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A framework for measuring groundwater sustainability

Vishnu P. Pandey [a,*], Sangam Shrestha [b], Saroj K. Chapagain [c], Futaba Kazama [a]

[a] International Research Center for River Basin Environment (ICRE), University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8510, Japan

[b] Water Engineering and Management Field of Study, School of Engineering and Technology, Asian Institute of Technology, P.O. Box 4 Klong Luang, Pathumthani 12120, Thailand

[c] Center of Research for Environment Energy and Water (CREEW), 259 Chandramukhi Galli, Baluwatar, Kathmandu, Nepal

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ABSTRACT

This paper develops a structured framework that considers an index of means for achieving sustainability, the 'groundwater sustainability infrastructure index (GSII)', as a measure of groundwater sustainability. The infrastructure here refers to the existing knowledge, practices and institutions whose adequate strengthening helps achieve groundwater sustainability. The index is composed of five components (groundwater monitoring-GwM, knowledge generation and dissemination-KgD, regulatory interventions-ReI, public participation-PuP and institutional responsibility-InR) which disaggregate into 16 indicators. The index is illustrated with Kathmandu Valley in Nepal as a case study site. The study results showed that overall situation of the 'groundwater sustainability infrastructures' in Kathmandu Valley is relatively poor (GSII = 0.22). The scores of all the components of the index lie on the lower side of the sustainability scale (0–1, 1 representing the highest degree of sustainability). Therefore, more attentions are required to strengthen the sustainability infrastructures and subsequently achieve groundwater sustainability in the valley. Results of the GSII application demonstrated that the index could highlight areas for improvement and ultimately guide appropriate action and policy-making towards sustainable groundwater management.

1. Introduction

Groundwater is the world's most extracted raw material with an estimated global withdrawal of 600–700 km^3/year (Foster, 2006). It is often developed without adequate understanding of the balance between its occurrence (in space and time) and replenishment (through recharge) and impact on the groundwater environment. As a result, depletion of water levels in aquifers, decline in design yield of water wells, land subsidence and salinity intrusion in coastal aquifers are becoming a major concern across the globe (Kendy et al., 2003; Konikow and Kendy, 2005; Pandey et al., 2010; Reddy, 2005; Shah et al., 2000). Groundwater quality is also deteriorating because of inadequate protection from anthropogenic activities like urbanization processes, industrial discharges and agricultural intensification. Climate change will exert additional pressures on the resource and jeopardize sustainability if appropriate adaptation strategies are not implemented (Shrestha and Kataoka, 2008). Nevertheless, groundwater often remained as a 'neglected resource' (Foster, 2006) with limited funding for the improvement of resource understanding, management and protection. Considering groundwater environment as a common resource of current and future generations, concerns for sustainable utilization of groundwater resources are growing in recent years (Hiscock et al., 2002; Kretsinger and Narasimhan, 2005; Shah et al., 2000).

* *Corresponding author*. Tel.: +81 55 220 8670; fax: +81 55 220 8193.
E-mail addresses: e_vishnupandey@yahoo.com, vishnu@yamanashi.ac.jp (V.P. Pandey).
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'Groundwater sustainability' may refer to the development and use of the resource in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et al., 1999). The sustainability represents an optimal state; however, this is neither fixed nor constant but rather time- and space-dependent (De Carvalho et al., 2009), and therefore, needs to be quantified in order to evaluate the progress in achieving sustainability over time and space. Nevertheless, adequate attempts to quantify it are not yet made in spite of its wide discussion in scientific, academic and water management arena. Part of the reason is that sustainability is itself a multi-dimensional concept (e.g., Llamas et al., 2006) and is not a purely scientific concept but rather a perspective that can frame scientific analysis (Alley and Leake, 2004).

Various assessment tools may be used in order to measure the progress in achieving sustainability, including simulations, the use of prescribed criteria, and indices. Simulation exercises with constructed models, while enabling the understanding of complex systems, need a wide range of data and therefore may not be truly useful in data-poor regions. On the other hand, the use of prescribed criteria can result in a measure that is too simplistic and may not adequately represent the real system. The use of indices in such cases can render complex assessments more manageable, depending on the number of indicators and the type of index adopted (De Carvalho et al., 2009). Composite indicators (or indices) provide the big picture to ease interpretation by summarizing complex or multi-dimensional issues in view of supporting decision-makers (Saisana and Tarantola, 2002). Therefore, they are increasingly recognized as a useful tool for policy making and public communication on conveying information on groundwater situation (Singh et al., 2009).

Some attempts to develop indices of water resources sustainability have already been initiated, for example, Canadian Watershed Sustainability Index-CWSI (Policy Research Initiative, 2007), Watershed Sustainability Index-WSI (Chaves and Alipaz, 2007), West Java Water Sustainability Index-WJWSI (Juwana et al., 2009), Sustainability Index for Integrated Urban Water Management-SIUWM (De Carvalho et al., 2009). Those indices use indicators representing the state of three components of sustainable development (i.e. environment, economy and society). However, indices to measure 'groundwater sustainability' are not developed so far. This paper argues that an index of *means for achieving groundwater sustainability* which is termed as 'groundwater sustainability infrastructures' in this study can be used as a measure of groundwater sustainability.

This study proposes 'groundwater sustainability infrastructure index (GSII)' as a framework for measuring groundwater sustainability in order to evaluate the progress in achieving the sustainability. Evaluating this progress and paying attention towards gradual strengthening of the infrastructure (as a long-term strategy for groundwater sustainability) has become a paramount necessity in the absence of effective management of groundwater 'as a resource' and considering future growth in water demand and sustainable use of groundwater resources. The 'infrastructure' here refers not to the physical infrastructures (e.g., engineering constructions) but to the knowledge, practices and institutions whose adequate strengthening may help achieve groundwater sustainability. This paper discusses results from testing the index on Kathmandu Valley in Nepal (Fig. 1) as a case study site and provides a way forward for continuation of the research.

2. Description of 'GSII' framework

2.1. *Development of GSII framework*

The GSII framework was developed following most of the steps proposed by Nardo et al. (2005) for the development of composite indices, and comprised the following steps.

2.1.1. *Building of theoretical framework*

Sustainability is a manifold concept, approachable from many points of view (hydrological, ecological, economics, social, legal, institutional, inter- and intra-generational and political)

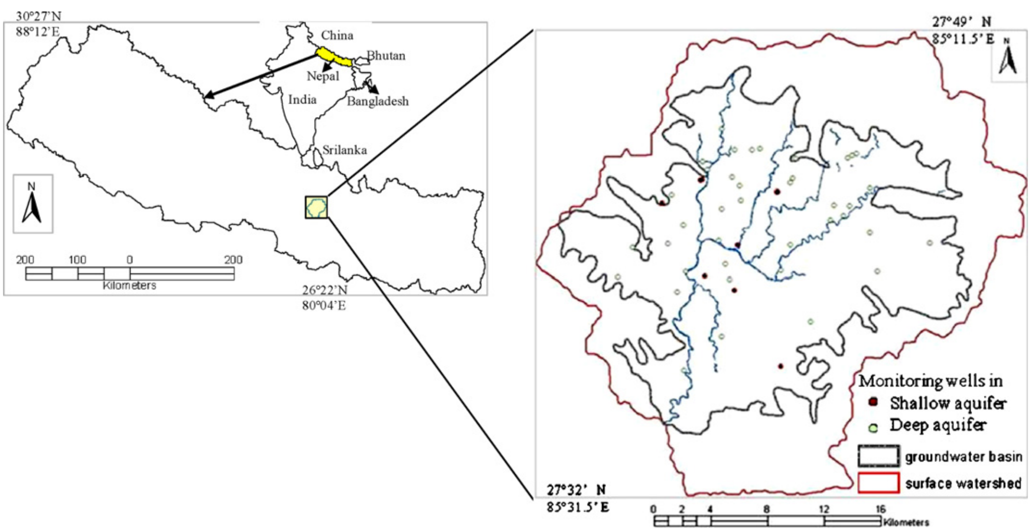

Fig. 1 – Location of study area: Kathmandu Valley in Nepal.

(Llamas et al., 2006). It is less likely that all the aspects of sustainability are achieved at a time. This study considers 'hydrological sustainability' as a focal point. The framework is based on the conceptualization of sustainability of Valentin and Spangenberg (2000) that addresses social, environmental, economic and institutional dimensions. In the process of assessing the means of achieving groundwater sustainability, this translates into the analysis of the following broad categories used as components of the GSII: public participation (PuP) for the social dimension; groundwater monitoring (GwM) for the environmental; regulatory interventions (ReI) for the economic; and institutional responsibility (InR) for the institutional dimensions. In addition, the GSII includes a component on knowledge generation and dissemination (KgD). There are arguments that appropriate groundwater management requires a significant degree of trust among stakeholders (e.g., Llamas et al., 2006). This mutual trust can be strengthened by data/information/knowledge generation and dissemination in transparent way to all the stakeholders. All these components are supposed to be universally applicable and are expected to encompass most of the means (of achieving groundwater sustainability) as indicators of the components (Fig. 2).

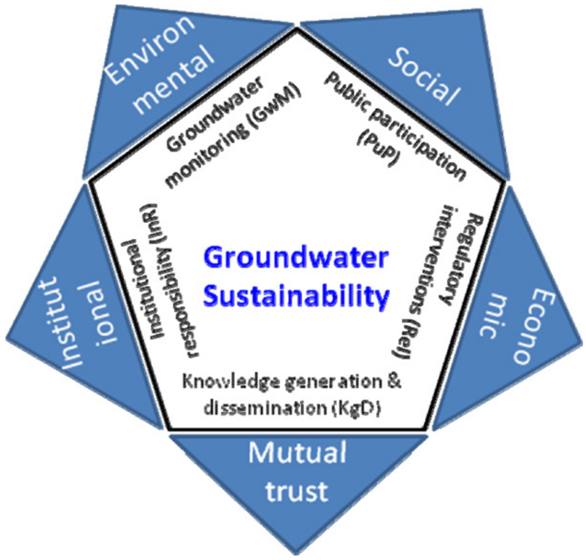

Fig. 2 – Five dimensions of sustainability and groundwater sustainability infrastructures.

2.1.2. *Indicator selection*

It involved selecting appropriate indicators for the five components given their appropriateness to the area in question, their scientific and analytical basis plus their ability to effectively represent the issues they are designed for. This involved an investigation of indices and indicators such as SIUWM, CWSI, WSI, WJWSI and UNESCO (2007); and review of literatures that discusses means of achieving 'groundwater sustainability' such as Bouwer (2002), Custodio et al. (2005), Dillon (2005), Foster (2006), Foster and Burke (2003), Hiscock et al. (2002), Kretsinger and Narasimhan (2005), Kumar et al. (2008), Menon (2007), Mills (2002), Scanlon et al. (2002) and Shah et al. (2000). Indicators measuring same or similar aspects were either excluded or replaced with other suitable indicator measures. Ultimately, 16 indicators were chosen

Table 1 – Groundwater sustainability infrastructure index, components and indicators.

Index	Component	Indicator	Description
Groundwater sustainability infrastructure index (GSII)	1. Groundwater monitoring (GwM)	1.1 Groundwater level 1.2 Groundwater extraction 1.3 Groundwater quality 1.4 Land subsidence	GwM enables a long-term understanding of groundwater availability and anthropogenic effects on groundwater resources. It helps protect groundwater environment
	2. Knowledge generation and dissemination (KgD)	2.1 Knowledge generation 2.2 Knowledge/data CSM 2.3 Provision for KID	KgD helps facilitate groundwater resources evaluation, planning and management. KgD also helps build 'mutual trust' among the stakeholders to achieve the goal of sustainability
	3. Regulatory interventions (ReI)	3.1 Groundwater rights 3.2 Groundwater licensing 3.3 Economic instruments	ReI aim to ensure sustainability through interventions like licensing, tax/subsidy, trading groundwater rights, etc.
	4. Public participation (PuP)	4.1 Awareness 4.2 Interest to participate 4.3 Availability of mechanism	PuP helps safeguard social wellbeing through sustainable use of the resource. It helps for informed decision making, conflict prevention and maximizing benefits (social, economic and technical)
	5. Institutional responsibility (InR)	5.1 Availability of authority 5.2 Legal framework 5.3 Institutional capacity	InR empowered with clear mandate, sufficient resources and legal framework increases strength of institutional leadership in groundwater management

'CSM' is compilation, storage and management; 'KID' is knowledge integration and dissemination.

(Table 1). They are discussed in Section 2.2 while describing the five components.

2.1.3. Computation of indicator values and normalization
The indicator chosen includes both qualitative and quantitative measures. However, for the index, the values of all indicators were determined through a qualitative expert rating approach. During the groundwater expert meeting (4–5 July, 2010) in Kathmandu, 10 experts (selected on an ad hoc basis) were requested to provide scores to the indicators after being presented with factual information and being provided with a structured view of indicators. The situation of each indicator in terms of achievement of groundwater sustainability was classified into four classes in a scale of 0–1: very poor (0.00), poor (0.25), acceptable (0.50), good (0.75) and excellent (1.0). The score values were already in a comparable form (scale: 0–1, 0 being the worst and 1 the best), therefore, normalization of the indicator value was not necessary. Seven of the experts responded to the score elicitation. On the basis of their input, the authors determined the scores. The score values were further supported by qualitative description of the situation of each indicator in the study area. This attempt enabled to compile large number of literatures and information related to groundwater in the study area.

2.1.4. Weighting
Weights could be assigned according to prioritized issues or statistically determined loads (De Carvalho et al., 2009). However, such weighting (or ranking) can be a delicate task as indicators are addressing different issues that may not be related (Blanc et al., 2008) and it may yield biased/misleading results if adequate attentions are not given to prioritize the issues. The weighting approach has drawn much criticism (e.g., Martinez-Alier et al., 1998) because it is an arbitrary process and no weighting structure can rationally justify the attribution of a given weight (e.g., greater weight) to a given indicator. As primary objective of this paper was to introduce the framework, equal weights were assigned to the indicators of each components and components of the GSII. Three reasons for assigning equal weights were: (i) to avoid bias in the result because of unequal weights, (ii) to give equal importance to each indicator of a component and each component of the GSII, and (iii) because of appropriateness of equal weights for a small sample size of less than 30 (as discussed in Raju et al., 1999).

2.1.5. Aggregation
A composite index approach was employed to compute the 'groundwater sustainability infrastructure index, GSII' score for the case study area, as the sum of all weighted components (Eq. (1)). The value for each component (X_i), was multiplied by the attributed weight (w_i), to give a value on a scale of 0–1, 0 being the worst and 1 the best. The score for the five components was determined in a similar manner, that is, by multiplying indicator value (X_i), with attributed weight (w_i).

$$\text{GSII} = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \qquad (1)$$

2.1.6. Application
The index was applied to assess the situation of 'groundwater sustainability' in Kathmandu Valley in Nepal where groundwater extraction has already exceeded recharge and groundwater management policy and plans are yet to come into effect.

2.1.7. Visualization and dissemination
Composite indicators (or index) must be able to communicate a story to decision-makers and other end-users quickly and accurately. Tables, albeit providing the complete information, can sometimes obscure sensitive issues immediately visible with a graphical presentation. Therefore, the indicator values, component indices and the GSII were presented in a form of table and the component scores were presented in a form of 'radar diagram' to enhance visualization.

2.2. GSII components and indicators

The index is composed of five components which disaggregate into 16 indicators (Table 1). The components are the broad categories of 'groundwater sustainability infrastructures' and are calculated as an aggregated score of the indicators representing the component. Each component is composed of 3–4 indicators (Table 1). The indicators presented here, however, are flexible and can be modified (add/remove) to best suit the study area(s). The GSII components are described hereunder.

2.2.1. Groundwater monitoring (GwM)
Data collection and monitoring with satisfactory space and time coverage enable a long-term understanding of groundwater availability and anthropogenic effects (of diversity of uses) on the groundwater resources. Monitoring data if used in parallel with mapping and modeling reflect a complete picture of the aquifer conditions needed for a proper and full assessment of the resource and benefit the decision-making process for protecting groundwater environment. Therefore, GwM is considered as an important infrastructure for groundwater sustainability. Groundwater monitoring can be made with a network of observation wells, time, continued financial support, and long-term commitment of the authority and stakeholders. Monitoring of groundwater level, quality, extraction volume, and land subsidence is considered as indicators of GwM in this study. The indicators can be rated based on their adequacy for spatial and temporal coverage, conditions of the monitoring infrastructures, quality of monitoring data, governments' commitment and continuous funding for monitoring activities; but not based on analysis of monitoring data itself.

2.2.2. Knowledge generation and dissemination (KgD)
Knowledge generation through evaluation, analysis and usage of available data and information and its compilation, integration and dissemination to the stakeholders helps facilitate groundwater resources evaluation, planning, and management. The sharing of knowledge helps build trust among the stakeholders to achieve the goal of groundwater sustainability. Therefore, it is considered as a 'groundwater sustainability infrastructures' in this study. The groundwater

knowledgebase includes but not limited to the geometry and hydrogeology (permeability/hydraulic conductivity, transmissivity, storage coefficient, groundwater storage volume, etc.) of each hydrogeologic units, continuously updated groundwater model, current and future status of groundwater environment (groundwater extraction, recharge, quality, stresses, etc.), etc. This component could be measured by rating the status of knowledge generation, practice of knowledge/data compilation storage and management and practice/provision for knowledge integration and dissemination. The second indicator refers to compiling knowledge generated by several agencies (either with or without coordination of knowledge management institution) and the third indicator refers to further integrated analysis of compiled knowledge and their dissemination.

2.2.3. *Regulatory interventions (ReI)*

Regulator interventions are considered as a part of whole groundwater management plans. The ReI are aimed at ensuring that distributions, rate, magnitude and duration of groundwater extractions and quality of groundwater resources are within the limits that are technically, socially, environmentally and politically acceptable. Three things basically important in regard to management interventions are: defining groundwater rights, groundwater licensing and economic instruments. Reliable inventory of groundwater rights is desirable in order to ensure adequate management (Llamas et al., 2006) whereas groundwater licensing is required to ensure that groundwater is being extracting with the spirit of management plans. Economic instruments, on the other hand, aims to control groundwater extraction and protect groundwater quality by means of taxation, subsidy and enabling water right trading. The instruments should be decided with due care for the total economic value of groundwater for all sectors of the economic: residential, agricultural, industrial, tourism, recreation. Though there are several issues related to the usage of economic instruments for managing groundwater extraction and pollution, for example, basis of taxation, acceptability of the proposed tax by the users, etc. (Koundouri, 2004), participatory approach in groundwater management may help implement the ReI. In the context of this paper the three indicators would be evaluated based on existing practices and progress in implementing the ReI.

2.2.4. *Public participation (PuP)*

Merely regulatory interventions like water rights, licensing and economic tools of water pricing may not be successful unless the different user groups are fully involved. The stakeholders like groundwater developers, private and public users, conservationists, water managers, administrators and policy-makers, etc. have wide-ranging positions about groundwater use as a result of their different interests and objectives. PuP at all stages, i.e. development, approval and implementation of the groundwater management plans, is important for sustainable use of groundwater resources. It helps in informed decision making (making use of stakeholders' experience) and conflict prevention, for social benefits (promote equity among users), economic benefits (optimizing pumping and reduce energy costs) and technical benefits (better estimate of water extraction). It also helps to safeguard social wellbeing through sustainable use of resources. Therefore, PuP is considered as one of the 'groundwater sustainability infrastructures' in this study. The PuP can be evaluated by rating the state of public awareness on groundwater situation/issues, their interest to participate and availability of practice/mechanism for PuP.

2.2.5. *Institutional responsibility (InR)*

Any groundwater management system requires the support of an appropriate governance framework. It refers to provision for authority to look after groundwater development and management, legal framework and control mechanism, and adequate capacity (availability of human resources, information and education) to carry out its duty. The InR – empowered with sufficient resources (for daily business and research activities), adequate policies, and laws and means to apply and enforce them – is necessary to conduct groundwater management activities. The institution is meant here to be defined as in political science, including not only organizations, but also mechanisms and orientations, etc. The InR is evaluated by rating the status of three indicators: availability of authority for groundwater management, legal framework and control mechanism and institutional capacity.

2.3. *Interpretation of the results*

The GSII would be useful in comparing the status of groundwater sustainability over space and time for the purpose of prioritizing the resource allocation and assessing the areas of improvements needed. If the priority is to be set among several study areas, the area(s) with lower value(s) of the GSII can be considered as the priority one(s). Afterwards, areas (i.e. five components that represent broad areas of the GSII) of improvements needed in the selected study area(s) can be highlighted based on the component score (i.e. higher priority to the component having lower score) and further prioritization within the selected area(s) can be made based on the indicator values.

3. Application of 'GSII' in Kathmandu Valley

Kathmandu Valley is located at central Nepal in South Asia (Fig. 1). The groundwater basin in the valley is situated at 1340 m asl and covers 327 km^2 of 664 km^2 watershed areas. The basin in 2001 was home for 1.53×10^6 people, 84.3% of them live in urban areas (Pandey et al., 2010). The population is expected to have increased by more than two times in the last decade, though no official data are available. Groundwater is a major source of domestic water supply for those populations (Metcalf and Eddy, 2000; Khatiwada et al., 2002). Groundwater is extracted from shallow and deep aquifers, which are separated vertically by a thick clay layer. Many wells have been drilled in the aquifers in haphazard manner. As discussed in Pandey and Kazama (2011), groundwater extraction is continuously increasing since 1970s. Aquifers are being mined faster than being recharged since mid-1980s in the absence of management intervention for the protection of groundwater environment.

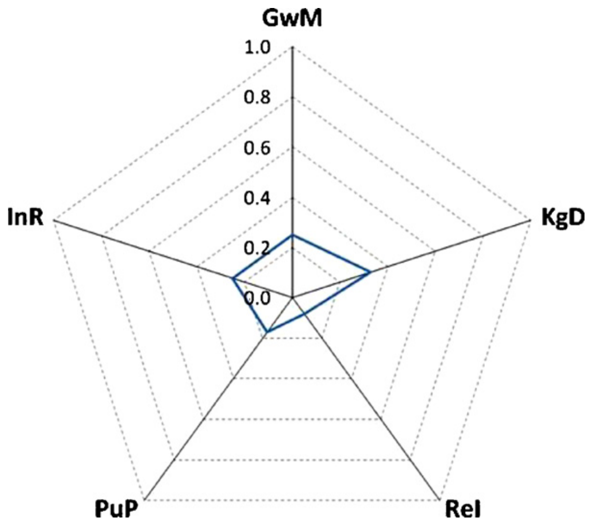

Fig. 3 – The GSII parameter values in Kathmandu Valley.

The situation of 'groundwater sustainability infrastructures' in Kathmandu Valley is discussed through an evaluation of the GSII, its five components and indicators. The situations of the indicators are discussed both qualitatively (by describing the situation in the study area) and quantitatively (by indicator scores). The scores were calculated with the procedure discussed in Section 2.1.3. Afterwards, the component scores were computed (using indicator scores), plotted in Fig. 3 and discussed in terms of their variations with each other and contribution in overall GSII.

3.1. *Groundwater monitoring (GwM)*

Current status of groundwater level, extraction volume, quality and land subsidence monitoring in the study area is discussed and appropriate rating is given to the indicators based on rating criteria discussed in Section 2.1.3. The aggregated score of the component is 0.25 (Table 2), i.e. current status of this infrastructure can be rated as 'poor'.

3.1.1. *Groundwater level*

Groundwater levels were observed since early 1970s. Unfortunately they were discontinued after completion of particular projects in different periods of time (e.g., Binnie and Partners, 1973, 1988; JICA, 1990) probably due to lack of long-term commitment and financial support. Continuous monitoring was initiated in 1999 under the project ''Urban Water Supply Reforms in Kathmandu Valley''. Fifty monitoring wells (8 in shallow and 42 in deep aquifers, shown in Fig. 1) were selected for the purpose. After the completion of the project in 2001, Groundwater Resources Development Project (GRDP)/Department of Irrigation (DOI) continued the monitoring. However, inadequate coverage (space and time), poor quality of data, inadequacy in storage and dissemination of data reflect the need of further strengthening the infrastructure. The current situation of this indicator can be rated as 'acceptable' (score = 0.50) (Table 2).

3.1.2. *Groundwater extraction*

Continuous monitoring of groundwater extraction is not yet started despite the fact that annual extraction has already exceeded recharge since mid-1980s (Pandey and Kazama, 2011) after the Nepal Water Supply Corporation (NWSC) introduced groundwater as a major part of its water supply system (Metcalf and Eddy, 2000). Attempts to document groundwater extraction wells and estimate extraction volumes were initiated by JICA (1990) and updated respectively by Metcalf and Eddy (2000) and Acres International (2004). However, information about exact number (and their locations) of extraction wells and continuous monitoring of groundwater extraction rate/volume from those wells (in daily/monthly/yearly time scale) are not yet available. The latest database is the one compiled by Acres International (2004) which has records of groundwater extraction from 250 plus wells in the year 1999 (one point of time only!).

Table 2 – Groundwater sustainability infrastructure indicators, components and index values.

S.N.	Indicator		Component		Index
	Name	Score	Name	Score	
1.1	Groundwater level	0.50	1. Groundwater monitoring (GwM)	0.25	0.22
1.2	Groundwater extraction	0.25			
1.3	Groundwater quality	0.25			
1.4	Land subsidence	0.00			
2.1	Knowledge generation	0.75	2. Knowledge generation and dissemination (KgD)	0.33	
2.2	Knowledge/data CSM	0.25			
2.3	Provision for KID	0.00			
3.1	Groundwater rights	0.00	3. Regulatory interventions (ReI)	0.08	
3.2	Groundwater licensing	0.25			
3.3	Economic instruments	0.00			
4.1	Awareness	0.25	4. Public participation (PuP)	0.17	
4.2	Interest to participate	0.25			
4.3	Availability of mechanism	0.00			
5.1	Availability of authority	0.50	5. Institutional responsibility (InR)	0.25	
5.2	Legal framework	0.00			
5.3	Institutional capacity	0.25			

'CSM' is compilation, storage and management; 'KID' is knowledge integration and dissemination.

Table 3 – A partial list of groundwater-related knowledge generation in Kathmandu Valley.

Knowledge/information	Source
Geometry of hydrogeologic units	Metcalf and Eddy (2000), Pandey and Kazama (2011)
Hydrogeology (hydraulic conductivity/transmissivity, storage coefficient, groundwater storage volume)	Binnie and Partners (1973,1988), JICA (1990), KC (2003), Metcalf and Eddy (2000), Pandey and Kazama (2011), Pandey et al. (in review), etc.
Groundwater extraction database	Acres International (2004), Metcalf and Eddy (2000).
Groundwater levels	GWRDP/DoI, Kathmandu, Nepal.
Water quality	JICA (1990), Khadka (1993), Jha et al. (1997), Kharel et al. (1998), Karmacharya and Pariyar (1999), ENPHO (1999, 2005), Metcalf and Eddy (2000), Khatiwada et al. (2002), Acres International (2004), Gurung et al. (2007), Chapagain et al. (2009), etc.
Recharge to aquifer	Binnie and Partners (1988), JICA (1990), Gautam and Rao (1991).
Current status of groundwater environment (Drive-Pressure-State-Impact-Response)	Pandey et al. (2010)
Groundwater model	JICA (1990), Acres International (2004). But, continuously updated groundwater model is not available
Vulnerability of shallow aquifer to pollution	Pathak et al. (2009)
Surface & groundwater interactions	Study on progress by the authors
Future status of groundwater under climatic and non-climatic change	Study on progress by the authors
GIS data: surface topography, land cover, river networks, etc.	NGIIP (2004).

The situation of this indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.1.3. *Groundwater quality*

Groundwater quality of shallow and deep aquifers in Kathmandu Valley was assessed by several studies since early seventies (Table 3) and reported seasonal and spatial variations in the quality (Chapagain et al., 2009; ENPHO, 2005). Despite of the studies in several points of time, they did not necessarily use the same wells for the analysis because of different objectives and scopes of the studies. Therefore continuous data of water quality are not available. The first comprehensive groundwater quality assessment was the one carried out by a Nepalese-Australian team using 75 monitoring wells (Jha et al., 1997) but was not continued for a long-term monitoring. In 1999, groundwater quality monitoring (along with water level) was initiated in 50 wells (8 in shallow and 42 in deep aquifers) which was later continued by GRDP/DoI. However, spatial and temporal coverage, data quality, data storage and dissemination aspects are inadequate. The overall situation of this indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.1.4. *Land subsidence*

As a result of groundwater mining from deep aquifer and subsequent lowering of piezometric head, overlying aquitard (clay and silt layers) and deep aquifer is expected to get consolidated by reducing pore water pressure. This may result in subsidence or settlement of the ground surface. Areas with risk of potential land subsidence are those, where declines in groundwater levels are greatest and subsoil structure contain a high percentage of compressible clay and silt layers. Such conditions are believed to exist in some areas towards northern and central part of the groundwater basin (Binnie and Partners, 1973, 1988; JICA, 1990; Kharel et al., 1998). However, no efforts have been made to monitor land subsidence and no evidence of land subsidence recorded so far. The overall situation of this indicator can be rated as 'very poor' (score = 0.00) (Table 2).

3.2. *Knowledge generation and dissemination (KgD)*

This component is evaluated based on discussion followed by rating of three indicators shown in Table 1. The aggregated score of this component is 0.33 (Table 2), i.e. current status of this infrastructure can be rated as 'poor to acceptable'.

3.2.1. *Knowledge generation*

Knowledge generations about groundwater environment were started from early 1960s. A partial list of the knowledge/information generated in the study area is summarized in Table 3. There could be many other unnoticed studies carried out in academic institutions in Nepal and/or abroad as a part of academic requirements and/or published in international journals. Therefore, the volume of knowledge generation can be considered as relatively good, albeit, issues of coverage (spatial and temporal), access and implementation do exist. The overall situation of this indicator can be rated as 'good' (score = 0.75) (Table 2).

3.2.2. *Knowledge/data compilation, storage and management*

Some of available data and study reports are available from GRDP/DoI and/or the NWSC library and/or several government offices, private consultants/companies or from some individuals. It shows that available data/information/knowledge are highly scattered non-coordinated and inaccessible to all the stakeholders (public, academia, research scholars, government and non-government authorities) upon request from a single-window (e.g., public outreach office) because of inadequate efforts and priority for compilation, storage and management of knowledge, data and information. The overall situation of this indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.2.3. Provision for knowledge integration and dissemination

Integration and collective interpretation of available knowledge and scientific findings, translation in easy-to-understand form (using charts, 2D or 3D visualization, etc.) and making them accessible to all the stakeholders from a single-window (e.g., public outreach office) would enable the stakeholders to understand the latest situation of groundwater environment. This helps build mutual trust between stakeholders and ignites the feeling for preserving groundwater environment through wise use of the precious resource. However, usefulness of the available knowledge/information and implementation of important findings from earlier studies is limited in the absence of legal provision for knowledge/information integration, collective interpretation and dissemination. This indicator can be rated as 'very poor' (score = 0.00) (Table 2).

3.3. Regulatory interventions (ReI)

This component is evaluated based on discussion followed by rating of three indicators shown in Table 1. Despite several recommendations in the past, groundwater management policy and plans which meant regulatory interventions are not yet coming into effect. As a result, provision of licensing and regulation of groundwater extraction and pollution control do not exist in reality. The aggregated score of this component is 0.08 (Table 2), i.e. current status of this infrastructure can be rated as 'very poor to poor'.

3.3.1. Groundwater rights

The Water Resources Act (1992) declares the state ownership of water resources and links groundwater directly to surface water. In reality, however, it appears that the practical right to groundwater is related to right to land. There are no practice(s) and legal provisions for trading groundwater rights. This indicator in the study area can be rated as 'very poor' (score = 0.00) (Table 2).

3.3.2. Groundwater licensing

Though, the Water Resources Act (1992) has provision for license need to utilize water resources (except non-commercial users); it is silent in regard to groundwater, and therefore, there is no practice of groundwater licensing. After the recommendation of the Kathmandu Valley Water Services Sector Development Program (KVWSSDP) funded by the Asian Development Bank (ADB), the Government of Nepal formed Kathmandu Valley Water Supply Management Board (KVWSMB) under Water Supply Management Board Act (2006) and entrusted the responsibility of taking the charge of groundwater management in the valley. The KVWSMB prepared the final draft of groundwater management and regulation policy after incorporating suggestions from two stakeholder consultation workshops and submitted to the line ministry (Ministry of Physical Planning and Works, MoPPW) in December 2010. The policy would come into effect after approval from the Ministry. The policy focuses on balancing groundwater extraction and recharge by controlling haphazard extractions. It has proposed to amend the existing Water Resources Act (1992) to make provisions for registering all the extraction wells (even tube wells dug for domestic purpose) with the board, licensing groundwater extraction for commercial purpose, protecting groundwater quality and promoting rainwater harvesting and recharging programmes to increase groundwater levels. Currently about 20 wells are registered with the board. The registration of groundwater extraction wells and licensing would be made mandatory after the policy which is waiting for approval from the ministry comes into effect. The current situation of this indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.3.3. Economic instruments

The economic instruments for groundwater extraction regulation and quality protection are yet to be in place in the study area. This indicator can be rated as 'very poor' (score = 0.00) (Table 2).

3.4. Public participation (PuP)

This component is evaluated based on discussion followed by rating of three indicators shown in Table 1. The aggregated score of this component is 0.17 (Table 2), i.e. current status of this infrastructure can be rated as 'very poor to poor'.

3.4.1. Awareness

Public are quite aware that excessive groundwater extraction has decreased groundwater level and that has led to drying of many 'dug wells' and 'stone spouts' in the study area. But, they are not made aware about potential areas, depths and extraction rates for groundwater pumping because of lack of knowledge dissemination. Some non-governmental organizations (NGOs) like Center of Research for Environment Energy and Water (CREEW) and The Small Earth Nepal (SEN) have initiated activities to encourage public participation in groundwater management by organizing national symposiums, groundwater expert meeting and awareness raising programmes. However, more efforts are needed in that direction to achieve the goal. The overall situation of this indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.4.2. Interest to participate

Based on encouraging public participation in other participatory environment management activities in the area, interest of public to participate in groundwater management activities can be anticipated if the institutional leadership is effective. However, no real examples are available to test the level of public interest to participate in groundwater management-related activities. The PuP could be encouraged by knowledge transfer, transparent management, public education and highlighting prospects of individual and community benefits. This indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.4.3. Availability of mechanism

The legal/social provision/mechanism for public participation is non-existent so far in the study area. Therefore, this indicator can be rated as 'very poor' (score = 0.00) (Table 2).

3.5. Institutional responsibility (InR)

This component is evaluated based on discussion followed by rating (and corresponding scoring) of three indicators shown in Table 1. The aggregated score of this component is 0.25

Table 4 – Pre-existing institutional arrangement relating to groundwater in Nepal.

Government agency	Groundwater related tasks
Ministry of irrigation (formerly Ministry of Water Resources)	
✓ Groundwater Resources Development Board (GRDB)	– Oversees policy related to groundwater
✓ Groundwater Resources Development Project (GRDP)	– Implementing body of GRDB
Ministry of Physical Planning & Works (MoPPW)	
✓ Department of Water Supply & Sewerage (DWSS)	– Drinking water supply (surface & groundwater) in areas outside the coverage of NWSC & KUKL
✓ Nepal Water Supply Corporation (NWSC)	– Regulation, operation and management of drinking water supply (surface & groundwater) in urban centers outside Kathmandu Valley
✓ Kathmandu Valley Water Supply Management Board (KVWSMB)	– Regulation and management of groundwater resources in Kathmandu Valley
✓ Kathmandu Upatyaka Khanepani Limited (KUKL)	– Operation of water supply (including groundwater) in Kathmandu Valley
Ministry of Industry (MoI)	
✓ Department of Mines and Geology (DoMG)	– Geological survey and databases
Ministry Environment (MoE)	– Groundwater quality protection
Ministry of Science & Technology (MoST)	
✓ Department of Hydrology & Meteorology (DHM)	– Collection & storage of climate data
District Water Resource Committee, in which, most of the water-sector-related government agencies are represented	– Authority to issue licenses for the use of water resources (including groundwater)
Water & Energy Commission Secretariat (WECS)	– Apex body for water resources policy & planning

Modified after Tuinhof and Nanni (2004).

(Table 2), i.e. current status of this infrastructure can be rated as 'poor'.

3.5.1. *Availability of authority*

A number of government agencies (ministries and departments) are available with some groundwater-related responsibilities (Table 4). The responsibilities are clearly overlapping. The Water and Energy Commission Secretariat (WECS) performs water resources policy and planning functions, but only at a very general level and do not include resource data basing, licensing or registration of water use nor water quality aspects. The Groundwater Resources Development Board (GRDB) (renamed in 1976 after *Department of Groundwater Survey established in 1968*) was supposed to be a primary government agency responsible for groundwater investigation, basic data generation, monitoring and development. However, its effectiveness is limited to the groundwater development for irrigation in southern plains of the country, and monitoring of water level and quality in Kathmandu Valley through its implementing agency GRDP. To address the overlaps in responsibilities the Government of Nepal established KVWSMB under the Water Supply Management Board Act (2006) as an institution having sole authority for groundwater regulation and management in Kathmandu Valley. The KVWSMB is responsible for groundwater data collection/processing, groundwater development planning, monitoring, regulation and research. The authority has recently prepared final draft of groundwater management and regulation policy. The progress in groundwater regulation is expected to accelerate after the policy comes into effect. The current situation of this indicator can be rated as 'acceptable' (score = 0.50) (Table 2).

3.5.2. *Legal framework*

Attempts for developing legal framework and control mechanisms for surface and groundwater management (e.g., groundwater licensing, promulgation of the groundwater management act, etc.) were initiated under the ADB funded Kathmandu Valley Water Services Sector Development Program (KVWSSDP). As a part of the attempt, a groundwater bill was developed at the initiative of the GRDB. The bill proposed to amend the existing Water Resources Act (1992) for making provisions for utilization and management of groundwater resources in Nepal; however, some important issues were not considered in that bill, for example the regulation of certain groundwater uses, registration of water wells in critical areas, and the licensing drilling companies to ensure that water wells are drilled adequately and their information is recorded. Unfortunately, the bill is still pending in the Parliament since 2004 as it was dissolved after the bill registered there. Recently, the GRDB has taken initiative to activate the bill in a form of a new bill for formulating Groundwater Act for the entire country rather than amending existing Water Resources Act (1992). For that purpose, a committee has been formed by GRDB in mid-2010 to modify the bill in the changed context incorporating important aspects not addressed in the earlier bill. In particular to Kathmandu Valley, the recently finalized groundwater management and regulation policy (as discussed in Section 3.2.2), which is waiting for approval from the line ministry, suggests for amending existing Water Resources Act (1992) to make legal provisions for groundwater management in Kathmandu Valley. In the absence of legal framework updated inventory of wells in shallow and deep aquifers, continuously maintained record of groundwater extraction, etc. are not available. The situation of this indicator can be rated as 'very poor' (score = 0.00) (Table 2).

3.5.3. *Institutional capacity*

A separate authority in charge for groundwater development and management in the valley is in place since 2006. The institutional capacity in terms of resource (human and economic) availability for daily business and research activities, policies, and means to apply and enforce them are inadequate. The current situation of this indicator can be rated as 'poor' (score = 0.25) (Table 2).

3.6. 'Groundwater sustainability infrastructure' index

The index value calculated with equal weights to each component is 0.22 (Table 2). This suggests that overall situation of 'groundwater sustainability infrastructure' in Kathmandu Valley can be rated as 'very poor to poor', and therefore, significant attentions are needed to strengthen the 'groundwater sustainability infrastructures' and subsequently achieve the goal of 'groundwater sustainability'. The scores of all the components of the index lie on the lower side of the sustainability scale (0–1, 1 representing the highest degree of sustainability); however, the situation of the KgD is relatively better (score = 0.33), ReI is the worst (score = 0.08) and the others are intermediate (Fig. 3).

4. Summary and conclusion

This study proposes a framework that considers an index of *means for achieving groundwater sustainability (GS)*, as a measure of the GS. The framework consists of an index (i.e. GSII), five components, and sixteen indicators. The study then applies the framework to evaluate situation of the GS in Kathmandu Valley. The study results show that coverage (spatial and temporal) of monitoring (groundwater level, extraction, quality and land subsidence) is inadequate and data quality, storage and dissemination aspects are poor in practice. Aquifers are being mined faster than being recharged in the absence of groundwater management policy and plans, management intervention and meaningful public participation. Knowledge generation is relatively good, albeit, highly scattered, non-coordinated and inaccessible from a single-window (e.g., public outreach office). Overall situation of the infrastructures in the valley is relatively poor (GSII = 0.22) as the value of the GSII lie on the lower side of the sustainability scale (0–1, 1 representing the highest degree of sustainability). It reflects the need of significant attentions to strengthen the sustainability infrastructures and subsequently achieve the goal of GS. All the components of the index are somewhere near to 'poor' and therefore needs higher attentions; however, they can be arranged in decreasing order of priority (based on their aggregated scores) as follows: ReI (score = 0.08), PuP (score = 0.17), InR (score = 0.25), GwM (score = 0.25) and KgD (score = 0.33). Even within the ReI, situation of groundwater rights and economic instruments are 'very poor' and therefore they should get higher priority. It is expected that after the groundwater management and regulation policy that is waiting for approval from the ministry comes into effect, the KVWSMB would play an effective role of institutional leadership for achieving groundwater sustainability in the valley.

The approach proposed in this paper is an attempt in the direction of developing a robust index for measuring progress in achieving groundwater sustainability. The five components of the GSII are supposed to be universal and are expected to encompass most of the means (of achieving groundwater sustainability) as indicators of the components. The indicators, however, are expected to be flexible and can be modified (add/remove) to best suit the study area(s). For wider applicability and robustness, the framework could further be improved by – (i) developing rating criteria based on some quantitative value of the indicator, and (ii) sensitivity analysis of the GSII value with variations in indicator composition, weighting schemes and methods of aggregation. It however, needs testing the index on several study areas having variety of settings, scales and stages of groundwater development and management. Furthermore, to enable appropriate use of the GSII as an advocacy and management tool, it is suggested to engage continuously with relevant stakeholders and develop regularly updated data banks.

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