this framework should not be regarded as a rigid template for carrying out such studies, but rather as a tool and guideline to be adapted on the basis of a basin's specific situation.

Because this is a working document for all the partners of the region, and improving this document will be an on-going process, all partners are encouraged to provide feedbacks for further improvements, based on experiences gained during the course of project implementation.

The financial support from the Government of Belgium to this project is gratefully appreciated.

2
Methodology

2.1 Vulnerability and Vulnerability Assessment of Water Resources

Water, the "blood" of the natural ecosystems, has an indispensable role for almost all functions of an ecosystem. Water also is one of the most critical resources needed to support the socioeconomic development of the human society. As a result of rapid population expansion, fast economic development, and mismanagement of water resource, however, water has now become one of the scarcest resources. Thus, sustainable water resource management has been on the priority list of many national agendas.

Formulation of an integrated water resource management policy will require a comprehensive knowledge support, with understanding of the vulnerability of water resources being a key element for this purpose. Vulnerability is usually a term used to describe any weakness or flaw existing in a system, the susceptibility of a system to a specific threat and harmful event, and/or the challenges a system faces in coping with the threat agents. From water resource management perspective, **vulnerability** can be defined as: *the characteristics of water resources system's weakness and flaws that make the system difficult to be functional in the face of socioeconomic and environmental change.* Thus, the vulnerability should be measured in terms of: (i) exposure of a water resources system to stressors at the river basin scale; and (ii) capacity of the ecosystem and society to cope with the threats to the healthy functionality of a water system.

Thus, this **vulnerability assessment** is an investigation and analytic process to evaluate a system's sensitivity to potential threats, and to identify key challenges to the system in reducing or mitigating the risks associated with the negative consequences from adversarial actions. Such an assessment for a water system takes into account the balance of the water supply and demands, and the tenure system and policy to support water resources conservation and management, as well as the hydrological variations under changing climate and other environmental factors. It also considers risks posed to the surrounding communities that can influence the water system. An effective vulnerability assessment serves as a guide to water utilities by providing a prioritized plan for security upgrades, modifications of operational procedures, and/or policy changes to mitigate the risks and vulnerabilities to the utility's critical assets. The vulnerability assessment provides a framework for developing risk reduction options and associated costs. In practice, for each identified issue, a water resource vulnerability assessment process needs to **determine driving forces; estimate the pressures; understand the current state and trends; analyze the impacts; and define and formulate responses to cope with vulnerability of the water system.**

2.2 Basic Principles

Vulnerability of freshwater resources will be explored by isolating strategically-important issues related to different functions (uses) of freshwater systems in a basin, and represents a considerable departure from preconceived notion of a "water crisis" being synonymously linked to vulnerability. Three degrees of freedom will lay the logical conceptual foundation, therefore being of paramount importance, comprising STRESS, ADAPTATION, and COOPERATION.

WATER STRESS is a term describing the state of water resources in meeting the demands of a region's overall socioeconomic development. Thus, water stress embodies two fundamental concepts, including water shortages in time and space, and conflict over sectoral usages, a decline in service levels, crop failure, food insecurity, etc. Water stress occurs when water demands exceed the available quantity of water during a specific time period, or when poor water quality restricts its use. Thus, water stress is caused by deterioration of freshwater resources, in terms of quantity (aquifer over-exploitation, dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.), being a result of unsustainable water resources development practices under a given biophysical and socioeconomic context. It is very important to understand that the notion of stress is also economically- and culturally-constituted. Beyond the 3 $L.d^{-1}$ required for basic human survival, water "demand" and even "need" are not absolute values. Rather, they depend on social and consumptive habits that also are culturally-bound, and differ between countries and within regions.

ADAPTATION relates to a process of societies and ecosystems dealing with water stresses, and refers to the capability of societies and ecosystems to handle their water resource threats. A basin or countries in a basin can be either well- or poorly-endowed with freshwater resource but still there is a need (acutely perceived by societies, administrative organizations, and managers responsible for dealing with freshwater stress) to find the appropriate societal tools for dealing with the social and environmental consequences of freshwater stress. However, the capacity of ecosystems and societies to adapt to the stressors varies from case to case, and the purpose of the vulnerability assessment needs to picture that to what a degree society and ecosystem are unable to accommodate the water stresses.

COOPERATION is introduced to give due cognizance to water use and ownership. Because river basins usually stretch over different administrative and geographical units and state borders, the potential for conflicts over the use of water resources exists for most river basins, especially transboundary basins. Although cooperation between competent actors to mitigate the conflicts is needed, it is usually a complicated issue. It is argued that, even if the basin is water-rich, and has the societal and economic choices to harness the resources, it may still lack a mechanism for redistributing water among uses and/or countries, depending on the political setting and the willingness to cooperate.

2.3 Approach

As discussed earlier, the vulnerability assessment of freshwater resources needs to measure the stressors faced by a water system, as well as the capability of the system to accommodate the stressors. A healthy state of a water resources system, however, can be seen as the result of the interactions between stressors and the system's adaptation processes. Thus, the vulnerability of a water resources system can be assessed with a diagnostic analysis of the state of the freshwater system under a given socioeconomic and biophysical context, in order to identify key problems existing in the system, and further causality analysis of the identified problems can be conducted to identify the main stressors and the accommodating capability of the freshwater system in the society. This process of vulnerability assessment represents a result-based assessment approach.

Figure 1 illustrates the water resources base in a river basin, and its relation to the hydrologic process and water resources development and use. Following the hydrologic process, and based on water resources development and use, a basin-wide water resources balance will include 4 key components, including: (1) water resources formulation from natural hydrologic processes; (2) development and use of water resources for maintaining human well-being and socioeconomic development; (3) water resources for maintaining the ecological/environmental functions of a river basin; and (4) management capacity (Figure 2.1).

A healthy water resource management system, therefore, can only be realized after establishment of a rational, coordinated relationship between the 4 fundamental components through appropriate management schemes. Thus, vulnerability assessment of a river basin must incorporate a precise understanding of the following 4 components, including its state, trends and relationship with its context, as follows:

(1). **Total water resource:** Analysis of the hydrologic balance *before* considering any water resource development and use, thus being the water resource formulation from a natural hydrologic process, and its relationship with global climate change and local biophysical conditions.

(2). **Water resource development and use:** Analysis of water resources supply and need balance, being mainly the water resources development capacity via an engineering approach, and its relation to water resource use, including domestic water use and development trends associated with urbanization and modernization, as well as water resources support to the economic development.

(3). **Ecological health:** Analysis of water resources *after* their development and use for domestic and economic use, for maintaining ecological health of the basin, and its supply and demand relations, as well as key issues in the process. At the same time, the analysis will need to be conducted on water quality, as a consequence of water resources development and use (pollution), and its further influence to water resources budgeting within a river basin.

(4). **Management**: The above 3 components focused on the natural process, or natural adaptation, of freshwater resources development and use. The natural process, however, is usually heavily influenced by the social adaptation capacity to freshwater resources (i.e., the management capacity of freshwater resources plays an important role in enhancing a healthy freshwater resources development and use system). Thus, the assessment should be further conducted on the management capacity to evaluate the state and trends of institutional arrangement, transboundary coordination, and other management factors in freshwater resources management.

It is clear that a sustainable freshwater system is the result of an integrated process between the natural system and the management system. Further, rational water resources management must ensure healthy operational relations between the three components in the water resources system, or any management schemes of water resources will affect these three components in some manner. Thus, a "result-based" assessment strategy is proposed. It is clear that the most fundamental part of the vulnerability assessment of water resources is to understand water accounts at the three different levels listed above, and how other factors (global climate change, local biophysical conditions, policy and management practices, etc.) influence the process for establishing a healthy relationship between these components. As shown in Figure 2.1, the fourth component of this framework is to try to analyze some of the key management elements' contributions to freshwater resources vulnerability, with such elements including establishment of institutions, technical development, policy drivers, etc.

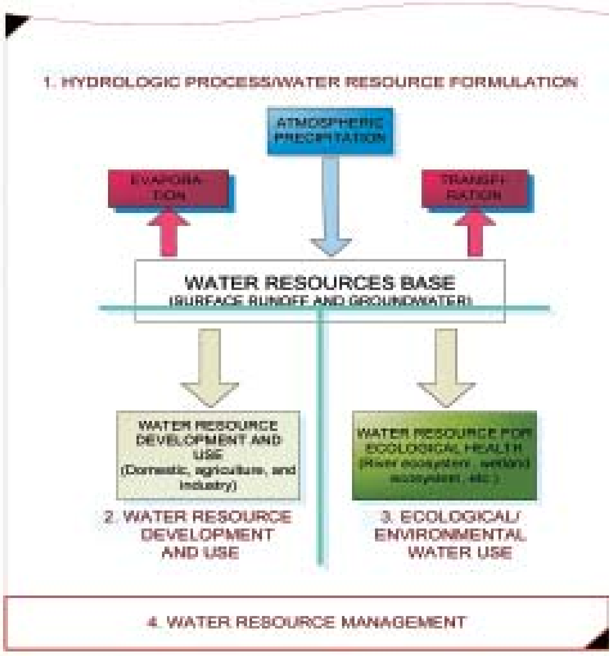

Figure 2.1 | Simplified framework of water resources base, and its development and use in a river basin

2.4 Procedures

The procedures given below represent a logical process for a river basin vulnerability assessment. All the listed steps should be included in an assessment work plan, although not necessarily followed in this exact temporal sequence:

(1). **Desk study:** An intensive study on relevant research papers, policy reports, maps, etc. is typically the first step in this process. Through this study, the research team should identify their own conceptual framework of analysis, and work out its detailed work plan accordingly;

(2). **Analysis of water resource state and identification of key issues:** Based on the desk study and official water resources reports, the state and characteristics of the water resources of the river basin, as well as its management system, should be further analyzed. A result of this analysis will be identification of the key issues influencing the vulnerability of water resources of the basin, as the basis for an in-depth DPSIR analysis toward a qualitative and quantitative description of the vulnerability of river basin's water resources and management.

(3). **In-depth DPSIR analysis:** For each issue identified in item (2) above, this effort builds up a DPSIR matrix, and conduct in-depth DPSIR analyses;

(4). **Comprehensive vulnerability assessment:** For a comprehensive assessment, an integrated Vulnerability Index (VI) should be calculated, based on the methods outlined in section 3.0, and analysis of contributions to the VI from the composing parameters will follow; and

(5). **Conclusion and policy recommendations.**

3
Method

The core method will involve a two-step exercise: (1) diagnosis of issues; and (2) in-depth assessment of the identified issues, based on a DPSIR framework. At the conclusion of this exercise, a comprehensive analysis of vulnerability will be carried out, following a Vulnerability Index calculation, and explanation of the results.

3.1 Analysis of State and Trends, and Identification of Key Issues

In this section, sufficient basic data must be collected from different sources regarding the current state and development history of the river basin, in terms of the water resources base and its management and use. The purpose of this section is to understand the water resources management status of the river basin, through ***telling a development history of the river basin.*** The product of this section is a detailed description of the water resources management history and key issues, following the conceptual analytic framework discussed above in Section 2. In general, the following data/information is needed:

(1). **Water resource data:** Precipitation, river runoff, groundwater, and water quality for the last 10 years, and even longer-term historic data series for analyzing the water resources development trends;

(2). **Water development/supply and use data:** Water resources development capacity and supply data (usually by two categories: surface water and groundwater), and water use data (usually by sectors) of the last 10 years and, again, longer-period data for analysis of development trends.

(3). **Ecological health data:** This component is generally characterized by limited data availability, with most of the data not being found in statistics or year books. Thus, “data mining” skills are needed to extract data from different sources (research papers, case studies, etc.). In terms of ecological water use, “base flow” is usually an important indicator of river health. Thus, research findings on minimum base flows/environmental flows of a particular river basin will represent the important data sources needed for this analysis. Water quality data also are needed to understand water quality as an important ecological health indicator, including wastewater discharges and water quality monitoring data.

(4). **Management capacity:** Information on management systems need to be collected, including both qualitative and quantitative data and information. The main data sets involve water use efficiency (e.g., water uses against economic growth), establishing management (institutions, etc.), and any policy, programs/projects for managing transboundary conflicts, etc.

(5). **Case studies:** In case the relevant issues cannot be explained with conventional statistical data, case studies can be the best data source for this purpose.

(6). **General information and data of the river basin:** As most of the analysis must be done within the biophysical and socioeconomic context of the river basin, the following data sets will be needed:

   (a). General information – Location, geographic and geological/topographic data, land area, etc.;

   (b). Climate data – Particularly temperature and other typical and special climate data sets;

(c). Land use – Land allocation to different land use categories, trends, etc.; and

(d). Socioeconomic data – Population, economic structure and scale, GDP, etc.

3.1.1 Total Water Resource State and Trends

The total water resources of a river basin is the total freshwater available for use to maintain healthy ecosystems and socioeconomic development. It is recharged through annual hydrologic processes, including surface water, groundwater and soil water from atmospheric precipitation (Figure 3.1).

Water Resources Estimates

- ***Precipitation:*** Precipitation of the whole river basin in mm,yr^{-1}. If relevant basin-wise data are not available, the data must be compiled from data from individually-selected meteorological stations within the basin boundary.
- ***River runoff:*** Precipitation received in a river basin will return to the atmosphere through evapotranspiration, and only a small portion will be retained as river runoff that represents the core component of water resources. This normally can be obtained from water sector statistics.
- ***Groundwater resource:*** Groundwater resources imply the total water recharge from surface to groundwater. Such data can be obtained from statistics and/or from site-specific surveys.
- ***Total water resource:*** The total water resource (i.e., the total volume of river runoff and groundwater resources, after correcting for evaporation losses).
- ***Distribution variation:*** This is mainly the distribution and strength of precipitation during rainy and dry seasons, and the frequency of extreme weather events (droughts, floods) over space and time.

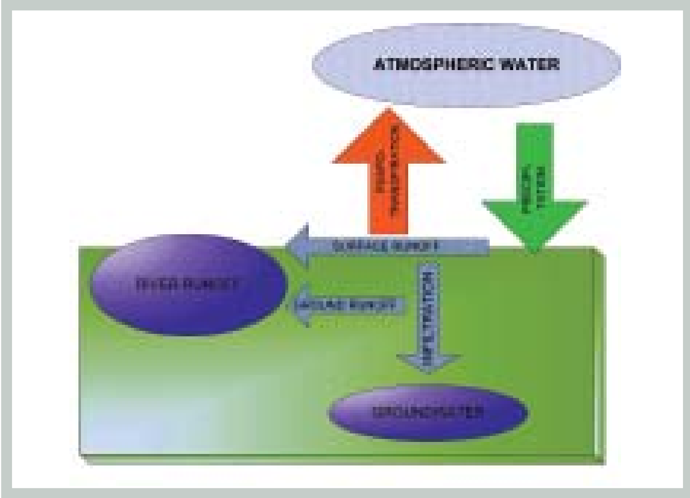

Figure 3.1 | Formulation of water resources

Water Resources Change Over Time

After estimation of the water resources base, a story of “water resources” should be told, using historical data that mainly comprise:

- Precipitation changes over time (e.g., last 50 years); and
- Main water resources-relevant disasters and trends.

Diagnostic Analysis of Key Issues

Based on the estimation of the water resources base and its development trends, the main issues should be identified. The focus of the analysis should focus on 2 aspects of the total water resources accounting system; namely, richness in general, and variations over time (see Figure 3.2). As illustrated in Figure 3, key questions that must be asked in the diagnosis are:

- How rich is the water resources base, in terms of the capacity to support human wellbeing, and the economic system?
- Is the water resources base stable, and what is its relationship with climate change and other relevant factors?

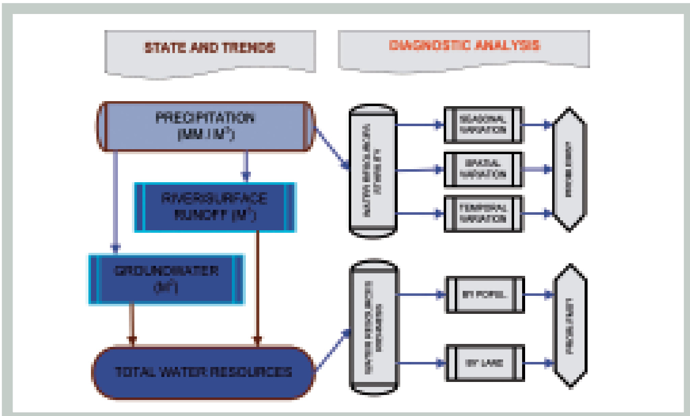

Figure 3.2 | Analytic framework for water resources base

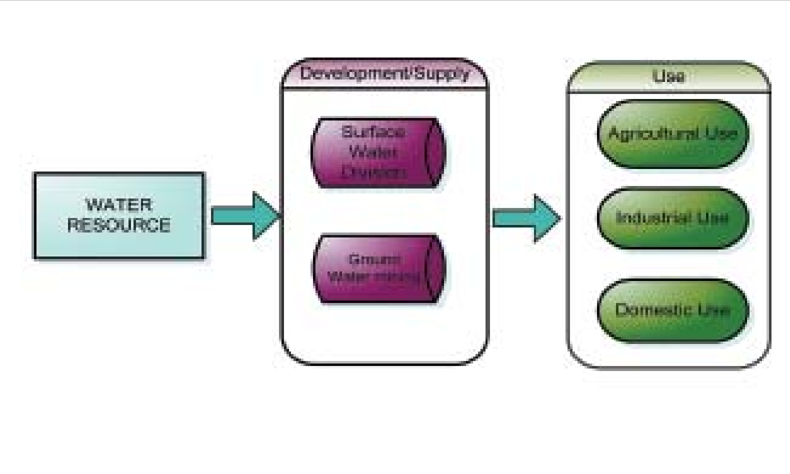

Figure 3.3 | illustrates a logical relationship between water resources development and use.

3.1.2 Development and use of water resources

The vulnerability of a river basin, in terms of its water resource, and beyond the water resources base, also closely linked to water resources development and use. Although total water resources represent a critical value for the maximum possible quantity of water supply, the actual water supply is largely determined by infrastructural facilities for water use, including water storage and transportation facilities. Water resources development and use is, through hydraulic works, to extract surface and groundwater to meet domestic and production water demands.

Estimation of Water Supply and Water Uses, and Development Trends

- ***Water supply:*** Description of water resource supply facilities (storage and transportation), and estimation of total water supply capacity by source (surface water; groundwater; other water sources), and its development trends. Special emphasis should be placed on the balance between water resources and development, particularly groundwater mining and other water resources development measures contributing to unsustainable water resources development, including water development rate, groundwater mining and water table changes, etc.
- ***Water use:*** Estimation of annual water uses by sectors (domestic; agriculture; industry; etc.) and its development trends. In addition to the general dataset presentation of the state of water use and trends by sectors, it includes further presentation of states and trends on rational water use patterns (e.g., relationship among different sectors, and different sections, of a river basin). Further, datasets also must be reviewed and presented on water use state and trends in contributing directly to achieving the MDG(2) (e.g., access to safe drinking water by different population (urban, rural) groups.

Diagnostic Analysis of Key Issues

Intensive analysis of water resources development and use should be conducted after the dataset presentation on the state and trends. As illustrated in Figure 3.4, which represents a logical framework for analyzing water resource development and use issues, the analysis should focus on 2 aspects of the problems; namely, the water balance, and the rationale for water development and use patterns:

- ***Water balance:*** The water balance is used to analyze the relationship between the water resources base and its development and use. The major purpose is to assess whether or not current water development and use practices contribute positively to a healthy renewable water resources base/hydrological process. The assessment should be carried out in two levels, including: (i) general water resources development/use rate, and (ii) water use balance for both surface and groundwater resources. The goal of the assessment is to answer the question, “is the current water resources development scheme sustainable, in terms of maintaining a healthy hydrologic process for the river base?”
- ***Rationale of water development/use patterns:*** After analyzing water development/uses among different sectors, and among different parts of the river basin, further analysis should be carried out to understand if the current pattern of water resources development and use are consistent with the economic development and water resources conservation strategy of the river basin. Emphasis should be given to how current water resources development and use practices contribute to achieving the MDG[1] (e.g., access to safe drinking water by different population (urban, rural) groups.

3.1.3 Ecological health

Ecological health implies the ecosystem health of a river basin. Because of their specific hydrological, natural and socioeconomic conditions, different river basins face different ecological and environmental problems. In general, however, all river basins face two fundamental issues: (i) the health of the river system; and (ii) the functioning of natural ecosystems. Thus, the vulnerability of water resources in supporting the ecological health of a river basin will focus on two aspects; namely, the environmental/base flows for maintaining the health of the river system, and the water supply for other natural ecosystem (e.g., wetlands). Further, water quality will be an important indicator of the health of a river basin, and also should be discussed in the analysis. Figure 3.5 provides a conceptual component for ecological health, as well as an analytic framework.

Estimation of Ecological Water Use

The estimation of ecological water use is usually difficult. It is normally done utilizing the best available scientific knowledge. It should focus on two fundamental questions: (a) demand (minimum water needs for maintaining ecological health); and (b) supply (water resources, after meeting "development and use" needs that is allocated to ecological uses).

To analyze environmental flows, the critical threats to a river system health must be identified. These threats may include sedimentation problems due to erosion, wastewater discharges, specific damage to biological habitats of key wildlife, etc. Determination of the quality and quantity of environmental flows is largely dependent on water needs to mitigate these threats. Analysis of the balance between water demands and water supply will require a better understanding of the state of environmental flows and, ultimately, the environmental health of the river system.

For analysis of the environment health of other ecosystems, key ecosystems and their relation to water resources should be assessed within the context of the overall functioning of the river basin ecosystems. Examples of key ecosystems include wetlands, lakes, etc. Because of the important roles of these ecosystems in the overall ecological functioning of a river basin, the water supply needed to meet the water needs of these ecosystems will impact directly on the overall ecological stability of the river basin.

Water Quality

There are many pollution sources with a river basin that can cause water quality problems. To better understand water quality problem and causes, the assessment should collect data on wastewater discharges (as a key pollution source), and also possibly other pollution sources in the river basin. There also is a need to develop a good quantitative description of the water quality state of a river, and its distribution in different parts of the river system. Based on the description of the water quality state, the trends in water quality changes should be further explored to better understand the potential problems, in terms of future water quality changes.

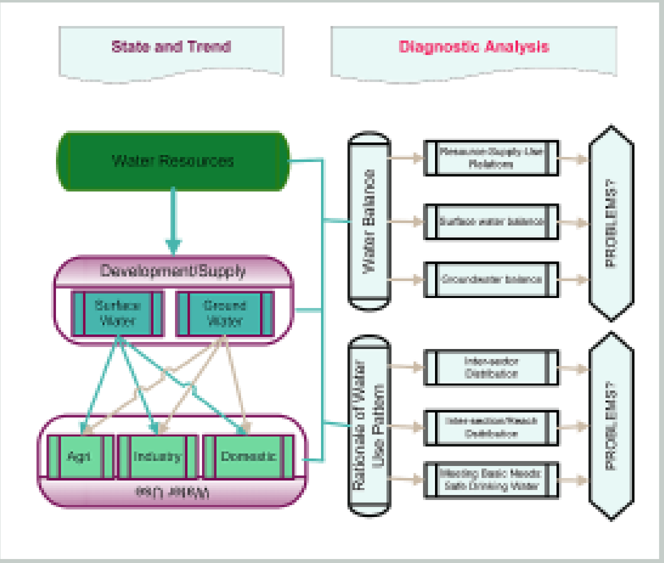

Figure 3.4 | Water resources development and use analysis framework

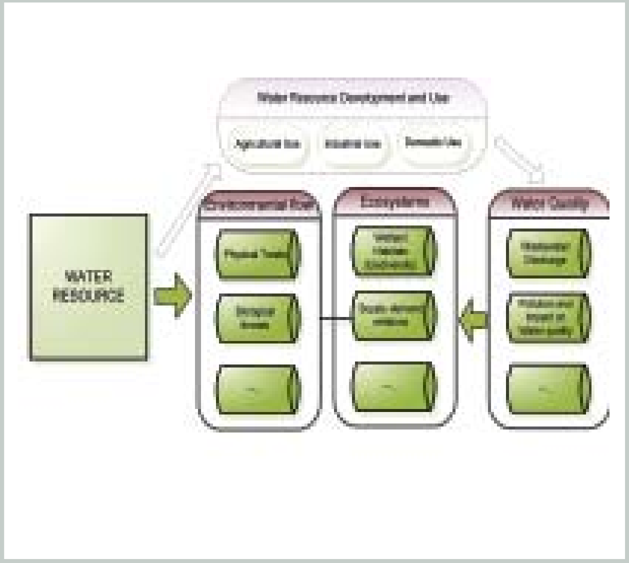

Figure 3.5 | Conceptual framework of ecological health analysis

Diagnostic Analysis

As shown in Figure 3.6, the diagnostic analysis should focus on three important issues, including: (i) environmental flows; (ii) ecosystem health; and (iii) and water quality. The questions to be posed should include the following:

(a). Are there any crucial health threats to the river system (e.g., sedimentation; pollution; etc.)?

(b). Are there any trends in damages to the habitats of important species, and to biodiversity conservation in general?

(c). Are there any potential threats of ecological disasters?

(d). What is the situation in regard to wastewater treatment and discharge change patterns and/or the influence on the water quality in the river basin?

(e). How does the water quality in the river basin change?

3.1.4 Water Resources Management

The above 3 components provide an assessment of the natural condition, and the adaptation process, of the natural system within a river basin. However,

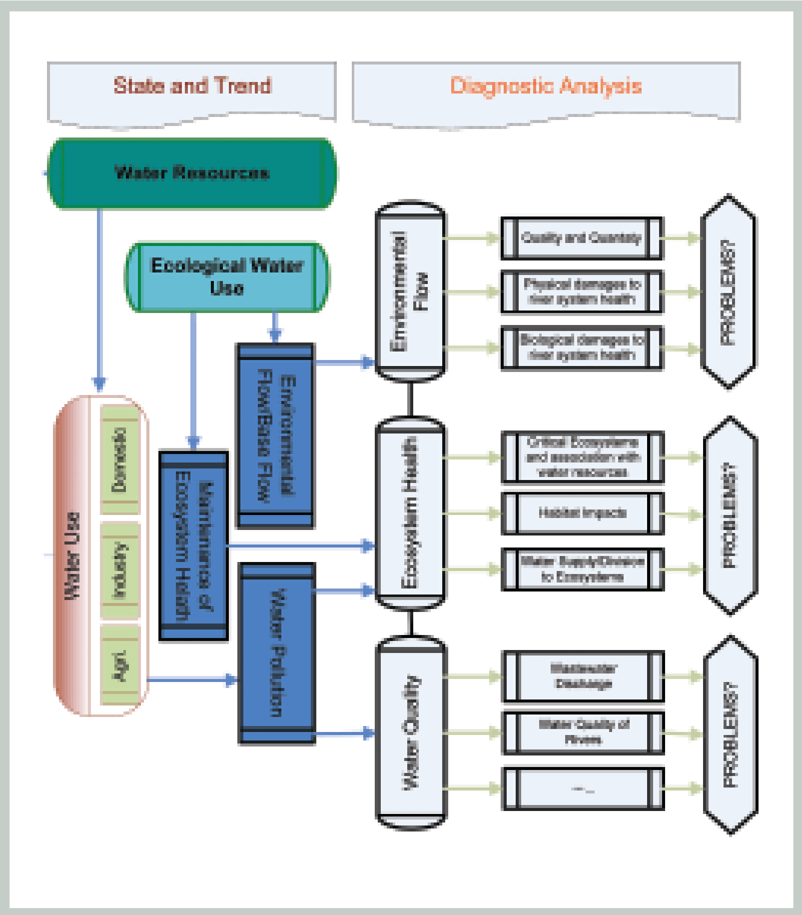

Fig. 3.6 | Ecological water use analysis framework

the reality is that no pure natural processes exist, meaning the above described state and change patterns are, in addition to the natural adaptive characteristics, largely influenced by human activities, or are partially a result of water resources management practices. Figure 3.7 presents a conceptual framework that highlights the important managerial aspects that should be considered in presenting the management capacity of the river basin. Similar to analysis of the natural system, assessment of management capacity also should be carried out in two steps: (1) description of the state and trends of the major management variables, including policies, institutions, research and development/ technology, and transboundary management; and (2) diagnostic analysis of existing issues, or issues likely to arise in the near future in regard to the above aspects.

State and Trends of Freshwater Management

Policy and institutions: In reviewing central and local legislative systems, special emphasis should be made on analysis of the practical policies relevant to freshwater resources development and use, as well as conservation of water resources. In the process of policy review and analysis, more focus should be put on such practical aspects of policy as management regulations at different levels. Further presentation of the state of the policy aspect is review of the implementation of such policies. In analyzing policy implementation, the state and trends within an institutional set-up should be analyzed in detail in order to indicate how current institutional set-ups and development trends contribute to an efficient freshwater resource management. The institutional analysis should include both formally/legally developed systems, but also informally-formulated systems contributing to freshwater management capacity of the river basin.

Research and Development/ Technology: Similar to other sectors, research and development (R&D) policy is an important factor in promoting efficient resource management. In this section, the governmental policy in supporting freshwater use technologies should be reviewed, with special analysis on how such R&D policies could contribute to improving efficiency of freshwater use.

Transboundary Management: Conflict management across a basin is usually a challenge in basin-wide water resources management. The transboundary management capacity should be reviewed on the basis of the following key indicators: (i) institutional set-up; (ii) agreements across the basin; (iii) communication mechanisms; and (iv) execution/implementation of agreements across the river basin.

Diagnostic Analysis

Similar to the diagnostic analysis of the natural process, the diagnosis of key issues should be carried out for water management issues. Figure 3.8 illustrates a logical framework for such analysis of water management issues. Linked to the 4 key aspects of the freshwater management (i.e., policy; institution; R&D; transboundary management), the diagnosis should attempt to identify potential problems in management that contribute to the vulnerability of the freshwater system in regard to the following 3 aspects:

(1). Policy review: To determine whether or not the current legislative system and policy framework contributes positively to efficient freshwater resources management, or whether or not specific problems exist in the current system that constrain healthy development of an effective management system.

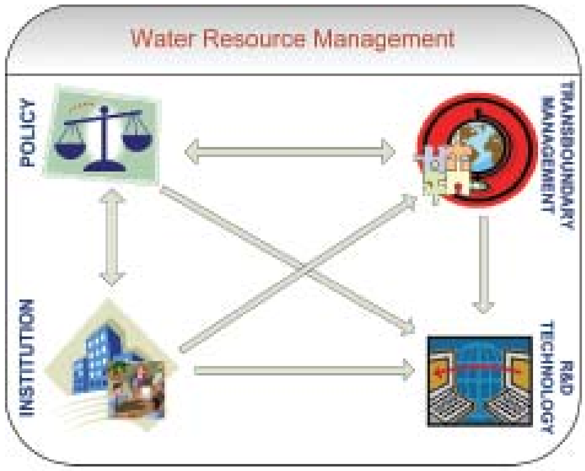

Fig. 3.7 | Conceptual framework for water resources management

(2). Water use efficiency: To examine the efficiency of current water use practices as an important indicator of R&D in the freshwater management sector. Comparisons can be made, in terms of R&D input level, and the consequent result of water use efficiency (e.g., GDP produced from 1 m^3 of water).

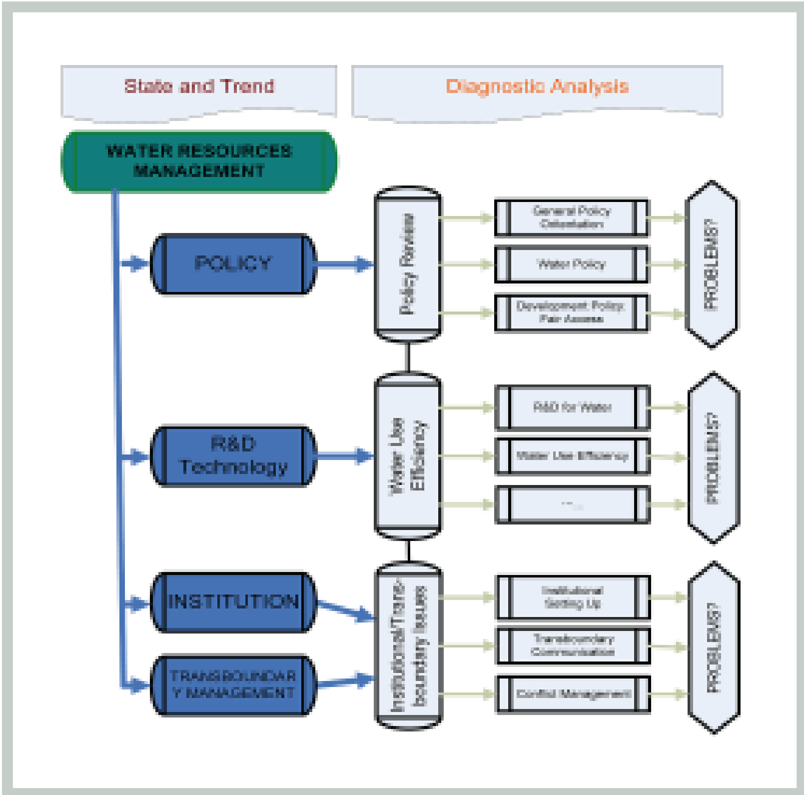

Fig. 3.8 | Water resources management analytic framework.

Table 3.1 | Vulnerability assessment matrix of water resources base of Huanghe (Yellow) River Basin, China – An example

ISSUES	DRIVERS	PRESSURES	STATE	IMPACTS	RESPONSES
Scarce Water Resources	Population expansion	Urbanization; economic development	Water stresses	Poverty and environmental degradation	Water use policy
Instability of water resourcs	Climate change	Land use	Increased occurrence of disasters	Low livelihood security	Environmental protection program

(3). **Institutional and transboundary issues:** To analyze the current institutional arrangements and transboundary management facilities, and their effectiveness in solving transboundary conflicts regarding freshwater resources development and use practices and, as a result, identify any apparent problems/difficulties in the field.

3.2 DPSIR Analysis

3.2.1 DPSIR framework and application

The analytical framework, known as the Drivers, Pressures, State, Impacts and Responses (DPSIR) framework[2], as used in the UNEP GEO process and others, is utilized to conduct the core analysis of the vulnerability assessment of water resources. This framework integrates all the factors related to both anthropogenic and environmental changes (i.e., caused by human activities and natural processes), incorporating social, economic, institutional and natural ecosystem pressures (Figure 3.9).

The DPSIR analysis will be done for each identified issue. Because the scale of the problem for each issue may vary, related to other issues, the drivers and pressures

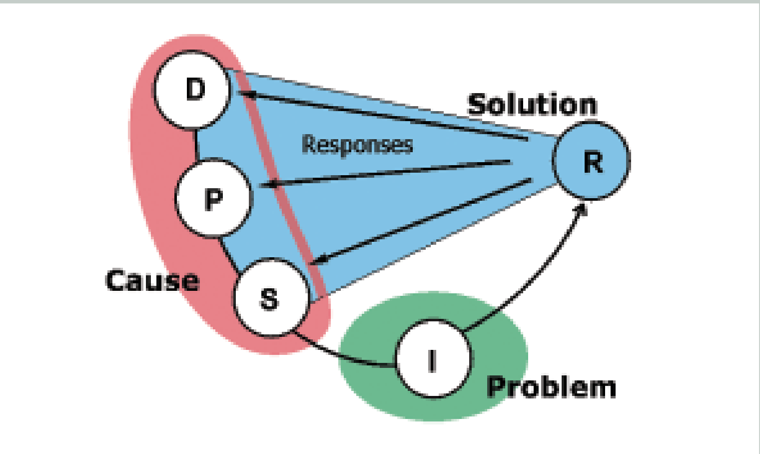

Figure 3.9 | DPSIR framework[1]

may be analyzed at different scales. The driving forces (**D**) represent major social, demographic and economic developments in societies, and the corresponding changes in lifestyles, and overall consumption and production patterns. Demographic development may be regarded as a primary driving force, whose effects are translated through related land use changes, urbanization, and industrial and agriculture development. The pressures (**P**) are produced as an effect of the driving forces. The pressures represent processes affecting the resource (water) by producing substances (e.g., emissions), physical and biological agents, etc. that consequently cause changes to the state (**S**) of water resources. Examples of pressure indicators include the emission of nutrients and pesticides by agriculture, effluent disposal in wastewater from sewage treatment, and flow regulation related to hydroelectric dams. The state may be described by adequate structural (e.g., river morphology), physical (e.g., temperature), chemical (e.g., phosphorus and nitrogen concentrations) and biological (e.g., phytoplankton or fish abundance) indicators. Depending on the changes of state, society may suffer positive or negative consequences. These consequences are identified and evaluated to describe impacts (**I**) by means of evaluation indices.

The best way of doing the DPSIR analysis is through a series of expert consultations. After completing the ***Analysis of Water Resources State and Identification of Key Issues*** described in Section 3.1, the core team should conduct a series of consultations to further confirm whether or not the identified issues are correctly understood, and then construct a DPSIR matrix for each issue (see following table as an example).

Based on the DPSIR matrix, detailed analysis should be carried out by providing more evidence to each of the boxes, and building-up the logical relationship between them.

3.2.2 Issues in Focus

Adaptive Capability: Issues related to the adaptive capability of societies and ecosystems to deal with stress are grouped into economic, social and natural dimensions. This includes needed information on such issues as population and urbanization processes, poverty and stratification (e.g., proportion of population without access to safe drinking water), land use and fragmentation, state of economic development, emissions, and water use efficiency (e.g., GDP from 1 unit of water resources).

Transboundary Cooperation: In the case of international rivers flowing from one country to another country within a basin, water use (or misuse) in one country can affect its quantity, quality and usage in the co-riparian countries. Water cooperation in this regard refers to how different co-riparian countries cooperate to protect and use water resources in a sustainable manner. Information needs for identifying issues of water cooperation include, but are not limited to, the water dependency ratio (ratio of the external annual renewable water resources to total annual renewable water resources [internal plus external annual renewable water resources]), the number of treaties, and riparian country collaboration.

3.3 Vulnerability Index and parameterization

The vulnerability of a river basin's water resources can be assessed from two perspectives: (a) the main threats of water resources and its development and utilization dynamics; and (b) the region's challenges in coping with these threats. Following the same DPSIR framework analysis, the threats can be assessed, again, from 3 different components of water resource and use (i.e., resource stresses; development and use conflicts; ecological security), while challenges in coping capacity can be measured within the context of the region's water resource management capacity. Thus, the vulnerability of a river basin can be expressed as:

$$VI = f\,(RS, DP, ES, MC)$$

where:

VI = Vulnerability index; RS = Resource stress; DP = Development pressures; ES = Ecological insecurity; and MC = Management challenges.

High vulnerability is apparently linked with higher resource stresses, development pressures and ecological insecurity, as well as severe management challenges. In order to quantify the vulnerability index, the indicators for each variable should be determined and quantified. The principles for this selection and quantification include:

(1). There should not be too many parameters, but the selected ones must be representative;

(2). The selected parameters are measurable, and easily expressed in formulations with available data support;

(3). Whenever the math expressions are determined, all the parameters should be valued in the range of 0 to 1;

(4). The contribution of each parameter to the vulnerability index should be weighted according to its importance; and

(5). The value of vulnerability index should range from 0-1, 1 being the most vulnerable, and 0 being non-vulnerable.

3.3.1 Parameterization

(1). Resource Stress (RS)

The general influence of water resources to vulnerability will be the quantity and quality of water resources, with the pressures from them being expressed as the "stress" and "variation" of water resources.

(i) Water Stress Parameter: The richness of water resources will decide to what extent it can meet the water demands of the population. Thus, the water resources stresses can be expressed as the per capita water resources of a region, compared to the generally-agreed minimum level of per capita water resources (1700 $m^3.person^{-1}$)[3], as follows:

$$\begin{cases} RS_s = \frac{1700 - R}{1700} & (R \le 1700) \\ RS_s = 0 & (R > 1700) \end{cases}$$

where:

RS_s = water stress parameter; and R = per capita water resources ($m^3.person^{-1}$).

(ii) Water Variation Parameter: The variation of the water resources can be expressed by the coefficient of variation (CV) of precipitation over the last 50 years. When data for the whole river basin is not available, one typical meteorological station data can be used for the calculation (CV = 0.3 is set as a critic level [i.e., when CV >0.3, the value of the parameter should set to the highest value (1)]). Therefore:

$$\begin{cases} RS_v = \frac{cv}{0.3} & (cv < 0.3) \\ RS_v = 1 & (cv \ge 0.3) \end{cases}$$

where:

RS_v = water resources variation parameter, and

$$cv = \frac{s}{\bar{p}}$$

$$\bar{p} = \frac{\sum_{i=1}^{n} P_i}{n}$$

$$s = \frac{\sqrt{\sum_{i=1}^{n}(P_i - \bar{p})^2}}{n-1}$$

where:

p_i = precipitation of the i^{th} year (in mm).

(2). Water Development Pressures (DP)

(i) Water Exploitation Parameter: Freshwater resources are recharged through a natural hydrological process. Over-exploitation of water resources will disrupt the normal hydrologic process, ultimately causing difficulties for the recharge of the water resource base. Thus, the water resources development rate (i.e., per cent of water supply, compared to the total water resource), can be used to demonstrate the capacity of a river basin for a healthy renewable process. Thus:

$$DP_s = \frac{WR_s}{WR}$$

where:

DP_s = Water resources exploitation parameter; WR_s = Total water supply (capacity); and WR = Total water resource.

(ii) Safe Drinking Water Inaccessibility Parameter: In addition to the water stress parameter, which indicates the natural process of adaptation capacity, the safe drinking water accessibility parameter is designed to present the state of social adaptation of freshwater use (i.e., how freshwater resources development facilities address the population's fundamental livelihood needs). This is an integrated parameter that reflects a comprehensive impact of the capacity of all stakeholders, from farmers to the government, to cope, as well as the availability of technologies, etc. Thus, the degree of stratification of water accessibility can be demonstrated by analysis of the proportion of the population with/without accessibility to improved water sources. According to the UN MDG monitoring indicators and method[5,6], the improved drinking water sources/supply include piped water, public taps, boreholes or pumps, protected wells, and protected springs or rainwater[4]. Thus, the contribution of the safe drinking water accessibility parameter (DP_d) can be calculated with the following equation:

$$DP_d = \frac{P_d}{P}$$

where:

DP_d = safe drinking water parameter; P_d = population without access to improved drinking water sources; and P = total population.

(3) Ecological Health (EH)

The ecological health of a river basin can be measured with two parameters; namely, the water quality/water pollution parameter and the ecosystem deterioration parameter.

(i) Water Pollution Parameter: In addition to their influence on the hydrologic process, water development and use activities will produce wastes, polluting the water resources base. Thus, another very important factor influencing the vulnerability of water resources is the total wastewater produced within the basin. The contribution of water pollution to water resources vulnerability, therefore, can be represented by the ratio between the total untreated wastewater discharge and the total water resources of a river basin. Case studies illustrate that mixed sewage carries about 24 mg NH_3-$N.L^{-1}$[5], which can make about 10 times the quantity of clear water totally unusable (the water quality category V allowed NH_3-N content is <2 $mg.L^{-1}$)[6]. Thus:

$$\begin{cases} EH_p = \frac{\frac{WW}{WR}}{0.10} & (WW < 0.10 * WR) \\ EH_p = 1 & (WW \ge 0.10 * WR) \end{cases}$$

where:

DP_p = water pollution parameter; WW = total wastewater discharge (m^3); and WR = total water resources (m^3).

(ii) Ecosystem Deterioration Parameter: As a result of the population expansion, the natural landscape was modified by the consequent urbanization and other socio-economic development activities. Removing vegetation from landscapes changed the hydrological properties of the land surface, and can cause severe problems in supporting the functioning of ecosystems, in terms of water resources conservation, and contributed to the vulnerability of the region's water resources. Thus, the land ratio without vegetation coverage can be used to represent the contribution of ecosystem deterioration to the vulnerability of water resources, expressed as:

$$EH_e = \frac{A_d}{A}$$

where:

EH_e = ecosystem deterioration parameter; A_d = land area without vegetation coverage (i.e., total land area, except that covered with forests and wetland, expressed in km^2); and A = total land area (km^2).

(4) Management Capacity (MC)

This component will assess the vulnerability of freshwater by evaluation of the current management capacity to cope with 3 types of critical issues, including: (i) efficiency of water resources use; (ii) human health condition closely dependent on, and heavily influenced by, accessibility to freshwater resources; and (iii) overall capacity in dealing with transboundary conflicts. Thus, the management capacity will be measured with 3 parameters representing the above 3 key management issues; namely (i) water use efficiency parameter; (ii) improved sanitation accessibility parameter; and (iii) transboundary management capacity parameter.

(i) Water Use Efficiency Parameter: The integrated capacity of water use policy and technology innovation will impact general water use efficiency. Thus, the inefficiency of a water resources management system can be demonstrated by examining the gap between water use efficiency and the defined world average water use efficiency. This can be represented by the GDP value of 1 m^3 of water, compared to the world average for selected

Table 3.2 | Conflict management capacity parameter assessment matrix

Category of capacity	Description	Scoring Criteria 0.0 ← → 0.25		
Institutional capacity	Transboundary institutional arrangement for coordinated water resources management	Solid institutional arrangements	Loose institutional arrangements	No existing institutions
Agreement capacity	Writing/signed policy/agreement for water resources management	concrete/detailed agreement	General agreement only	No agreement
Communication capacity	Routine communication mechanism for water resources management (annual conferences, etc.)	Communications at policy and operational levels	Communication only at policy level or operational level	No communication mechanism
Implementation capacity	Water resources management cooperation actions	Effective implementation of basin-wide river projects/programs	With joint project/program, but poor management	No joint project/program

countries, as follows:

$$\begin{cases} MC_e = \dfrac{WE_{wm} - WE}{WE_{wm}} \ (WE < WE_{wm}) \\ MC_e = 0 \ (WE \geq WE_{wm}) \end{cases}$$

where:

MC_e = water use inefficiency parameter; WE = GDP value produced from 1 m^3 of water; and WE_{wm} = mean WE of selected countries.

(ii) Improved Sanitation Inaccessibility Parameter: Sanitation facility accessibility is highly dependent on the availability of freshwater resources. One of the crucial aims of wise freshwater management should be making water sources accessible by communities (rural and urban) to support their basic livelihoods. Thus, the management system should make efforts to achieve this goal, increasing the availability of water sources to communities to meet their basic livelihood needs. Accessibility to improved sanitation, therefore, is used as a typical parameter to measure the capacity of a management system to deal with livelihood improvement matters. Similar to the accessibility to improved drinking water sources, the UN MDG monitoring indicators and method should be followed for this specific parameter computation (i.e., the improved sanitation should be defined as facilities that hygienically separate human excreta from human, animal and insect contact [including sewers, septic tanks, poor-flush latrines and simple pits])[7]. Computation of the parameter will be the proportion of population without accessibility to improved sanitation facilities, as follows:

$$MC_s = \frac{P_d}{P}$$

where:

MC_s = improved sanitation accessibility parameter; P_d = population without access to improved sanitation; and P = total population.

(iii) Conflict Management Capacity Parameter: T his is a parameter that demonstrates the capacity of the river base management system to deal with transboundary conflicts. A good management system can be assessed by its effectiveness in institutional arrangements, policy formulation, communication mechanisms, and implementation efficiency. Thus, the conflict management capacity can be assessed utilizing the matrix illustrated in Table 3.2. The final score of the conflict management capacity parameter (MC_s) can be determined by an expert consultation. based on the scoring criteria.

1 **1. Boat in the river, Dhaka, Bangladesh**
Source: www.freephotosbank.com/saikat ahmed

2 **2. Sjerpa woman, Nepal**
Source: www.sxc.hu/Peter Hermeling

3 **3. Rice terraces, Bontoc, Phillipines**
Source: Nadhika Mendhaka

3.3.2 Weighting

Based on the above-noted formula, and following the expert consultation for assigning weights to each parameter, the vulnerability index can be calculated as follows:

$$VI = \sum_{i=1}^{n}\left[\left(\sum_{j=1}^{m_i} x_{ij} \times w_{ij}\right) \times W_i\right]$$

where:

VI = Vulnerability index; n = number of parameter category; m_i = number of parameters in i^{th} category; x_{ij} = value of j^{th} parameter in i^{th} category; w_{ij} = weight given to j^{th} parameter in i^{th} category; and W_i = weight given to i^{th} category.

In order to keep the final VI value in the range from 0–1, the rules highlighted below can be used to determine the relative weights:

(1). The total of weights given to all parameters in each category should be equal to 1; and

(2). The total of weights given to all categories should be equal to 1.

Because the process of determining relative weights can be biased, making the final results difficult to be compared to each other, it is recommended that equal weights should be assigned among the parameters in the same category, and also among different categories.

It is possible to use different weights for different parameter within each category, and for each category at sub-basin or basin levels within a country. The procedure to determine the weight for each parameter or each category should follow a participative, consultative process involving all the stakeholders, and adequately incorporating the knowledge and experience available for the basins assessed.

3.3.3 Explanation of the Results and Policy Recommendations

After obtaining the results from the calculation (e.g., as shown in Table 3.3 above), further explanations are needed as the basis for policy recommendations. To get a better understanding and application of the resulting VI estimation, Table 4 provides a reference sheet to help interpret the VI calculation results. Generally speaking, a 2-step assessment process should be applied to link the VI result with policy recommendations, as follows:

(1). According to the overall VI score, general conclusions should be made on the vulnerability state of the river basin; and

(2). Policy recommendations should then be made after further review of the parameter results in the four sections (i.e., resource stress; development pressure; ecological security; management capacity), and specific policy interventions can then be made accordingly.

4. Report Writing

See the sample report outline, as presented in the Appendix 1.

Table 3.3 | Calculation of Vulnerability Index for Huanghe (Yellow) River Basin, China

Category	Resource Stress		Development Pressure		Ecological Health		Management Capacity		
Parameter	RS_s	RS_v	DPs	DPd	EHp	EHe	MC_e	MCs	MC_c
Calculated	0.6841	0.3470	0.6559	0.2500	0.4531	0.5200	0.9952	0.25	0.4000
Weight in category	0.5	0.5	0.5	0.5	0.5	0.5	0.33	0.33	0.33
Weighted	0.3421	0.1735	0.3280	0.1250	0.2265	0.2600	0.3317	0.08333	0.1333
Component total	0.5153		0.4530		0.4865		0.5483		
Weight for category	0.25		0.25		0.25		0.25		
Weighted	0.1289		0.1132		0.1216		0.1121		
Overall Score	**0.4758**								

Table 3.4 | Reference sheet for interpretation of Vulnerability Index

Vulnerability Index	Interpretation
Low (0.0 - 0.2)	This indicates a healthy basin, in terms of resource richness, development practices, ecological state, and management capacity. No serious policy change is needed. It is still possible, however, that moderate problems exist in the basin in regard to one or two aspects of the assessed components, and policy adjustments should be taken into account after examining the VI structure.
Moderate (0.2 – 0.4)	This indicates the river basin is generally in a good condition in regard to realization of sustainable water resources management. It may still face major challenges, however, in regard to either technical support or management capacity-building. Thus, the basin's policy design should focus on the main challenges identified after examining the VI structure, and strong policy interventions should be designed to overcome key constraints for the river basin.
High (0.4 – 0.7)	This indicates the river basin is experiencing high stresses, and great efforts should be made to design policy to provide technical support and policy backup to mitigate the pressures. A longer-term and appropriate strategic development plan should be made, with a focus on rebuilding management capacity to deal with the main threatening factors.
Severe (0.7 – 1.0)	This indicates the river basin is highly degraded in regard to being a water resources system with a poor management structure. Restoration of the river basin's water resources management will require major commitment from both government and general public. Restoration will be a long process, and an integrated plan should be made at the basin level, with involvement from international, national and local level agencies.

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Appendix

Sample outline of a river basin vulnerability assessment (Huanghe River Basin, China)

Executive Summary

1. INTRODUCTION

1.1 Rationale and Objectives

1.2 Method

2. DESCRIPTION OF THE HUANGHE RIVER BASIN

2.1 Topography

2.2 Climate and Hydrology

2.3 Land Use

2.4 Socioeconomic State

3. STATE OF WATER RESOURCES AND KEY ISSUES

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3.1.1 Water Resource Estimate

3.1.2 Water Resource Change

3.1.3 Water Pollution

3.1.4 Identification of Key Issues

3.2 Development and Use of Water Resource

3.2.1 Water Supply

3.2.2 Water Use

3.2.3 Identification of Key Issues

3.3 Ecological Water Use

3.3.1 Base Flow and Sedimentation Dynamics

3.3.2 Wetland Ecosystem