Indices and Indicators for Measuring Ground Water Condition and Vulnerability: Ground Water Quantity

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Summary

The report attempts to provide a conceptual outline for the development of indicators and indices to determine ground water condition and vulnerability from a ground water quantity perspective for the UN World Water Assessment Programme (WWAP). This work is a component of the work related to the water-related indicator development activity of WWAP.

Groundwater systems typically are physically complex, and characterizations of such systems are further complicated with the general lack of data worldwide. Though groundwater contributes to about 30% of the total global freshwater resources, the general understanding about the resource as a whole is limited.

The first step is to understand the physical groundwater system – aquifer hydrogeology. Given an understanding of the aquifer hydrogeology, the next step is to determine how much the system can yield, compatible with the stability of the supply – the estimation of sustainable yield.

The use of groundwater expands to irrigation as agricultural water use, industrial water use, and for water supply. Use of groundwater can bring with it adverse consequences if the system is not properly managed. The increasing trend of anthropogenic stresses on water resources systems has led to over exploitation of the resource, and has made it vulnerable. Adequately assessing the vulnerability of groundwater systems is particularly important, as it is usually very costly to restore the resource once it reaches certain deterioration thresholds.

In terms of groundwater quantity, over exploitation can lead to lowered water table, saltwater intrusion and land subsidence. The vulnerability potential of an aquifer to ground water contamination is in large part a function of the susceptibility of its recharge area to infiltration.

This report provides a review of concepts and techniques to assess the ground water condition and vulnerability of aquifers with respect to groundwater withdrawals. Available indicators are reviewed, and indices proposed which may then be verified through the WWAP indicator test-bed studies.

An important aspect in the development of a composite index will be the aggregation of the various indicators.

The report provides conceptual proposals of developed methodologies for subsequent testing in the WWAP process.

INTRODUCTION

Analysis of the world water quantity reveals that ground water constitutes about thirty percent (Chow, et al., 1988) of the world's fresh water resources. This amounts to about 10.5 million km^3 and though ground water is not a nonrenewable resource, such as a mineral or petroleum deposit, it is neither completely renewable in the same manner and time frame as solar energy. Recharge of ground water from precipitation continually replenishes the ground water resource but may do so at much smaller rates (can vary from days to thousands of years) than the rates of ground water withdrawals. Furthermore, both recharge and pumping from groundwater systems vary with both space and time. Complex hydrogeologic settings marked with complex spatio-temporal stress patterns and typically limited data, poses considerable challenge in understanding ground water systems and to develop long-term perspectives. Fostering a long-term perspective to the management of ground water resources is perhaps the most important attribute to the concept of ground water sustainability.

So, how can we view ground water sustainability? Conceptually, looking at the ground water system through time, a long-term approach to sustainability may involve frequent temporary withdrawals from ground water storage that are balanced by intervening additions to ground-water storage. However, the concept of ground-water sustainability and its application to real situations is multifaceted and complex. The effects of many human activities on ground water resources and on the broader environment need to be clearly understood.

The priorities for sustainable groundwater management should address: (1) sustainable long-term yields from aquifers; (2) effective use of the large volume of water stored in aquifers; (3) preservation of ground-water quality; (4) preservation of the aquatic environment, conservation of streamflows and wetlands sustained by groundwater by prudent abstraction; (5) integration of ground water and surface water into a comprehensive water and environmental management system (Downing, 1998; IAH, 1999). Thus groundwater sustainability is therefore linked to the concept of ground water over exploitation. Several terms have been commonly associated with ground water sustainability and over exploitation, safe yield, ground-water mining and overdraft, among others.

Definitions of selected terms and concepts necessary to evaluate ground water condition and for the development of ground water related vulnerability indices is outlined in the following sections. This report outlines a conceptual framework for developing indices to fit into the overall methodological framework of indicator and index development of the World Water Assessment Programme (WWAP). The objective is to develop a set of criteria to evaluate the susceptibility of aquifers to over exploitation – ground water quantity. Induced pollution due to over exploitation will be investigated in a subsequent report.

DEFINITIONS and CONCEPTS

A number of terms have been used in literature to describe the concept of over exploitation, and pertinent concepts necessary for indicator development are reviewed and discussed in this section.

Safe Yield: (Domenico and Schwarz, 1990). The objective of many ground water resource investigations is to determine how much water is available for pumping. Frequently, this is interpreted as the maximum possible pumping compatible with the stability of the supply. Lee (1915) first introduced safe yield as the indicator for this maximum use rate. Lee defined safe yield as *the limit to the quantity of water, which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve.* This definition was expanded by Meinzer (1923) who defined safe yield as *the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to the extent that withdrawal at this rate is no longer economically feasible.*

Though Lee and Meinzer points out about dangerous depletion levels and economic feasibility, it does not provide how the rates are to be determined or what should be the magnitudes. Conkling (1946) attempted to specify the conditions that constitute a safe yield. It was described as the annual extraction of water that does not, where, $Q(t)$ is the total rate of groundwater withdrawal; $R(t)$ is the total rate of groundwater recharge to the basin; $D(t)$ is the total rate of groundwater discharge from the basin; and dS/dt is the change of storage in the saturated zone of the basin. Given a situation where the pumping rates are increasing continuously, an unstable situation may arise where the declining water table reaches a depth below which the *maximum* groundwater recharge rate can no longer be sustained. After this state, same annual precipitation rates will not be able to provide the same percentage of infiltration to the water table. The value of Q at which such instability occurs has been referred to as the *maximum stable basin yield*.

As an indicator it would be necessary to look into the extent to which a basin has been developed as a fraction of the *maximum stable basin yield*, using the historic trends in groundwater development for the given basin. This concept also emphasizes the important interrelationships between groundwater flow and surface runoff. However it should be recognized that though conceptually it is a pertinent choice, determining its value is not a simple task.

Stabilization Time: Considering for example, a homogeneous, isotropic confined aquifer and using dimensional analysis a Fourier number (N_{FO}) can be derived for all unsteady flow problems, and is expressed as (Domenico and Schwartz, 1990),

$$N_{FO} = \frac{T/S}{L^2/t_e} \qquad (2)$$

where, T is the transmissivity of the aquifer $[L^2T^{-1}]$, S is the storage coefficient of the aquifer, L is some characteristic length of the aquifer [L], and t_e is some characteristic time [T]. Equation (2) can be used to calculate the equilibrium time required for a basin subject to unsteady conditions. Based on empirical observations Custodio (1992) has reported values of N_{FO} varying between 0.5-2.5. By knowing the basin geometry and aquifer characteristics, and using a representative value of N_{FO} we can calculate the time t_e required to attain equilibrium. That is the length of time during which the water levels and recharge/discharge in the groundwater system adjust to reach steady state. Figure 1 (after Custodio, 1992) provides a relationship between stabilization time, aquifer geometry, aquifer type and aquifer properties. Rearranging Eq. (2) we get,

$$t_e = \frac{N_{FO} L^2}{T/S} \tag{3}$$

Thus from Eq. (3) it is evident that when the hydraulic diffusivity (ratio of transmissivity to storage coefficient) is low and the aquifer is large, to attain equilibrium may take thousands of years (refer to Figure 1). So the stabilization time may be used as a measure of the vulnerability of the ground water system from the ground water quantity viewpoint.

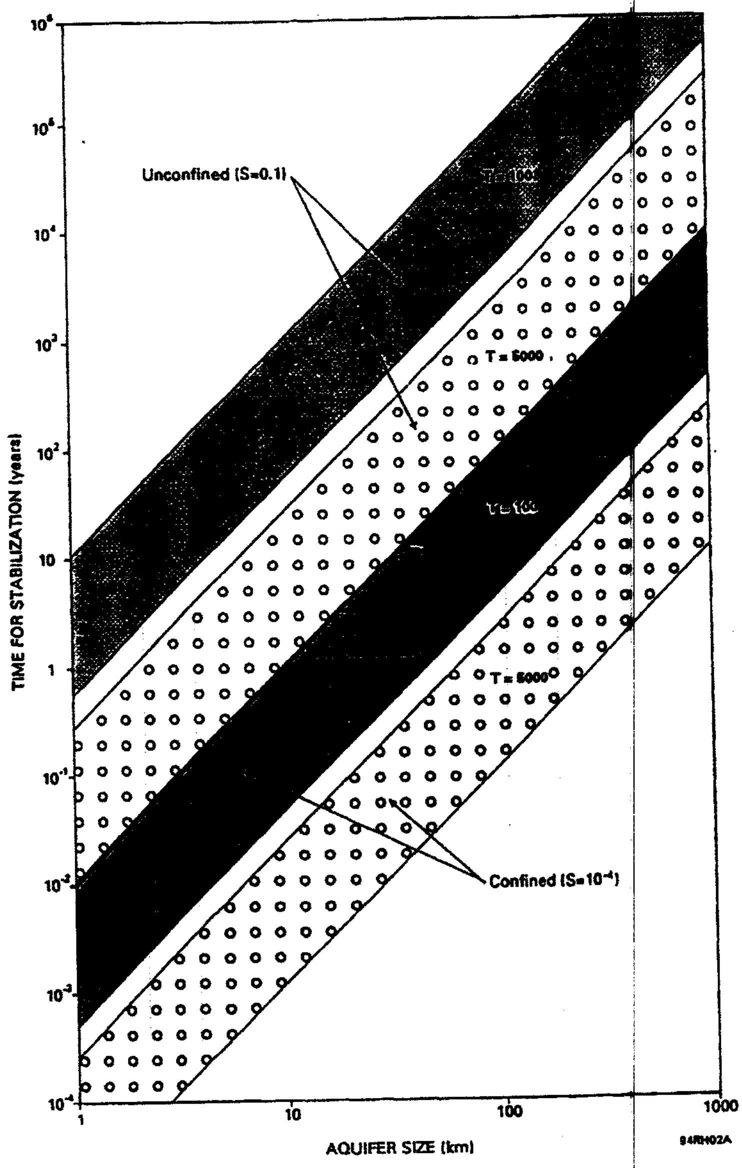

Figure 1 Time for stabilization of drawdown (in years) in an aquifer after a sudden change in the water balance, according to size (L, in km) and as a function of transmissivity (T, in m^2/day) and the storage coefficient (S); (after, Custodio, 1992).

Aquifer Geometry and Types: Aquifer geometry both shapes and size can vary from isolated small weathered pockets on basement rocks to large sedimentary basins.

The volume of the aquifer and hence its saturated thickness is the key parameter in determining the volume of water stored in the formation. The thickness of the aquifer provides a measure to what extent an aquifer will be affected by water level decline. For completeness a brief description of the different aquifer types is provided here.

Groundwater occurs in aquifers under two different conditions. Where water only partly fills an aquifer, the upper surface of the saturated zone is free to rise and decline. The water in such aquifers is said to be *unconfined,* and the aquifers are referred to as *unconfined aquifers*. Unconfined aquifers are also widely referred to as water table aquifers, and at the water table the pressure is equal to the atmospheric pressure. Any confining layer above it does not restrict the unconfined aquifer, and its upper boundary is the water table, which is free to rise and fall. Where water completely fills an aquifer that is overlain by a confining bed, the water in the aquifer is in *confined* state. Such aquifers are referred to as *confined aquifers* or as *artesian aquifers.*

In many hydrogeologic settings the confining beds contribute leakage flux to the adjacent aquifer(s). Such aquifers are referred to as *leaky aquifers*. The leaky aquifers are sometimes called as *semi-confined or leaky confined aquifer.* A semi-confined aquifer is a completely saturated aquifer which is bounded above by a semi-pervious layer (less hydraulic conductivity than the main aquifer body), and below by a layer that is either impervious or semi-pervious. Though the confining bed is less pervious than the main aquifer, horizontal flow in it is not negligible, and pumping will induce vertical flow from the semi-confining layer into the pumped confined aquifer.

IMPACTS OF GROUND WATER DEVELOPMENT

Ground water development has impacts on (1) flow to and from surface water bodies, (2) ground water quality – salt water intrusion, and (3) ground water storage – land subsidence.

Ground Water–Surface Water Interaction: As development of land and water resources intensifies, it is well understood that development of either ground water or surface water affects the other (Winter et al., 1998). The interactions affect streams, lakes, and wetlands. The next brief review follows from USGS (1999).

Streams either gain water from inflow of ground water (gaining stream) or lose water by outflow to ground water (losing stream). Many streams do both, gaining in some reaches and losing in other reaches. Further more, the flow directions between ground water and surface water can also change seasonally. Thus, even in settings where streams are primarily losing water to ground water, certain reaches may receive ground-water inflow during some seasons.

Lakes, both natural and human made, are present in many different parts of the landscape and can have complex ground-water-flow systems associated with them. Lakes interact with ground water in one of three basic ways: some receive ground-water inflow throughout their entire bed; some have seepage loss to ground water throughout their entire bed; and others, perhaps most lakes, receive ground-water inflow through part of their bed and have seepage loss to ground water through other parts. Lowering of lake levels as a result of ground water pumping can affect the ecosystems supported by the lake, diminish lakefront esthetics, and have negative effects on shoreline infrastructures.

Wetlands can be quite sensitive to the effects of ground water pumping. Ground water pumping can affect wetlands not only as a result of progressive lowering of the water table, but also by increased seasonal changes in the altitude of the water table. The amplitude and frequency of water-level fluctuations through changing seasons, commonly termed the hydroperiod, affect wetland characteristics such as the type of vegetation, nutrient cycling, and the type of invertebrates, fish, and bird species present. The effects on the wetland environment from changes to the hydroperiod may depend greatly on the time of year at which the effects occur. For example, lower than usual water levels during the nongrowing season might be expected to have less effect on the vegetation than similar water-level changes during the growing season. The effects of pumping on seasonal fluctuations in ground-water levels near wetlands add a new dimension to the usual concerns about sustainable development that typically focus on annual withdrawals (Bacchus, 1998).

The interaction between streams and ground water sources are accounted in the calculation of sustainable basin yield. The interaction of ground water with wetlands should be followed up following the indicator report on ecosystems.

Saltwater Intrusion: Saline water intrusion is probably the most common type of pollution problem in fresh ground water. Intrusion implies the displacement or mixing of fresh water and salt water, and can result from several sources: (a) encroachment of sea water in coastal aquifer, (b) inland connate sources, sea water entrapped in geologic formations, (c) endorhic sources, and (d) irrigation return flows, among others. The intrusion mechanisms however fall into three categories (Das Gupta, 1996).

(1) Reduction or reversal of ground water gradients, which allows denser saline water to displace the lighter fresh water. This situation is common in coastal aquifers in hydraulic continuity with the sea, and when pumping of wells disturb the natural hydrodynamic balance.

(2) Destruction of natural barriers that separate fresh and saline waters. Examples would be the construction of a coastal drainage canal that enables tidal water to advance inland to percolate into a fresh water aquifer or accidental destruction of formations that act as natural flow barriers during construction processes.

(3) Subsurface disposal of saline water such as into disposal wells, landfills, or other waste repositories.

Problems of saline water intrusion are acute not only in coastal aquifers, but also in many inland areas. The fundamental mechanism for mixing is the pressure difference or hydraulic gradient between fresh water and saline water sources when these two fluids are hydraulically connected. It is often the case that an aquifer is underlain by saline water and is separated from it by an impermeable stratum. Destruction of this natural barrier either during drilling operations, or by leakage through abandoned wells, or the development of a steep pressure gradient due to over pumping can induce the intrusion process.

In this report the focus is on ground water quantity and induced pollution is more relevant to discussions related to water quality – ground water quality condition and vulnerability.

Land Subsidence: Different geologic processes such as, movements of tectonic plates, earthquakes, and fluid removal from the earth's surface can cause land subsidence. With respect to aquifer over exploitation it implies subsidence due to excessive withdrawal of ground water.

Mechanisms influencing land subsidence has been proposed by various authors (Terzaghi, 1925; Theis, 1935; Biot, 1941; and Helm, 1982; among others), and discussions on these theories is beyond the present scope. However, the three important factors that influence land subsidence due to over pumping are: (1) stratification of the aquifer, (2) combined thickness of aquitards, and (3) compressibility of aquitards.

To estimate land subsidence due to excessive ground water extraction typically a consolidation model is linked with a ground water flow model. In addition to models reported in individual case studies for example, Venice City (Gambolati and Freeze, 1973), Mexico City (Rivera et al., 1991), and Bangkok City (AIT, 1981), the USGS (United States Geological Survey) generic code MODFLOW (McDonald and Harbaugh, 1988) can also be used for land subsidence computations.

GROUND WATER INDICATORS

One of the fundamental problems with the ground water resource unlike surface water is that, the resource is not physically visible. Decision makers and society become aware of ground water management needs in most cases only after ground water problems reach proportions where it is difficult and even in many cases impossible to address effectively. Ground water indicators therefore should provide diagnostics to evaluate ground water *condition* and *vulnerability* and provide a means to appraise the ground water situation. In this report the focus is to address indices and indicators for measuring ground water condition and vulnerability with a focus on ground water quantity.

The indicators related to *ground water condition* are designed to evaluate existing ground water condition in the basin. The *ground water vulnerability* indicators are designed to indicate how various factors influence the susceptibility of aquifers and cause future problems to occur. Table 1 provides a list of potential variables to be considered in evaluating the condition and vulnerability of ground water with respect to ground water quantity.

Table 1 List of potential variables to be considered in evaluating the *condition* and *vulnerability* of ground water with respect to ground water quantity.

Ground Water Quantity		
NAME	**VARIABLE(S)**	**DATA**
Condition		
Ground water reliance	Annual average ground water withdrawals	Primary/Secondary
	Annual average total withdrawals (surface and ground water)	Primary/Secondary
Ground water depletion	Annual average ground water withdrawals	Primary/Secondary
	Annual average baseflow	Secondary/Analyzed
Encroachment ratio	Horizontal displacement of salinity front from a reference point	Primary/Analyzed
	Distance of control point from the reference point	Primary/Secondary
Subsidence ratio	Maximum subsidence with respect to a chosen datum	Primary/Analyzed
	Minimum elevation of land surface with respect to chosen datum	Primary/Secondary
Vulnerability		
Ground water level decline	Hydraulic diffusivity	Primary/Secondary/Analyzed
	Heterogeneity	Primary/Secondary/Analyzed
	Annual recharge	Primary/Secondary/Analyzed
	Volume of aquifer	Primary/Secondary/Analyzed
Salt water intrusion	Hydraulic gradient	Primary/Secondary/Analyzed
	Permeability	Primary/Secondary/Analyzed
	Effectiveness of hydraulic barriers	Primary/Secondary
Land subsidence	Stratification of aquifer	Primary/Secondary
	Total thickness of aquitards	Primary/Secondary
	Compressibility of aquitards	Primary/Secondary/Analyzed
Stabilization time	Hydraulic diffusivity	Primary/Secondary/Analyzed
	Characteristic length of basin	Primary/Secondary
	Basin constant	Empirical

Table 1 follows from the methodological framework for indicator development for the World Water Assessment Programme (Strzepek, 2001). Description of the variable names and their implications are discussed below.

Ground Water Reliance: Ground water reliance is calculated as the ratio of annual average ground water withdrawals to annual average total withdrawals (surface water and ground water).

Ground Water Depletion: Ground water depletion is defined as the ratio of annual average ground water withdrawals to annual average baseflow, reflecting the extent that ground water use rates may be exceeding recharge.

Encroachment Ratio: The encroachment ratio is defined as the ratio of the horizontal displacement of salinity front from a reference point to the distance of control point from the point of reference.

Subsidence Ratio: The subsidence ratio is defined as the ratio of the maximum subsidence with respect to a chosen datum to minimum elevation of land surface with respect to a chosen datum (for example, the mean sea level).

Ground Water Level Decline: The susceptibility of an aquifer depends on several factors but the most important ones are hydraulic diffusivity, heterogeneity, annual recharge, and volume of the aquifer.

Salt Water Intrusion: From the mechanisms involved in salt water intrusion the susceptibility of an aquifer to salt water intrusion depends on the hydraulic gradient, permeability, and effectiveness of hydraulic barriers.

Land Subsidence: Compaction of the soil matrix and the susceptibility of aquifers to fluid withdrawal depends on the stratification of aquifer, total thickness of aquitards, and compressibility of aquitards.

Stabilization Time: The stabilization time measures the time required to attain equilibrium from an unsteady state and the contributing factors are, hydraulic diffusivity, characteristic length of basin, and a basin constant (empirical constant).

DATA

An outline of the data required to estimate the variables are given in Table 2 (note that all the data are not required in the present analysis).

Table 2 Principal types of data and data compilations required for analysis of ground water systems.

Physical Framework
Topographic maps showing the stream drainage network, surface-water bodies, landforms, cultural features, and locations of structures and activities related to water
Geologic maps of surficial deposits and bedrock
Hydrogeologic maps showing extent and boundaries of aquifers and confining units
Maps of tops and bottoms of aquifers and confining units
Saturated-thickness maps of unconfined (water-table) and confined aquifers
Average hydraulic conductivity maps for aquifers and confining units and transmissivity maps for aquifers
Maps showing variations in storage coefficient for aquifers
Estimates of age of ground water at selected locations in aquifers
Hydrologic Budgets and Stresses
Precipitation data
Evaporation data
Streamflow data, including measurements of gain and loss of streamflow between gaging stations

Hydrologic Budgets and Stresses (continued)
Maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normally seasonal flow
Estimates of total ground-water discharge to streams
Measurements of spring discharge
Measurements of surface-water diversions and return flows
Quantities and locations of interbasin diversions
History and spatial distribution of pumping rates in aquifers
Amount of ground water consumed for each type of use and spatial distribution of return flows
Well hydrographs and historical head (water-level) maps for aquifers
Location of recharge areas (areal recharge from precipitation, losing streams, irrigated areas, recharge basins, and recharge wells), and estimates of recharge
Chemical Framework
Geochemical characteristics of earth materials and naturally occurring ground water in aquifers and confining units
Spatial distribution of water quality in aquifers, both areally and with depth
Temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers
Sources and types of potential contaminants
Chemical characteristics of artificially introduced waters or waste liquids
Maps of land cover/land use at different scales, depending on study needs
Streamflow quality (water-quality sampling in space and time), particularly during periods of low flow

(*Source:* Alley, W.M., et al., 1999)

Furthermore, the data sources for a global assessment such as the WWAP is diverse and to start all possible data sources should be explored. In Table 1, the possible data types have been mentioned. Data sources to calculate each of the variables is presently under review.

METHODOLOGICAL APPROACH

The variables used in the above section are used to describe the *condition* or *vulnerability* of a ground water system. The first step is to assign classes to classify the *ground water system condition* and classes to classify the *ground water system vulnerability*. Then intersection of these classes can be used to define both the condition and vulnerability of the ground water system. The three proposed categories to classify the ground water condition are: (1) satisfactory ground water condition, (2) ground water condition with less serious problems, and (3) ground water condition with more serious problems. The three proposed categories to characterize ground water vulnerability are: (1) low, (2) medium, and (3) high. These two sets can be combined to create the following spectrum:

(1) Basins with satisfactory ground water condition and low vulnerability.
(2) Basins with satisfactory ground water condition and medium vulnerability.
(3) Basins with satisfactory ground water condition and high vulnerability.
(4) Basins with less serious ground water problem and low vulnerability.
(5) Basins with less serious ground water problem and medium vulnerability.
(6) Basins with less serious ground water problem and high vulnerability.
(7) Basins with more serious ground water problems and low vulnerability.
(8) Basins with more serious ground water problems and medium vulnerability
(9) Basins with more serious ground water problems and high vulnerability.
(10) Data sufficiency threshold not met.

Data sufficiency thresholds must be set for data for both the condition and vulnerability categories (USEPA, 1997). The thresholds ensure that sufficient data exist to make valid judgements. For example, both for the condition and vulnerability data for at least 50% (suggested cutoff, more analysis is necessary) of the proposed indicators in each case should be available. Otherwise it would be concluded that data is insufficient.

Categorization: The indicator components proposed above are a first attempt, and through the proposed meetings and discussions in WWAP the methodology will evolve over time. Assuming that with available data (primary, secondary or analyzed data) the *values of the indicators* (Strzepek, 2001) are computed, the key questions now comes as to what thresholds to assign, and how to aggregate this information to classify and represent a basin in an appropriate category? The issues related to assigning thresholds and aggregation are discussed below.

Thresholds: The determination of thresholds depends on the spatial and temporal scales of interest of the case in hand. For example, the use of a fixed number 1700 m^3/capita/year (Falkenmark et al., 1989) to conclude that a country is water stressed is debated in discussions of water stress indicators. So it is difficult to assign such unique threshold levels. However, the problem can be addressed within a statistical framework. This is particularly important to assess the *condition* of the situation in this case a particular ground water system. *Vulnerability* assessment can be done more objectively as the variables involved are physical attributes of the system, and can typically be assigned weights derived from sensitivity analysis.

***Assessing Ground Water Condition*:** Following the three proposed categories to define the ground water situation, (1) satisfactory ground water condition, (2) ground water condition with less serious problems, and (3) ground water condition with more serious problems. Analysis of the condition implies the evaluation of the present state of the system. Evaluation of the present state requires knowledge of the evolution of the system with time. Thus to do a comprehensive analysis time-series data is essential. This however in many cases will not be available. The three above mentioned categories are proposed with the statistical notion of quartiles. The first category would therefore correspond to the lower 25^{th} percentile (first quartile), and the third category would correspond to the upper 25^{th} percentile (third quartile). The second category would therefore fall within the interquartile range. Once again, the question may arise, what cutoff values would represent these quartiles? One of the objectives of the proposed indicator test-bed studies and the WWAP case studies would be to collate and analyze data to setup some of the threshold values for the indicator variables.

For example for the *ground water reliance indicator*, we may assume that a value of 10% corresponds to the lower 25th percentile and hence values less than 10% (ratio of annual average ground water withdrawals to annual average total withdrawals < 0.01) would be placed in the first category. For the second category the bounds may be, $0.01 \leq$ ground water reliance ≤ 0.025; and the third category is defined by, ground water reliance > 0.25 (25%). Are these thresholds unique? The answer probably is no. The physical setting of the problem, and the spatio-temporal scales of the processes involved in addressing the specific problem govern these thresholds. However after several well-focussed case studies some generalizations may be derived.

To estimate the quartiles time series data will be necessary, and from the start of the indicator development process effort has to be made to obtain time series data from primary and secondary sources or to derive them through analysis for example statistical and numerical modeling.

For the *ground water depletion indicator*, the assumed threshold for the three aforementioned categories respectively, are less than 25%, 25-50%, and greater than 50%.

The indicator for salt water *encroachment ratio* depends on the salinity levels of interest for a given use of the water. Once the primary use of water in the study area is known, the critical concentration level for that use can be identified. Critical salinity concentration levels for different uses are in general well established. For example, if ground water is being used as a primary supply for drinking water, it would be of interest to observe the rate of movement of the 300 mg/L or the 600 mg/L chloride concentration contours. It has to be borne in mind that this measure is related to the implications on ground water quality due to ground water extraction. To calculate this ratio the distance of the fronts from the control points is also necessary. The thresholds for the three categories respectively may be assumed to be, less than 25%, 25-50%, and greater than 50%.

Land subsidence due to ground water over exploitation has implications for flooding and infrastructural damage. From topographical data it is important to know the minimum elevation of the locations or control points with respect to a chosen datum for example, the mean sea level (msl). As such damages can be significant, the applicable thresholds should account for a high factor of safety. To start the proposed thresholds for the indicator *subsidence ratio* for the three condition categories are, less than 10%, 10-25%, and greater than 25%.

It should be understood that these threshold levels to an extent are arbitrary, and as mentioned earlier the WWAP process will help to iteratively evolve the definitions. The thresholds described in this section are summarized in Table 3.

Table 3 Proposed threshold levels for the ground water condition indicators.

INDICATOR NAME	GROUND WATER CONDITION		
	Satisfactory	***less serious problems***	***more serious problems***
Ground water reliance	< 10%	10-25%	> 25%
Ground water depletion	< 25%	25-50%	> 50%
Encroachment ratio	< 25%	25-50%	> 50%
Subsidence ratio	< 10%	10-25%	> 25%

Assessing Ground Water Vulnerability: Ground water vulnerability assessment is based on the physical setting of the ground water system. In some ways determination of the vulnerability of an aquifer can be done more objectively. Present knowledge is significantly advanced to understand the dynamics of the ground water flow system under different hydrogeological settings and the sensitivity of the different parameters involved in understanding the physics of ground water flow. Depending on the physical situation different weights can be attributed to the variables to describe its influence on the susceptibility of an aquifer when subjected to stress. Vrba and Zaporozec (1994) provide a detail review of ground water vulnerability mapping with respect to ground water contamination. Description on each of the variables and their influence on ground water vulnerability are given below (Adams and Macdonald, 1995).

(1) Ground water level decline: though it depends on several factors the four variables considered are given in Table 1. Hydraulic diffusivity defined as the ratio of transmissivity (T) to storage coefficient (S) is directly proportional to the volume of water that an aquifer can yield. So a higher values of hydraulic diffusivity would make the ground water system more susceptible to water level declines.

Similarly heterogeneous systems are more vulnerable than homogeneous ground water systems. Following the classical definition of heterogeneity there is no such thing as a homogeneous formation as all geologic formations to an extent exhibit spatial variation in hydraulic conductivity values. So heterogeneity has been addressed within statistical framework using modes of probability density functions. However, for operational reasons if it is assumed that the mean hydraulic conductivity is independent of position within a geological formation, the formation can be assumed to be homogeneous (Freeze and Cherry, 1975). As data will not be available in several cases to sufficiently characterize many of the ground water systems, judgement has to be made based on limited information and also on qualitative descriptions of the system. Homogeneous formations will be less susceptible to ground water over extraction and hence ground water level decline.

It is obvious that more recharge an aquifer receives the lesser would be its decline of water level. Protection of recharge areas is of vital importance as less recharge would pose a significant threat to the ground water system.

The volume of an aquifer is the product of the areal extent of water bearing strata and the saturated thickness of the aquifer. So larger the aquifer volume, obviously the lesser is the susceptibility of the aquifer to water level declines. The above discussions are summarized in Table 4.

Table 4 Ground water level decline susceptibility to the different variables, high (↑) and low (↓).

Variable		Ground Water Level Decline Susceptibility
Hydraulic diffusivity	↑	↑
Heterogeneity	↑	↑
Annual recharge	↑	↓
Volume of aquifer	↑	↓

Now the question comes, what is high and low and how to scale the effects to signify the implications of high and low?

Adams and Macdonald (1995) provide weights to quantify the degree of susceptibility of the four variables. Apart from annual recharge, which can vary considerably between years mainly due to climatic variations, the other variables can be ascertained with a higher degree of confidence. As the recharge component contributes significant uncertainty, the susceptibility of a ground water system to recharge should be addressed conservatively. This is reflected by using a higher weight value to this variable.

Table 5 Relative weights used to estimate ground water level decline susceptibility due to high, moderate and low values of the four contributing variables.

Value	Ground Water Level Decline Susceptibility			
	hydraulic diffusivity	***heterogeneity***	***annual recharge***	***volume of aquifer***
High	3	3	1	1
Moderate	2	2	3	2
Low	1	1	6	3

(*Source:* BGS Technical Report WC/95/3; Adams and Macdonald, 1995)

The values high, moderate and low can be attributed to physical magnitudes or possibly a better approach once again would be to use quartiles. For example, values less than the first quartile would be considered as low, and values greater than the third quartile would be considered as high. Values falling within the first and third quartiles would be considered as moderate.

The next issue would be, how to establish quartiles. To estimate quartile values data analysis has to be carried out. For the intrinsic variables, hydraulic diffusivity, heterogeneity and aquifer volume, significant literature exist to establish the quartiles. For annual recharge, time series analysis and water balance studies would be necessary.

Once weights (w_i) are assigned to signify the level of susceptibility due to variable i, the next question comes how to aggregate these weights and then to classify into one of three categories of low, medium and high vulnerability. Adams and Macdonald (1995) used simple summation ($W = \sum_{i=1}^{4} w_i$), and the classification was, (i) low vulnerability: $W < 8$; (ii) medium vulnerability: $8 \leq W \leq 11$; and (iii) high vulnerability: $W > 11$. Still using the simple summation as the aggregation method, the thresholds were recomputed and adjusted conservatively to correspond to approximate the three quartiles. So the proposed classification is, (i) low vulnerability: $W < 6$; (ii) medium vulnerability: $6 \leq W \leq 11$; and (iii) high vulnerability: $W > 11$. In the section on *aggregation* (below), details of some of the aggregation techniques and their implications are discussed.

To start the ground water indicator development work for WWAP the above framework would provide a starting point.

(2) Salt water intrusion: The variables used to describe the salt water intrusion problem are given in Table 1. Following Adams and Macdonald (1995) each of the variables have been assigned equal weights. For the ground water basin under consideration there has to be evidence of this problem either directly due to sea water intrusion or intrusion of saline water from inland connate sources. The relative weights used for this case are shown in Table 6.

Table 6 Relative weights used to estimate salt water intrusion susceptibility due to high, moderate and low values of the three contributing variables.

Value	**Salt Water Intrusion Susceptibility**		
	hydraulic gradient	***permeability***	***effectiveness of hydraulic barrier***
High	3	3	1
Moderate	2	2	2
Low	1	1	3

(*Source:* BGS Technical Report WC/95/3; Adams and Macdonald, 1995)

The problem of ground water quality deterioration is complex and this scheme only addresses a specific problem due to ground water over pumping. Once again the concept of quartiles can be used to classify high moderate and low values. If a simple addition of weights scheme is used, the three vulnerability categories according to total weight W would be, (i) low vulnerability: $W < 4$; (ii) medium vulnerability: $4 \leq W \leq 7$; and (iii) high vulnerability: $W > 7$.

(3) Land subsidence: Adams and Macdonald (1995) provides a detail outline on estimating land subsidence in both unconfined and confined aquifer systems. The susceptibility of an unconsolidated aquifer to subsidence can be evaluated using Table 7. The three variables used to estimate susceptibility are – the stratification of the aquifer, the combined thickness of the saturated aquitard (including confining layers), and the aquitard compressibility. Each of the variables have been considered of equal weight, but in unconfined aquifers the susceptibility to subsidence computed using this scheme will in general be computed as low. However this is not always true (Poland, 1984), and adjustments to the weights would be necessary to address local conditions. Furthermore, consolidated aquifers can also be susceptible to subsidence if compressible aquitards are present.

Table 7 Relative weights used to estimate unconsolidated aquifer subsidence susceptibility due to high, moderate and low values of the three contributing variables.

Value	Unconsolidated Aquifer Susceptibility to Subsidence		
	stratification of aquifer	*combined thickness of aquitards*	*compressibility of aquitards*
High	3	3	3
Moderate	2	2	2
Low	1	1	1

(*Source:* BGS Technical Report WC/95/3; Adams and Macdonald, 1995)

The high, moderate and low values can be attributed to quartile values. Once again, using a simple addition of weights scheme, the three vulnerability categories according to total weight W would be, (i) low vulnerability: $W < 4$; (ii) medium vulnerability: $4 \leq W \leq 7$; and (iii) high vulnerability: $W > 7$. If aquitard compressibility cannot be estimated, then only aquifer stratification and aquitard thickness should be used. The vulnerability categories, low, medium and high correspondingly should be adjusted to $W < 3$, $4 \leq W \leq 7$, and $W > 5$, respectively.

(4) Stabilization time: The stabilization time (t_e in years) is a measure of the amount of time an aquifer will take to revert back to equilibrium. The expression to measure this indicator is given in Eq (2) and an empirical analysis is provided as Figure 1 (after Custodio, 1992). From a ground water management perspective the proposed thresholds of vulnerability are, (i) low vulnerability: $t_e \leq 1$, (ii) medium vulnerability: $1 < t_e < 10$, and (iii) high vulnerability $t_e \geq 10$. Figure 1 can be used to estimate the stabilization time once values have been attributed to the three contributing variables.

Aggregation: Aggregation is the key to index and indicator development. An index or an indicator is a means devised to reduce a large quantity of data down to its simplest form, retaining essential meaning for the questions that are being asked of the data (Ott, 1978). In the previous section the use of the statistical concept of quartiles is proposed to classify values (Strzepek, 2001) into proposed groups – three for ground water condition and three for ground water vulnerability, and a data insufficiency threshold. Let us consider the example given in Table 8 for further discussion.

The information flow starts with the identification of the indicators and the variables that describe the functional relationship with that indicator. Here it has been implicitly assumed that these functions are linear, although limitations are associated with this assumption (Ott, 1978), the linear functions are the simplest functional forms. Through the schemes described in the previous sections indicator values can be derived and the state of the system in terms of that indicator can be described qualitatively. In deriving the indicator value there has already been a step of aggregation, and there is information loss implicit in an aggregation process. However, the information loss is accumulative and can gets compounded. As seen in Table 8(a), for the ground water condition there are three indicator values (or sub-index of ground water condition), and one indicator which is not observed in this case. For ground water vulnerability, Table 8(b), there are three indicators to assess ground water vulnerability, and one indicator, which is not observed in this case.

These sub-indices are represented by the, (i) condition sub-indices: I_{C1}, I_{C2}, I_{C3}, and I_{C4}, and (ii) vulnerability sub-indices: I_{V1}, I_{V2}, I_{V3}, and I_{V4}. Now comes the important question, how to aggregate these sub-indices to come up with a ground water condition index based on ground water quantity, and a ground water vulnerability index based on ground water quantity?

Ott (1978) provides a comprehensive discussion on aggregation of sub-indices. Ott points out that here is where most of the simplification and hence distortion is likely to be introduced. The common general forms of the aggregation functions and their characteristics are given in Table 9. The index form used in this report is what Ott refers to as the increasing scale index, i.e., condition or vulnerability deteriorates with an increase in the index value.

Table 8(a) Hypothetical case for assessing ground water condition in a basin.

Indicator Name	Variables	Data	Value	Indicator Value/Sub Index	Index
Condition					
Ground water reliance	Annual average ground water withdrawals	Primary and Secondary	---	45% (say) (more serious problem) $I_{C1}=3$	How to aggregate the sub-indices to compute ground water condition index based on ground water quantity?
	Annual average total withdrawals (surface and ground water)	Primary and Secondary	---		
Ground water depletion	Annual average ground water withdrawals	Primary and Secondary	---	30% (say) (less serious problem) $I_{C2}=2$	
	Annual average baseflow	Analyzed	---		
Encroachment ratio	Horizontal displacement of salinity front from a reference point	Analyzed	---	20% (say) (satisfactory) $I_{C3}=1$	
	Distance of control point from the reference point	Primary	---		
Subsidence ratio	Maximum subsidence with respect to a chosen datum	Analyzed	---	(not observed) I_{C4}	
	Minimum elevation of land surface with respect to chosen datum	Secondary	---		

Table 8(b) Hypothetical case for assessing ground water vulnerability in a basin.

Indicator Name	Variables	Data	Value	Indicator Value/ Sub Index	Index
Vulnerability					
Ground water level decline	Hydraulic diffusivity	Secondary and Analyzed	---	9 (say) (medium vulnerability) $I_{V1}=2$	How to aggregate the sub-indices to compute ground water vulnerability index based on ground water quantity?
	Heterogeneity	Secondary	---		
	Annual recharge	Primary and Analyzed	---		
	Volume of aquifer	Secondary	---		
Salt water intrusion	Hydraulic gradient	Secondary and Analyzed	---	5 (say) (medium vulnerability) $I_{V2}=2$	
	Permeability	Primary	---		
	Effectiveness of hydraulic barriers	Secondary	---		
Land subsidence	Stratification of aquifer	Primary and Secondary	---	(not observed) I_{V3}	
	Total thickness of aquitards	Primary and Secondary	---		
	Compressibility of aquitards	Analyzed	---		
Stabilization time	Hydraulic diffusivity	Secondary and Analyzed	---	10 (say) (high vulnerability) $I_{V4}=3$	
	Characteristic length of basin	Secondary	---		
	Basin constant	Empirical	---		

Two terms that have been used by Ott to describe the characteristics of the various aggregation functions are, (i) ambiguity – regions where a linear sum can exaggerate the state, and (ii) eclipsing – regions where the state is underestimated rather than an exaggeration.

Table 9 Characteristics of aggregation functions for increasing scale indices; (I_i = sub-index from indicator i, n = total number of sub-indices).

Aggregation Type	**Function**	**Characteristic**
Additive Forms		
Linear Sum	$I = \sum_{i=1}^{n} I_i$	Ambiguity; no eclipsing
Weighted Sum	$I = \sum_{i=1}^{n} w_i I_i$ where $\sum_{i=1}^{n} w_i = 1$	Eclipsing; no ambiguity
Root-Sum-Power	$I = \left[\sum_{i=1}^{n} I_i^p \right]^{1/p}$	Minimizes eclipsing and ambiguity as p approaches '
Maximum Operator	$I = \max \{I_1, \ldots, I_i, \ldots, I_n\}$	No eclipsing; no ambiguity
Multiplicative Forms		
Weights Product	$I = \prod_{i=1}^{n} I_i^{w_i}$ where $\sum_{i=1}^{n} w_i = 1$	Not applicable
Minimum Operator	$I = \min \{I_1, \ldots, I_i, \ldots, I_n\}$	Not applicable

(*Source:* Adapted from Ott, 1978)

Using the different aggregation schemes outlined in Table 9, and referring to the sub-indices in Tables 8(a)-8(b), the final outcome can be different. To illustrate this point let us consider the *ground water condition sub-indices*, and apply the different functional forms. The overall classification of the index is still based on the concept of quartiles, where values less than or equal to the first quartile (Q_1) are classified in the category satisfactory, the inter-quartile range covers the category of less serious problems and values greater than or equal to the third quartile (Q_3) fall under the category of more serious problems.

Linear Sum: Carrying out a linear sum of the sub-indices I_{C1}, I_{C2}, and I_{C3} (sub-index I_{C4} is not observed in this case) yields $I=6$. As only three indices exist, the minimum sum on a three-point scale (the three categories used in this report) would be 3 and the maximum sum would be 9. Therefore in this case, $Q_1 = 4.5$ and $Q_3 = 7.5$. As, $Q_1 \leq I \leq Q_3$, the ground water condition in this ground water system can be classified as a case of *less serious problem*.

Weighted Sum: If it is assumed that all the three sub-indices have equal weight, then the *ground water condition index* value would be $I=2$. Also using equal weights it can be found that $Q_1 = 1.0$ and $Q_3 = 3.0$. Again, $Q_1 \leq I \leq Q_3$, the ground water condition in this ground water system can be classified as a case of *less serious problem.*

Root-Sum-Power: Taking $p=2$, the value of the index I would be 3.74. Considering three variables, the lower and upper bound of the aggregated index I would be $\sqrt{3}$ = 1.732 and $\sqrt{27}$ = 5.196 respectively. Using simulation it was determined that the lower (Q_1) and upper (Q_3) quartiles were approximately, 2.60 and 4.40 respectively. Once again, $Q_1 \leq I \leq Q_3$, and the ground water condition can be categorized to be of *less serious problem.*

Maximum Operator: Calculating $I = max \{I_{C1}, I_{C2}, I_{C3}\}$, we get, $I = 3$, and this would imply that the ground water system is in a state of *more serious problem.*

As we are using an increasing scale index the *weight product* and the *minimum operator* functional forms are not tested here.

It is seen that the use of additive forms of the aggregation assessed the ground water condition to be in a state of less serious problem. The maximum operator however revealed that the ground water condition is in a state of more serious problem. The next question therefore is, which one is correct? Referring to Table 9, it is seen that the additive forms of aggregation has drawbacks in term of both ambiguity and eclipsing, the maximum operator however overcomes these two limitations. Furthermore, from a conservative design perspective it would be prudent to classify the ground water condition in this example *basin with more serious problems.*

The similar exercise can be carried out with the *ground water vulnerability sub-indices*. If we chose to use the maximum operator once again (refer to Table 8(b)), the basin would be considered as one of *high vulnerability.*

Hence overall, the basin has more serious ground water problems and has a high vulnerability.

CHALLENGES, TARGETS and GROUND WATER INDICATORS

The development of all indicators in the WWAP process is aimed to address the seven challenges set out in The Hague Ministerial Declaration. These seven challenges are:

(1) **Meeting basic needs**: to recognise that access to safe and sufficient water and sanitation are basic human needs and are essential to health and well-being, and to empower people, especially women, through a participatory process of water management.

(2) **Securing the food supply**: to enhance food security, particularly of the poor and vulnerable, through the more efficient mobilisation and use, and the more equitable allocation of water for food production.

(3) **Protecting ecosystems**: to ensure the integrity of ecosystems through sustainable water resources management.

(4) **Sharing water resources**: to promote peaceful co-operation and develop synergies between different uses of water at all levels, whenever possible, within and, in the case of boundary and trans-boundary water resources, between states concerned, through sustainable river basin management or other appropriate approaches.

(5) **Managing risks**: to provide security from floods, droughts, pollution and other water-related hazards.

(6) **Valuing water**: to manage water in a way that reflects its economic, social, environmental and cultural values for all its uses, and to move towards pricing water services to reflect the cost of their provision. This approach should take account of the need for equity and the basic needs of the poor and the vulnerable.

(7) **Governing water wisely**: to ensure good governance, so that the involvement of the public and the interests of all stakeholders are included in the management of water resources.

Strzepek (2001) provides an initial mapping of the WWAP indicators to address these challenges. The fundamental problem is still, how to represent these challenges quantitatively? What are the implications of the indicators in monitoring targets and meeting the above challenges?

To deal with the above issues, the fundamental question in the present context perhaps is, what is the role of ground water in light of the above challenges? Some initial thoughts in carrying out the analysis are presented in this section.

It is anticipated that an analysis at the national scale will have targets proposed by the different nations. For example, by 2010 a particular country would like to have 90% of its population with access to "safe drinking water". For sure, attaining this target is not only a function of the ground water resources, but the objective of the present discussion is, what is the role of ground water to meet this target? The next questions are, to achieve the aforementioned target, for example, what should be the ground water reliance ratio, what should be the depletion ratio? Now thresholds have been set which to an extent is arbitrary at this stage, stating how the condition of the system will change if the thresholds will be exceeded.

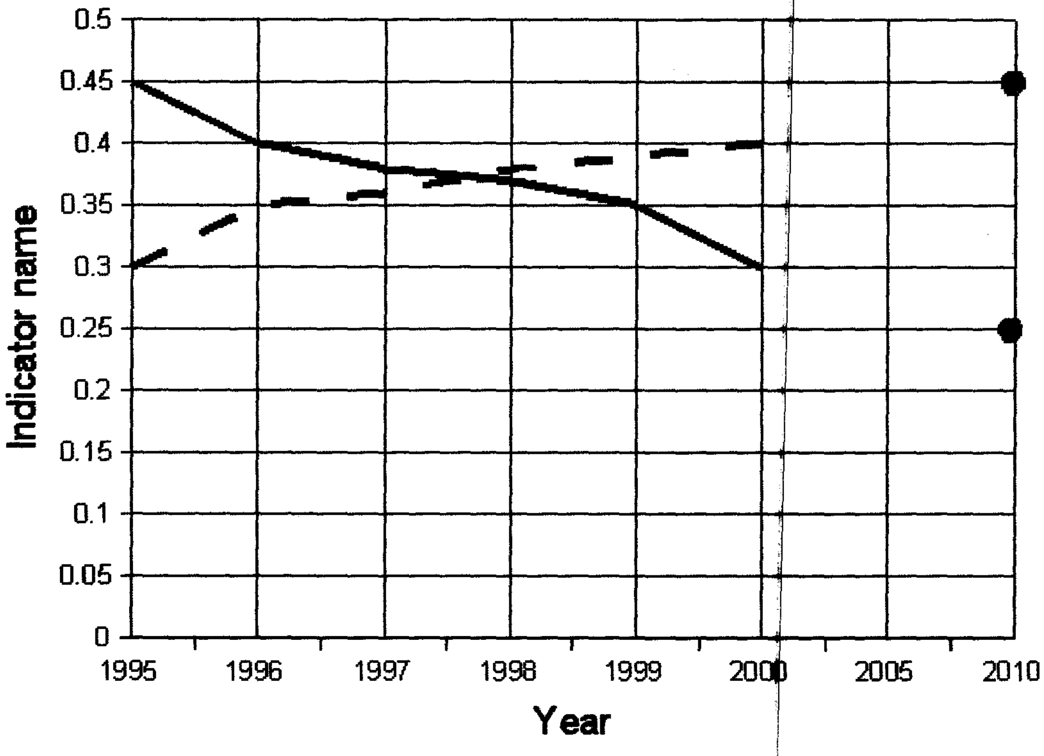

Figure 2 Meeting the challenge of basic needs, the variation of the ground water reliance indicator (solid line) and the ground water depletion indicator (dashed line) along with the 2010 proposed targets (circles, 0.25 for gw reliance; 0.45 for gw depletion).

Figure 2, shows the trend in the two indicators of ground water condition – ground water reliance and ground water depletion. Apparently this figure is contradictory, but the challenge is to meet demand of water supply but at the same time improve the condition of the ground water system. As of 2010 it is foreseen that the ground water reliance should drop down to 25% and then this indicator would characterize the ground water condition to be of less serious problem.

Similar exercise can be carried out for some of the other challenges, and the resource as a whole can be evaluated. However, it is essential to look into the other indicator reports and further analyze the problem.

This is some preliminary concepts and would be further developed through the WWAP process.

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