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PAPER

The role of groundwater governance in emergencies during different phases of natural disasters

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Abstract The establishment of water governance in emergency situations supports timely and effective reaction with regard to the risk and impact of natural disasters on drinking-water supplies and populations. Under such governance, emergency activities of governmental authorities, rescue and aid teams, water stakeholders, local communities and individuals are coordinated with the objective to prevent and/or mitigate disaster impact on water supplies, to reduce human suffering due to drinking-water failure during and in the post-disaster period, and to manage drinking-water services in emergency situations in an equitable manner. The availability of low-vulnerability groundwater resources that have been proven safe and protected by geological features, and with long residence time, can make water-related relief and rehabilitation activities during and after an emergency more rapid and effective. Such groundwater resources have to be included in water governance and their exploration must be coordinated with overall management of drinking-water services in emergencies. This paper discusses institutional and technical capacities needed for building effective groundwater governance policy and drinking-water risk and demand management in emergencies. Disaster-risk mitigation plans are described, along with relief measures and post-disaster rehabilitation and reconstruction activities, which support gradual renewal of drinking-water services on the level prior to the disaster. The role of groundwater governance in emergencies differs in individual phases of disaster (preparedness, warning, impact/relief, rehabilitation). Suggested activities and actions associated with these phases are summarized and analysed, and a mode of their implementation is proposed.

Keywords Groundwater governance · Emergency groundwater resources · Disaster · Groundwater monitoring · Groundwater vulnerability mapping · Water supply

This article belongs to a group of articles that consider groundwater resources for risk reduction in emergencies

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Introduction

Major natural and human-caused disasters, including floods, droughts, landslides, earthquakes, and pollution events, threaten human health and life. Global climate variability and change are expected to manifest in a growing trend in the occurrence, frequency and severity of major water-related disasters (e.g., droughts, floods, storms and precipitation-induced landslides) globally, regionally and seasonally, as stated in the 2005 Hyogo Declaration (UNISDR 2005), the United Nations World Water Development Report 3 (UNESCO-WWAP 2009), and the World Reconstruction Conference in Geneva, 2011 (GFDRR, 2011). Immediately after physically securing the endangered population, the distribution of drinking water is the most pressing priority following a disaster. However, regular public water supplies as well as domestic wells are almost always physically damaged and/or polluted by disaster events. Availability of low-vulnerability groundwater resources becomes imperative for drinking-water security in disaster-prone regions (Vrba and Verhagen 2011). Securing drinking water from groundwater resources that have been proven safe and protected by geological features, and with long residence times, makes water-related relief activities during and after an emergency more rapid and effective. Such emergency resources have to be identified, investigated, developed, protected and adequately managed in order to substitute for affected standard drinking-water supplies. Developing an effective emergency water governance policy to strengthen disaster preparedness and warning and to reduce risks associated with disaster impacts on groundwater and drinking-water sources is needed, therefore, on all levels (international, national, local).

An overview of the use of groundwater resources for risk reduction in emergencies is given in the accompanying essay in this volume of *Hydrogeology Journal* by Vrba and Renaud (2015). This paper deals with groundwater governance in emergency situations and institutional and technical capacities in emergencies and their role in particular sequences of disaster events (preparedness, warning, impact/relief and rehabilitation). In this respect, the following topics will be discussed:

- The role of emergency groundwater governance associated with prevention of the risk and remediation of the impact of natural disasters on groundwater resources and drinking-water sources and services to make the water resources and dependent ecosystems more resilient to the disaster events.
- The role of institutional and technical capacities in building: (1) effective groundwater governance policy and structures in emergencies, (2) a robust framework for sustainable pre-disaster management and preventive protection of drinking-water sources in disaster-prone areas, (3) rapid and effective relief response to the impact of disasters on drinking-water facilities and infrastructure and (4) specification of human and physical resources, investment means and post-disaster restoration plans needed for gradual renewal of affected regular drinking-water facilities and services at the level prior to the disaster.

Groundwater governance and integrated water resources management

Several definitions of water governance exist (UNESCO-WWAP 2012, 2006), although an internationally accepted unified definition has not yet been agreed. However, it is widely accepted that water governance can be effective when it involves society as a whole and is not the exclusive domain of governments (Pierre 2000). Water governance is based on multi-sectoral and interdisciplinary approaches in planning, decision-making and management processes and involves governmental authorities at all levels, the public and private sectors, water stakeholders, various society groups and communities (Vrba and Verhagen 2011. The Food and Agriculture Organization of the United Nations (FAO), the United Nations Educational, Scientific and Culture Organization (UNESCO), The World Bank, the Global Environment Facility (GEF) and the International Association of Hydrogeologists (IAH) launched in 2011 the initiative "Groundwater Governance: a Global Framework for Action". The outcomes of this project (GEF Groundwater Governance Project undertaken by FAO) are presented in a special edition for the World Water Forum 7 (FAO 2015a, b). In the context of this project, groundwater governance comprises the enabling framework and guiding principles for responsible collective action to ensure control, protection and socially sustainable utilization of groundwater resources for the benefit of human kind and dependent ecosystems, i.e. a shared global vision on groundwater governance for 2030 (FAO 2015c).

Implementation of groundwater governance policy supports the safety and sustainability of groundwater resources as a vital necessity for human life, economic development and the healthy functioning of ecosystems. All have to be in conformity with ethical, religious and cultural traditions of society. In developing countries, equitable governance and management of groundwater resources is the key for sustainable living and poverty alleviation (Vrba and Verhagen 2011).

Effective water governance relies on catchment-based integrated water-resources management (IWRM). The Global Water Partnership formulated IWRM as a process that promotes the coordinated development and management of water (both surface and groundwater), land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP 2000). Principles and processes of IWRM were formulated by the United Nations-Department of Technical Co-operation for Development/International Bank for Reconstruction and Development/United Nations Development Program (UN-DTCD/IBRD/UNDP 1991), summarized in UNESCO-WWAP report 1 (UNESCO–WWAP 2003) and deeply discussed by Young et al. (1994), Gordon at al. (1994), Visscher at al. (1999), UNESCO–WWAP (2006), Davison at al. (2005) and others.

IWRM and water governance are interdependent, support sustainable water resources development, utilization of water resources for social and economic benefits, and support health provisions of society. Both are linked to land use planning and practices, are attentive to historical traditions of the society, and are based on a participatory approach by decision and policy makers, planners, water stakeholders and the general public (Vrba and Verhagen 2011). In this regard, several deficiencies have been registered up to this time, e.g.:

- *Economic*. Lack of appropriate water pricing policy to make water accessible for all; subsidy of water price leading to wasteful and uncontrolled use; illegal use of public water sources; low efficiency in drinking-water services (e.g. high water losses in public pipelines); inadequate investments in water projects and in development of drinking-water infrastructures

- *Social.* Uneven water allocation within the hierarchy of society; lack of uptake on the public's right to be informed and to participate in water resources planning and decision-making processes and on the environmental impact assessment procedure
- *Legal.* A water legislative framework (particularly water-supply protection zones and drinking-water standards) and water property rights in emergencies are often imperfect or absent; the professional water authorities do not display adequate legal competence
- *Political*. Unequal rights of water stakeholders in the decision and policy-making process; underdeveloped institutional water structures; conflicting upstream and downstream changes in land use and/or diverse interests in development and protection of water resources; inadequate political will to objectively coordinate interests of water developers and water users in emergencies; management of transboundary aquifers is not adequately internationally coordinated and/or unfavourable affected by political decisions
- *Environmental.* Protection of water dependent ecosystems against disasters, as well as man-made groundwater resources depletion and pollution, are not yet adequately controlled, monitored and managed; deficiencies in protection and conservation of groundwater dependent ecosystems against pollution

Groundwater governance in emergency situations

There are several institutional, legal and policy issues specifically related to groundwater governance in emergency situations. In particular, risk managers, civil defence agencies, army and other special rescue and aid teams are important participants of groundwater governance oriented towards the mitigation of the risk and impact of disasters on drinking-water sources and populations.

Relevant governmental and disaster-risk authorities coordinate diverse interests of the various water stakeholders and water consumers in emergencies. They also manage groundwater resources according to drinking-water emergency plans and integrate emergency drinking-water sources into overall management of drinking-water services.

The following obstacles impinge seriously on groundwater governance in emergency situations: (1) communication gaps and low compatibility between all interested groups at governmental and community level, (2) the absence of local communities in the water related planning and decision–making processes, (3) gaps in the legal framework relevant to water rights in emergency situations, (4) lack of qualified and trained human resources, emergency information structures, and early warning and groundwater-monitoring systems.

The technical and economic potential to manage and mitigate disaster impact on groundwater resources in emergency situations differs in developing countries. The rural populations of developing countries depend particularly on shallow dug wells. Such low cost sources of drinking water are highly vulnerable to disasters and their loss significantly affects the population's social and economic conditions.

A very important aspect of groundwater governance in emergencies in drawing the attention of governments, organizations and individuals to the concept of preparedness for establishing alternative drinking-water supplies, is empowerment (Vrba and Verhagen 2006). Very often a local population is rendered helpless following a disaster, cut off from its traditional water supplies and faced with delays in aid from outside. Empowerment enables local people to take charge immediately after disaster, with their own knowledge and instrumental means to restore water supplies from their own groundwater resources. Highly vulnerable local communities living in hazardous-prone areas have to be involved and well informed about emergency and safety plans, inclusive of emergency drinking-water distribution systems. This will reduce human exposure and suffering with respect to future disasters, and raise the adaptation capacity of populations living in disaster-prone areas. Both protecting and empowering vulnerable groups to build local communities more resilient to disasters and to reduce disaster future risks was stressed during the 2011 World Reconstruction Conference (WRC) held in Geneva (GFDRR 2011).

Institutional and technical/scientific building related to groundwater governance in emergency situations

Implementation of groundwater governance in emergency situations depends on all the dimensions of a country's institutional and technical/scientific capacities and whether such capacities are applied in a coherent and integrated manner (Fig. 1)

Institutional capacity building

Institutional capacity building in emergencies refers mainly to non-structural measures: governmental emergency water authorities, the legal framework, water protection policy, the availability of professional human resources and capacities, and information and involvement of the public (Fig. 1). They play a decisive role in (1) building emergency water governance structures and capacities for prevention of disaster risk and mitigation of disasters impact, (2) formulating efficient drinking-water risk management plans, and (3) addressing drinking-water demand management in disaster-prone regions.

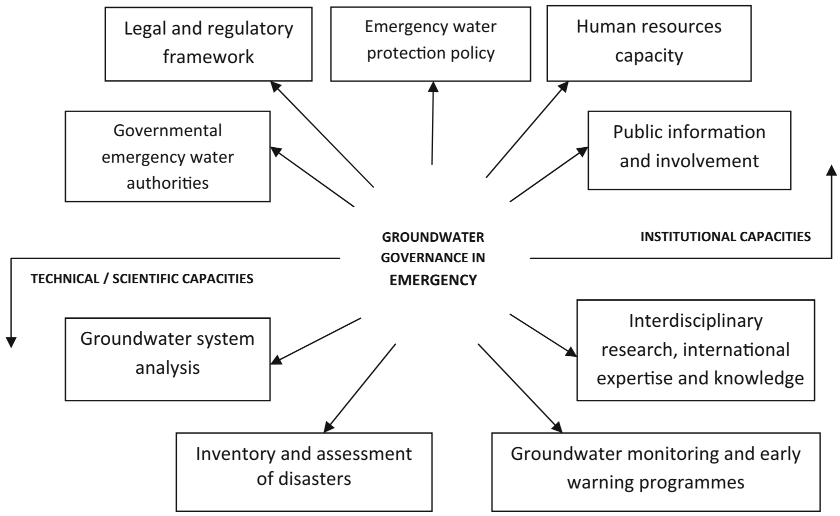

Fig. 1 Framework of institutional and technical capacities in groundwater governance for emergency situations

Governmental emergency water authorities

Governmental water authorities coordinate and implement water disaster risk and mitigation measures, and drinking-water demand management in emergencies, and they support the operation of monitoring and early warning systems. They also ensure dialog and information flow between different sectors, water stakeholders, rescue, aid and army teams, civil protection forces, local communities and non-governmental organizations (NGOs). These enhance governance for disaster risk preparedness, investments in disaster protective measures, potential for immediate launching of relief and rehabilitation of damaged drinking-water infrastructure, and effective management of post-disaster rescue activities. Existing emergency authorities should be strengthened and, if missing, have to be built in countries prone to natural disasters. For example, the specific objective of the UNESCO project (UNESCO 2011) to combat the effects of drought in the Horn of Africa is "to strengthen in Somalia, Kenya and Ethiopia, institutional and technical capacities on drought preparedness related to the provision of safe drinking water for affected populations in emergency situations".

Legal and regulatory framework

The delegation of responsibilities to secure and regulate drinking-water services and the right to use water sources in emergency situations are applied in water law and in water-related emergency rules, regulations and practices. Such legal framework has been endorsed in the UNESCO-WWAP report 2 (UNESCO-WWAP 2012). The establishment of well-defined and coherent water rights is essential in formulation of responsibilities for protection and exploitation of water resources in emergencies. The so-called 1998 Aarhus Convention, overseen by the United Nations Economic Commission for Europe (UNECE 1998), endorsed "the right of the public to participate in integrating land use planning and environmental decision-making processes and to be informed and to have access to all information which could enable the public to take measures to prevent or mitigate harm arising from the threat caused by natural causes or due to human activities" (Article 5, §1). The Aarhus Convention was enforced on 30 October 2001. The human right to safe drinking water and sanitation was adopted by the UN General Assembly (Resolution 18/1) in the year 2009 (UNGA 2009).

Emergency water-protection policy

Emergency water-protection policy in disaster-prone areas deals with, among others, the maintenance of stream networks, river regulation works, establishment and operation of early warning and water monitoring systems, delineation of inundation and other risk areas, water supply protection zones in areas prone to flooding, tsunami and other disasters, and protection of groundwater recharge areas. It also includes protective measures for low-vulnerability groundwater resources used, or considered for use as an emergency source of drinking water. Existing pollution sources located in disaster-prone areas have to be registered and relevant protective measures based on "prevent pollution at source" applied. A specific budget has to be secured for implementation of emergency drinking-water protection policy; the approach "the polluter pays principle" has to be applied to identified polluters operating refineries, industrial and oil storage facilities or waste disposal sites in disaster-prone areas without relevant protective provisions of groundwater.

Human resource capacity

Human resources, properly qualified, experienced, trained and motivated, are a crucial component of emergency water governance in all phases of coping with the impact of disasters on water resources. In the anticipatory and warning phase, engineering and managerial services prevail, e.g. hydrogeologists, hydrologists, water quality specialists, as well as water and land use managers and planners. During the impact and relief phase, the participation of groundwater and surface water experts and water quality advisers is of critical importance. In the rehabilitation phase, national and local governmental authorities jointly with water managers and engineers and hydrogeologists are the key specialists participating in (1) the restoration of damaged drinking-water infrastructures, (2) remediation of polluted drinking water and (3) supervision over development of new emergency drinking-water sources.

Many less developed low-income countries face the lack of skilled personnel and financial funds to formulate and implement prevention and reconstruction programmes, and to secure protective measures that will reduce the disasters impact on drinking-water sources and the population. Strengthening the cooperation of international organizations with developing countries and knowledge transfer is, therefore, an urgent task in building resilience to disasters. The role of training and education programmes and human capacity building focused on risk management of drinking water in emergencies is pointed out.

Public information and involvement

Further important measures related to water governance in emergencies include: increased access to emergency information, raised awareness to water resources, active public involvement in the protection of drinking-water facilities in emergencies, and endorsement of the population's ability to cope with disasters. It is critical to decentralize decision-making and to empower local communities to play an active role in actions and plans for disaster preparedness measures. Rapid and effective disaster responses based on historical experience and knowledge of local communities support governance policy as well. In many countries (e.g. EU countries), active public involvement is based on a legal basis (Plate 2003). Governments (national and local) have to increase the collaborative approach and introduce specific measures to inform, educate and train the local population in all aspects of mitigation of disaster risk and impact on drinking-water services. The World Health Organization proposed the following disaster-related information important for local communities (WHO 2005): knowledge of disaster risks (causes and dynamics), forecast, warning, mitigation and impact (safety instructions to alleviate injuries and lives). In UNESCO's International Hydrological Programme (IHP) publications—Affeltranger (2001), Dooge (2004), Vrba and Verhagen (2006), the UNESCO-WWAP reports and McDaniels at al. (1999) the role of populations within the framework of water governance policy in emergencies is thoroughly discussed.

Technical/scientific capacity building

Technical and scientific capacity building refers to groundwater system analysis, inventory and assessment of natural disasters with regard to the impact on groundwater resources, groundwater monitoring and early warning, interdisciplinary research and international expertise and knowledge transfer (Fig. 1).

Groundwater system analysis

Groundwater system analysis refers to the current knowledge of occurrence and accessibility of groundwater resources related to both recent and earlier hydrological cycles (non-renewable/fossil groundwater). Setting up a conceptual model based on delineation of hydraulic boundaries, evaluation of recharge rate, flow nets and hydraulic characteristics of the studied groundwater system supports (1) the assessment of groundwater resources resistant to natural disasters and (2) identification of the crucial factors influencing the quantity, quality and vulnerability of groundwater resources in disaster-prone areas. The conceptual model should cover the uncertainties in defining the groundwater behaviour and provide the basis for determining further data requirements for developing a mathematical model for prediction of the impact of a disaster on the groundwater system.

Inventory and assessment of disasters

An inventory and assessment of disaster impact with regard to the effect on and vulnerability of groundwater resources and populations are of particular importance. These involve the collection and evaluation of historical and contemporaneous records about the nature and return periods of natural disasters, and data about their registered impact on groundwater quality and quantity and water supply facilities. Such an inventory, along with an inventory of significant groundwater pollution sources located in disaster-prone areas, is crucial in prevention policy in the disaster preparedness phase.

Groundwater monitoring and early warning programmes

Groundwater monitoring and early warning programmes produce data essential for (1) assessing the current status of groundwater quality and quantity, (2) recognizing and foreseeing the threats of disaster on the groundwater system while they are still controllable and manageable, (3) decreasing uncertainties associated with the groundwater impacts from such threats and (4) application of relevant protective measures of emergency groundwater resources. The 1992 Dublin International Conference on Water and the Environment (World Meteorological Organization 1992) and the UNESCO–WWAP (2006, 2009) reports stressed the responsibility of governments to promote awareness and provide conditions for the establishment, operation and coordination of programmes for early warning. This prevents and/or reduces impacts of disasters on human life and on water and ecological systems. The need to ensure that rapid and coordinated action is taken in an alert/emergency was highlighted among the priorities for action during 2005–2015 at the World Conference on Disaster Reduction in 2005 in Kobe, Japan (UNISDR 2005). Methods of early warning with respect to surface water and groundwater were discussed at the international Global Environment Monitoring (GEMS)/Water Expert Consultation meeting in Koblenz, Germany (IHP/OHP 1994) and described by Vrba and Adams (2008). However, at the national scale, early warning and groundwater monitoring activities are still underdeveloped due to financial and logistic problems, particularly in developing countries. For example, data concerning groundwater are severely lacking or sporadic in Caribbean countries. Data are available from two out of the 15 Caribbean countries that participated in the 2010 UNESCO international workshop in St. Kitts (UNESCO 2010).

The World Hydrological Cycle Observing System (WHYCOS) plays an important role with regard to disaster warning and prevention. The system helps to (1) bridge gaps of data from terrestrial observation, (2) integrate in-situ terrestrial and satellite-based observations and (3) support data useful for water-related disaster protection policy (e.g. delineation of inundation areas, location of emergency wells, changes in groundwater level and storage of large aquifers, surface changes of lakes, vegetation cover, soil properties). Satellite images also provide data for location of paleo-channels and underground buried streams. Both contain significant groundwater resources which may be used in emergencies (Meijerink 2007). Remote sensing techniques have been successfully applied in China (Fig. 2) to locate, e.g. groundwater seepage patterns and buried rivers, stream paleo-channels and water-bearing fracture patterns in igneous rocks and to delineate groundwater recharge areas and inundation areas. Identification of paleo-channels by remote sensing based on the moister content in the soils and vegetation patterns above the buried channels has been applied in the north of the Erdos Plateau (Zhou 2011; Fig. 2). In India, application of remote sensing data supported delineation of paleo-buried channels with groundwater reservoir with vast storage capacity in the arid terrain of western India (Sinha 2007). The implementation of remote sensing data to paleo-channels delineation has been based on (1) spatial and genetic relationships between surface material and underlying paleo-channels fills, (2) physical and spectral contrasts between paleo-channel fills and surrounding terrain and (3) the nature of paleo-river dynamics (Sinha 2007).International cooperation and coordination in collection, evaluation, exchange and dissemination of groundwater data significantly support groundwater governance in emergencies, particularly in the case of transboundary aquifers.

Interdisciplinary research, international expertise and knowledge transfer

Interdisciplinary research, international expertise and knowledge transfer are important vehicles in improving water governance in emergency situations and need the support of international organizations and national governments. The outcomes and strategic goals of the World Conference on Disaster Reduction (2005) in the Hyogo Framework for Action 2005–2015 pointed out the importance of transferring knowledge, technology and expertise. That approach enhances capacity building for disasters risk

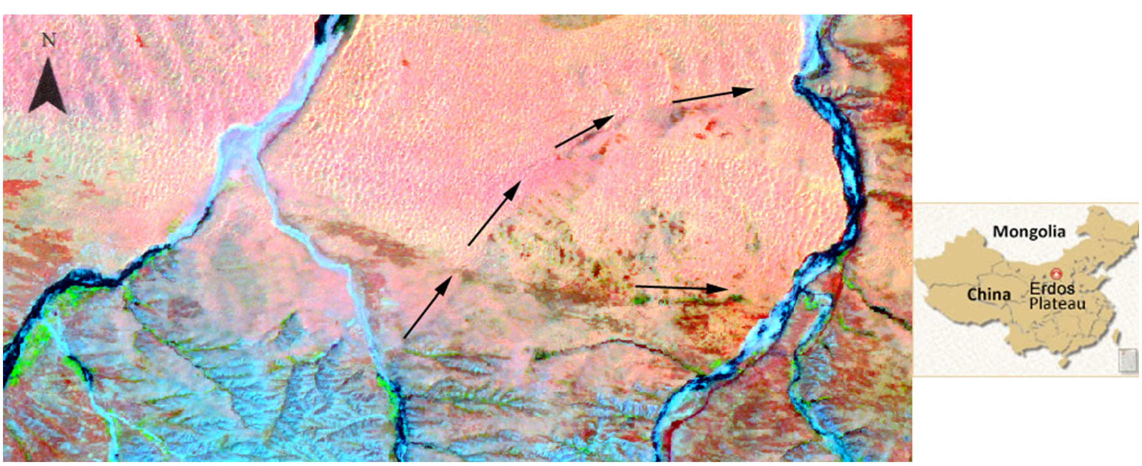

Fig. 2 Landsat TM Band 641 RGB composite showing palaeochannels in the north of the Erdos Plateau, China (approximate scale 1:2,250,000). The *dark blue* is surface water and the *light blue* shows underground streams and moisture. The *arrows* indicate the location and trend of interpreted buried paleochannels with potential emergency groundwater resources (Zhou 2011)

reduction and the sharing of research findings, lessons learned and best practices.

Some of the main objectives of the current eighth phase (2014–2021) of the UNESCO International Hydrological Programme (IHP) (UNESCO-IHP 2014) are to: (1) put science into action, (2) establish a knowledge and communication platform between scientists, water stakeholders and communities, (3) develop new ideas that would support policy-making and decision-taking, and (4) help IHP member states adapt new strategies to be more resilient to the impact of climate variability and change.

The role of groundwater governance in emergencies during different phases of disaster

The principles of water governance are discussed among others by Young et al. (1994), Affeltranger (2001), Plate (2003), Dooge (2004) and in documents of various UN organizations (e.g. WMO 1999, UNESCO-WWAP and UNISDR reports). This section focuses on emergency groundwater governance and risk-management activities in different phases of a disaster, as proposed by Dooge (2004) and discussed by Vrba and Verhagen (2011; Fig. 3).

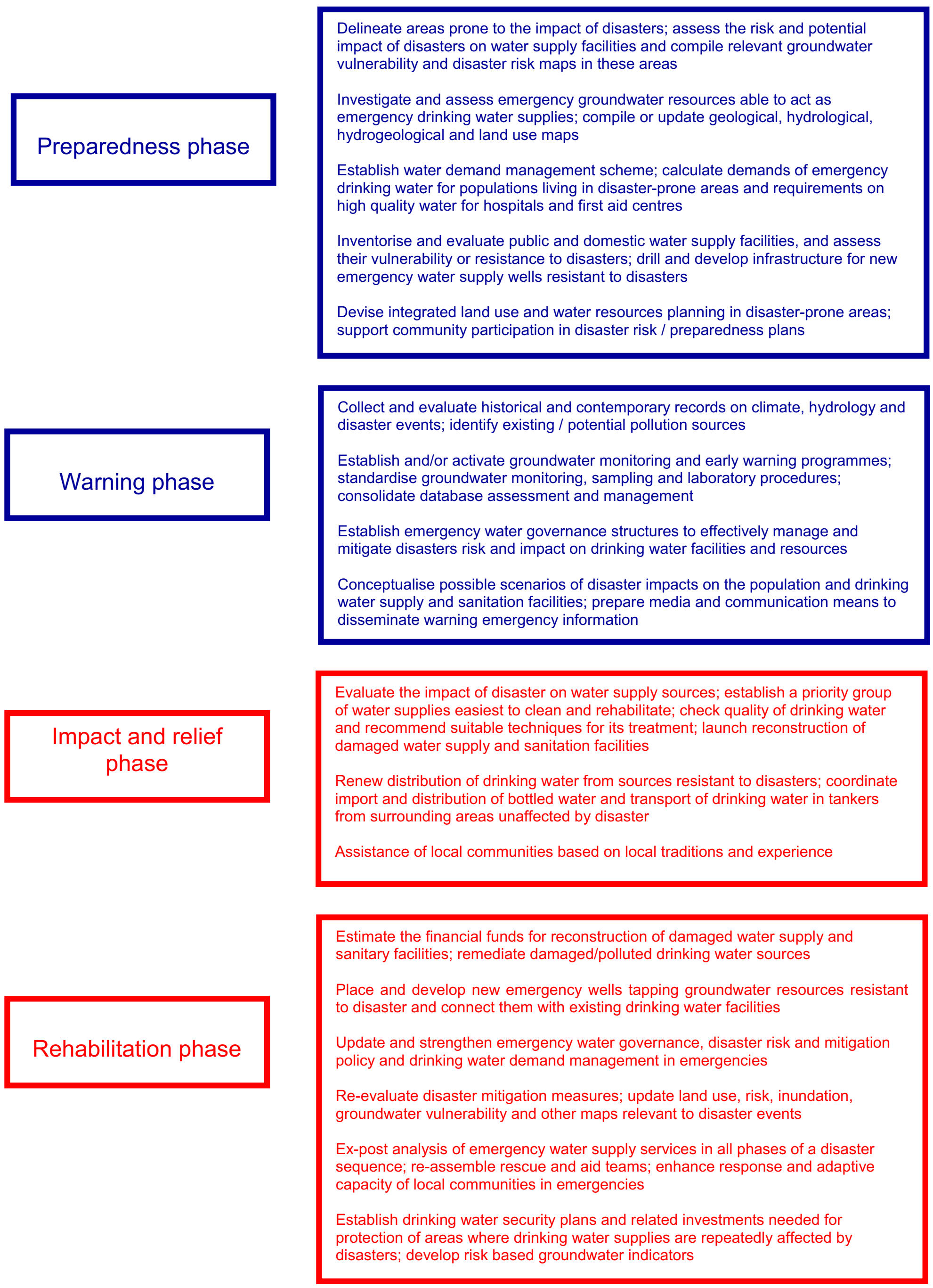

Fig. 3 Overview of emergency groundwater governance and risk management activities in different phases of a disaster sequence. *In blue*: preparedness and warning phases. *In red*: impact, relief and rehabilitation phases

The preparedness (anticipatory) phase

An assessment of the risk of disastrous events on water supply sources and populations supports the formulation and implementation of effective pre-disaster groundwater governance in emergencies. However, some uncertainties have to be considered because sudden catastrophic events of hydrological and geological origin and their unexpected impact on water supplies are reported worldwide. To secure drinking-water services in an emergency in disaster-prone areas, the following preparedness activities are listed:

- The delineation and mapping of areas prone to disasters impact
- The evaluation of the potential risk and impact of disasters in these areas as well as evaluation of vulnerability or resistance of existing public and domestic water supply facilities to disasters
- The quantitative and qualitative evaluation of groundwater resources and drinking-water supplies resistant to natural disasters able to act as emergency drinking-water sources
- The elaboration of water demand management in emergencies; the available water resources have to be managed with regard to the drinking-water requirements (water demand per person, per day) of the number of people endangered, inclusive of water demand for hospitals and other health centres and sanitary purposes (particularly in municipal areas)

With regard to disaster preparedness measures and disaster risk mitigation policy, several insufficiencies are registered in disaster-prone regions:

- Relevant documents are not available for integrated water and land use planning and management in emergencies, like (1) urban and rural development plans, (2) drinking-water emergency plans, (3) vulnerability maps depicting areas prone to inundation and to the risk of other disasters, and (4) scarcity of data related to groundwater quality and groundwater level records in these areas.
- High vulnerability of people (and their drinking-water supplies, mainly shallow domestic wells) living in unplanned urban or rural settlements in areas affected by sudden cataclysmic events, e.g. below the flood line in areas likely to be inundated, in the foothills of volcanic cones or in landslide-prone areas.
- Unsustainable land-use practices, e.g. deforestation, have led to soil erosion and microclimate changes in many regions worldwide and thus decrease their resistance to floods, droughts and landslides. The industry development, urbanization growth and intensification of agricultural production reflect significant changes in land use patterns and vegetation cover, degraded soil quality, impinged water resources quantity and quality, and functioning of groundwater dependent ecosystems.
- Unsustainable land use leads to the deterioration of conditions for groundwater recharge and subsequently facilitates a decline of groundwater storage, inclusive of that which can be used in emergency. For example, extensive deforestation in catchment areas in Haiti significantly reduces groundwater recharge and causes extensive erosion (UNESCO 2010).

The following preparedness measures with respect to groundwater governance in emergencies are listed:

- Geological, hydrogeological and land use maps, combined with disaster risk and groundwater vulnerability maps (Fig. 4), satellite imagines and panoramic aerial photomaps are important tools for outlining and assessing groundwater resources resistant to natural hazards. Where such maps at a suitable scale are not available in disaster-prone areas and knowledge about groundwater is inadequate, complementary hydrogeological investigation, mapping and groundwater monitoring are urgently needed. Such activities become imperative in development and management of groundwater resources resistant to natural disasters.
- Water wells resistant to flooding and other disaster impacts have to be regularly tested and evaluated with respect to their use and functionality during and after a disaster, recorded in emergency plans and depicted in disaster risks maps and associated emergency documentation.
- Groundwater from confined, deep aquifers resistant to disasters or even non-renewable groundwater bodies need to be addressed and tested for providing adequate emergency yields. Such an emergency supply should not be seen as a substitute for a regular resource. It should be earmarked and temporarily extensively exploited only during emergencies, until the regular water-supply system can be restored and re-activated both in quantity and quality. However, in some cases, newly developed groundwater resources resistant to disasters make possible their regular sustainable exploitation by deep wells. Such wells replace existing facilities, usually shallow wells located in vulnerable aquifers (Sukhija and Narsimha 2011). New emergency wells should be equipped with pumps and diesel driven generators maintained at well localities and should be accessible to tankers or mobile cisterns for transporting and distributing drinking/cooking water during and after emergency (House and Reed 2004; WHO 2005; Vrba and Verhagen 2011). These wells should be periodically tested and plotted on relevant maps. Local governments and the population have to be informed about their specific use and location. Groundwater from highly productive emergency wells can be also be used for sanitary purposes

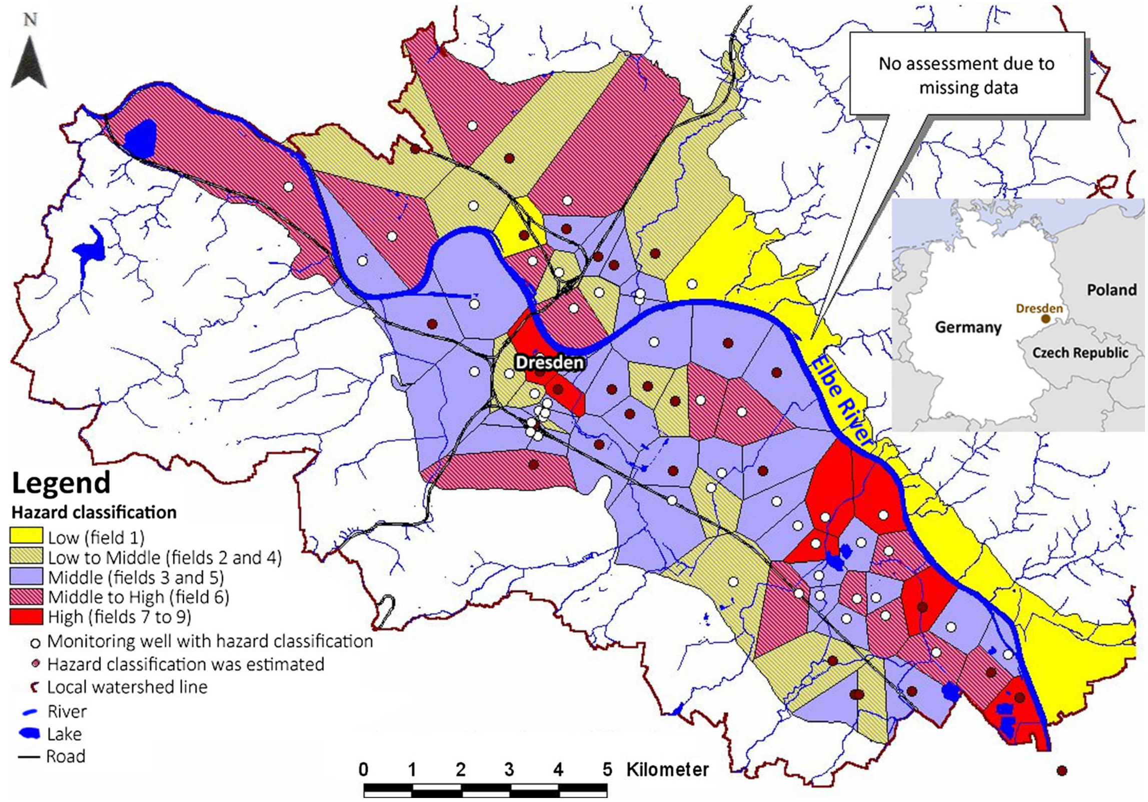

Fig. 4 Example of a map of classified groundwater flood hazard in 2002 in Dresden, Germany. The *field numbers* are the field numbers in the grid of hazard potential. This figure is reproduced with permission from the author (Sommer 2007; Sommer and Ulrich 2005)

(toilet flushing) and if surface water is not available for firefighting during earthquakes or other disasters.

- Availability of qualified and experienced human resources significantly supports groundwater governance in the disaster preparedness phase. Teams of water experts in cooperation with local community representatives take the responsibility to coordinate, control and manage water-related activities focused on disaster risk reduction.
- Community awareness and public information and active participation are essential in developing, protecting and safeguarding local water supply infrastructure that will function successfully in case of emergency.

The warning phase

The establishment and operation of water monitoring networks and early warning systems are the key activities in the warning phase. Both produce information that makes it possible to (1) identify, recognize and give advance warning of a possible disaster impact on water resources, (2) reinforce emergency decision making of governmental authorities and emergency and rescue teams and (3) endorse groundwater governance in emergencies. In particular, reliable monitoring data lead to a better understanding of the risk and impact of natural disasters on water supplies and populations. Data also assist in (1) conceptualising potential scenarios of disaster impacts on groundwater resources, (2) evaluating available emergency groundwater resources, and (3) building effective alarm systems and water protective measures against disasters. Measurements of groundwater level, temperature, electrical conductivity, pH and Cl are not technically and financially demanding; however, their regular monitoring significantly help in the studies of the effects of natural disasters on groundwater systems and in the establishment of effective groundwater governance in emergencies.

Social impacts and economic losses resulting from a scarcity of water data related to natural disasters have been pointed out at the 1992 Dublin Statement on Water and Sustainable Development (World Meteorological Organization 1992): "Development is being set back for years in some developing countries, because investments have not been made in basic data collection and disaster preparedness". Water data insufficiency and need of regular water monitoring have been stressed in UNESCO-WWAP reports, e.g. in report 2 (UNESCO-WWAP 2006): "Major investments are needed to reverse the decline of hydrologic information networks, including surface water and groundwater".

Data related to historical disasters have to be collected and evaluated in regions affected by recurrent natural disaster events. Historical data analysis helps to estimate the recurrence period and intensity of future disasters and their potential social, economic and environmental consequences. However, such data are not always available or data series are fragmented or even missing. Integrated hydro-climatologic regular monitoring systems and early warning in regions vulnerable to floods, storms and drought are not yet available in many countries (UNESCO-WWAP 2009). That, along with growing influence of climate variability and change introduces uncertainty into the forecasting of the impact of water-related disasters. With respect to geological disasters, early warning systems have been developed and are in operation in many regions prone to earthquakes, volcanic activities and landslides. Early warning systems exist or are being developed in tsunami-prone regions.

The following activities significantly support implementation of water-related disaster-warning provisions: (1) drilling of new monitoring wells located and screened with respect to the potential impact of specific disasters on the groundwater system, (2) standardized and regular groundwater measurements and sampling and laboratory procedures, (3) standardized process of data assessment, management and reporting on country or transboundary levels, and (4) availability of relevant professional staff and financial sources for operation of monitoring networks.

Data from groundwater-monitoring networks, particularly in highly vulnerable floodplain and coastal areas, arid and semi-arid regions and small islands, are essential for the study of the impact of climate variability and change on groundwater, and for evaluation and management of emergency groundwater resources. With regard to transboundary aquifers, there are often discrepancies arising from groundwater data sharing, inconsistency and poor compatibility between countries. International units (commissions) established by neighbouring countries could more actively cooperate (1) on the establishment and operation of transboundary monitoring and early warning programmes and (2) facilitate exchange and dissemination of groundwater data and information (UNESCO-IHP 2010).

Groundwater governance in the disaster-warning phase (1) strengthens decision making of the responsible governmental and community authorities related to disasters risk, (2) helps to coordinate activities of professionals, rescue and aid teams and local communities, and (3) assists in minimising the disaster risk to drinking-water services. Early warning data also help to reduce social and economic vulnerability of populations and give time for preparation of the effective warning provisions and evacuation plans for populations living in flood plains or other disaster-prone areas. All types of media and communication means should be used to rapidly disseminate disaster-warning information.

The impact and relief phase

An effective post-disaster response and emergency water governance in the impact and relief phases require (1) identification and evaluation of the impact and consequences of disasters on water supply sources and drinking-water distribution networks, (2) immediate water-supply-rehabilitation efforts during and after disastrous events, and (3) the organization of local and external assistance in supplying drinking water for the affected populations.

In floodplains and coastal areas affected by floods, tsunamis and storms, immediate assessment of the physical condition of water supply wells (well construction, pump function) and tests of basic drinking-water chemical and biological parameters, provide initial information about the water wells function and drinking-water quality. Dewatering, cleaning and disinfecting of the polluted wells, repeatedly if necessary, is often sufficient to renew their function (House and Reed 2004; WHO 2005; Vrba and Verhagen 2011). Well yield should be checked against pre-disaster values. Water use for hospital and health services in emergencies requires comprehensive quality testing (Tanaka 2011). Shallow aquifers are particularly vulnerable to flood events and cannot act as a safe source of drinking water in emergencies. For example, domestic water supply wells located in shallow aquifers in Pakistan were seriously physically damaged and polluted by pesticides released from storage, and by uncontrolled leakages from oil tanks and waste disposal sites during unprecedented flooding in the Indus basin in 2010 (GFDRR 2011). Intense and prolonged precipitation produced extreme floods in the year 2002 in the Czech Republic and in Central Europe; flooding made unusable many public and domestic water supplies located in shallow vulnerable aquifers in fluvial deposits of Labe (Elbe) River. Under post-disaster rescue provisions, hydrogeological investigation in the flood-prone area identified confined and productive deep aquifers resistant to the flooding; they were tapped by deep wells which have gradually replaced existing vulnerable water supplies (Silar 2003).

In coastal aquifers, pumping rates of emergency wells have to be carefully controlled to prevent upconing of the underlying brackish water and related groundwater quality degradation. A compensatory source of drinking water from emergency wells drilled in the preparatory or warning phase has to be secured within disaster relief and largely in the rehabilitation phase.

Drought differs from other emergencies (e.g. floods, storms) in the rate of their onset, duration and long-term effects (Verhagen 2011; UNESCO 1999). Drought affects particularly groundwater resources in shallow aquifers sensitive to recharge variation and with seasonal storage replenishment. Effective emergency water governance policy in the relief phase in drought-prone regions has to be based on data of groundwater recharge, groundwater level measurements, amount of groundwater abstraction and aquifer hydraulic characteristics and storage; however, such complex data are not always available.

Implementation of water-demand reduction measures, as immediate groundwater governance response to drought emergency and associated risk to community livelihoods, is considered the most effective action. Deepening of wells is another effective and immediate relief response if the wells are located in thick, productive and low-vulnerability aquifers (Verhagen 2011; Verhagen et al. 2007). The role of early warning and regular groundwater monitoring to observe contemporary groundwater status and related drought impact on groundwater system is stressed. Based on the assessment of hydrogeological conditions of drought-prone regions (Wenpeng at al. 2007), additional groundwater resources can be developed (e.g. groundwater from deep confined aquifers, non-renewable groundwater) or other safe emergency sources of drinking water have to be found near the affected area.

Earthquakes modify groundwater systems and regimes significantly. Basic data from a groundwater-monitoring network located in areas affected by earthquakes (groundwater level, temperature, pH and relevant chemical components) suggest possible precursors to earthquake events (Oki and Hiraga 1998; Chadha at al. 2006) and facilitate evaluation of earthquake impact on groundwater systems. A drastic decline or rise of the water table is frequently observed and groundwater level can react at very long distances (Fig. 5). Changes in groundwater chemistry and in the isotopic and dissolved gasses composition have also been recorded (e.g., Tokunaga 1999). Significant increases in the discharge of springs (temporal, or long term) are often registered as well as rise of new springs and disappearance of others (Yoshioka 2006).

Damaged shallower wells can be rapidly reconstructed and used for supplying drinking water. Deep wells, pumping facilities and water distribution pipelines are often seriously affected. Their reconstruction usually requires several days, weeks or even months. Hand pumps and diesel/petrol driven pumps have to be available in the earthquake relief phase as electricity supply is often disrupted. Compensatory emergency water sources can be secured by surface water particularly for firefighting purposes. In Japan, groundwater from deep wells with a membrane filtration system and proper power plant facility, introduced by a number of hospitals in earthquake-prone areas, serves as a significant emergency source of high quality water (Tanaka 2011).

Registered effects on water wells and water distribution networks in areas affected by landslides show that landslides are generally less destructive than earthquakes (Cruden 1991), e.g. in India (Berger and Olafsdottir 2005) and China (Vrba and Verhagen 2011). Water supply wells and pipelines are usually physically damaged. Their timely and technically demanding reconstruction or relocation away from the landslide area is mostly realized under the rehabilitation phase.

Volcanic eruptions and associated volcanic activities have significant influence on the people living in volcanic-prone areas as well as on their drinking-water sources. Volcanic eruptions often modify the shape and pattern of streams, affect runoff, increase the risk of flooding, impact groundwater levels, increase water turbidity, and affect landscape morphology and vegetation cover and thus groundwater recharge conditions. With regard to groundwater, volcanic activity affects the water table and chemical composition. Both may be influenced by a number of volcanic toxic gases and by upward flux of thermal water rich in dissolved solids. These render groundwater unsuited for drinking purposes. The role of regular groundwater monitoring is highlighted. The following groundwater indicators may signal potential eruption: sudden drop or rise of groundwater levels, change of spring temperature and flow rate, enrichment of groundwater in sulphate, chloride and fluoride concentration (Lee 1998; Kikawada et al. 2003; Armienta et al. 2003).

Drinking-water relief activities in volcanic areas are focused on (1) immediate physical reconstruction of damaged water supply wells, (2) reconnection of the roof-fed water-supply tanks for rainfall collection when volcanic activities

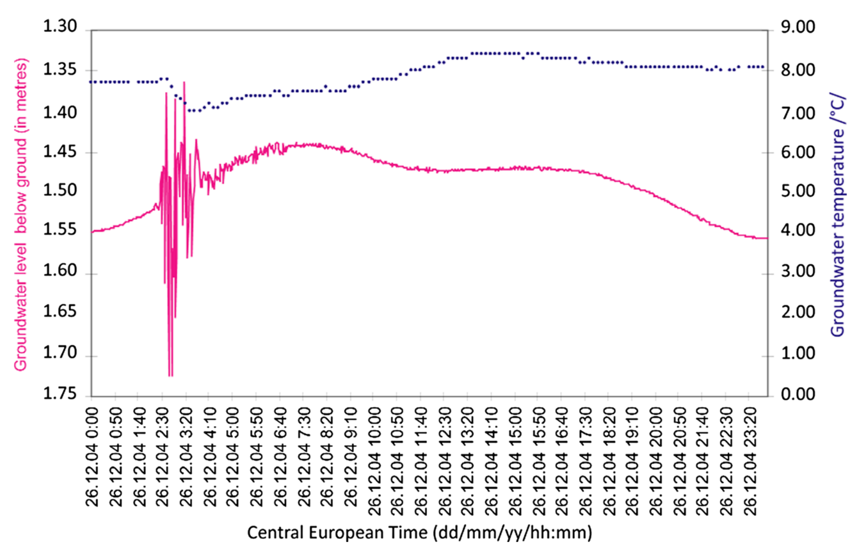

Fig. 5 The considerable and rapid reaction of the groundwater level in a deep monitoring well (Czech Republic) to the South-East Asia earthquake of 26 December 2004 (7.58 a.m. local time). The delay of 13 min for a distance of more than 10,000 km indicates the remarkable sensitivity of the groundwater system to earth seismic activities (Pospíšil 2005)

cease and (3) designation, installation and start-up of operation of pollution treatment facilities to restore groundwater to drinking quality.

Generally, three scenarios for the distribution of drinking water can be distinguished in the relief phase (Vrba and Verhagen 2011). Their efficiency depends on groundwater-related activities realized in the previous disaster phases:

1. In disaster-prone areas where safe emergency groundwater resources have already been identified, investigated and developed, the distribution of drinking water from emergency wells during disaster relief and rehabilitation phases will be rapid and effective. However, up until now, such an approach has been implemented in only a few countries, e.g. in India (Sukhija and Narsimha 2011) and Japan (Tanaka 2011).
2. Following the disaster, new water supply wells can be rapidly drilled already within the relief phase where aquifers resistant to natural disasters have been investigated and evaluated, but not yet developed. Implementation of such a scenario requires the availability of drilling and pumping facilities, relevant professional staff and the financial means.
3. In the absence of such hydrogeological knowledge, relief responses with regard to emergency drinking-water services will be severely delayed, exacerbating the impact on the social and health conditions of the population. Bottled water then has to be imported or water transported by tankers from distant unaffected drinking-water sources. These temporary measures are expensive and technically, logistically and financial demanding and cannot be sustained long term.

The availability of disaster-risk-remediation and drinking-water-risk-management plans, coordination of activities of governmental authorities and rescue teams, and active participation of local communities, play a decisive role in effective emergency water governance policy in the disaster relief phase. The role of relief teams is particularly important in (1) checking the physical state and quality of groundwater from public regular and emergency wells, (2) establishing a priority group of domestic water supply wells easiest to clean, restore and use, and (3) recommending suitable treatment techniques for remediation of polluted drinking water. However, it must be noted that every natural disaster produces a unique emergency situation in terms of drinking-water supply security and services, for which the solution requires a specific approach and level of skill.

The response of affected local communities to disaster impact, and their ability to empower themselves and implement interventions in the process of self-recovery, are based on local experience and traditions (Vrba and Verhagen 2011). Both support rapid implementation of relief measures to restore people's social conditions and livelihoods and drinking-water supply services (Blaikie at al. 1994).

The rehabilitation phase

The following priority items realized under groundwater governance in emergencies in the rehabilitation phase are pointed out: (1) assessment of the effect of disaster remediation activities implemented in the relief phase, (2) rehabilitation and/or reconstruction of damaged and/or polluted drinking-water facilities, monitoring networks and early warning systems, and (3) formulation and implementation of other relevant proposals aimed at reducing impact of actual disaster on drinking-water facilities and services.

The above listed drinking-water-related activities are realized in two phases: *short-term post-disaster activities* implemented within days or weeks and already initiated within the relief phase, and *long-term post-disaster activities* which are technically and financially demanding and depend on the extent of the impact of disasters. Where groundwater drinking-water supplies are polluted by chemicals, remediation can range from months or even years.

Based on assessment of disaster impact on drinking-water supplies and the need to renew population access to drinking water, the following post-disaster rehabilitation activities are highlighted.

- Reconstruction of damaged water supply and sanitary facilities and remediation of polluted drinking water
- Development of new emergency wells tapped groundwater resources resistant to disaster impacts and their connection with existing drinking-water infrastructure
- Strengthening of emergency water governance based on updating (1) disaster risk and mitigation policy, (2) drinking water demand management in emergencies, (3) legal framework related to drinking-water rights in emergencies, and (4) drinking-water distribution plans in emergencies
- Re-evaluation of land use plans and updating of inundation, risk and groundwater vulnerability maps in disaster-prone areas (Vrba and Richts 2015)
- Re-evaluation of the activities of technical and aid teams responsible for drinking-water supply in emergencies and possible improvements in the composition of teams
- Enhancement of the adaptive capacity of local communities in emergencies; propose improvements in the management and protection of drinking-water sources considering the population's historical experience and knowledge
- Development of disaster-risk-based groundwater indicators and a groundwater vulnerability assessment scheme relevant to different types of disasters

Comprehensive cooperation between policy and decision makers, rescue teams, water managers, groundwater experts, technical staff, and public is needed in designation of (1) areas with priority exigency on emergency services of drinking water and (2) methods of rehabilitation of damaged water supplies. The rapid solution is to start with pumping of existing emergency wells tapping water from deep aquifers resistant to disaster impact. Another possibility is to develop groundwater from low-vulnerability aquifers in areas where their occurrence, properties and productivity have been already investigated and tested. For example, the super cyclone which devastated the coast of Orissa State, India, in the year 1999, damaged and highly impacted by salinization almost all shallow domestic wells, and rendered them unusable for drinking purposes (Chandra et al, Central Groundwater Board (India), unpublished report, 2002, entitled "Surface and borehole geophysical investigations for fresh water aquifers of coastal Orissa"; Choudhury at al. 2009; Sukhija and Narsimha 2011). Based on existing hydrogeological data, additional hydrochemical and geophysical investigation and isotope studies, governmental authorities undertook an immediate rehabilitation initiative in drilling a number of wells, 150–300 m depth, tapping groundwater from confined aquifers resistant to flood and storm impact. The drinking-water supply was restored within 4 months, supplying 100 L of water per capita/day to approximately one million people living in the affected area.

Drinking-water distribution by tankers should be also organized and coordinated, taking account of limited tanker capacity and the turnaround time of a tanker that may run into hours (House and Reed 2004). This intervention and the import of large quantities of bottled water can only be a temporary solution.

Implementation of equitable emergency groundwater governance in the disaster rehabilitation phase helps to (1) reduce water deprivation in the post-disaster period, (2) secure emergency drinking-water sources resistant to disasters, and (3) mitigate the risk and impact of potential future disasters on diverse water-supply facilities and populations.

Concluding remarks

The growing trend in the occurrence and increasing frequency of natural disaster events influences water resources in terms of both their quality and quantity. In a single year, millions of people around the world are affected and thousands lose their lives in such events (UNISDR 2005; Huq at al. 2004; Merabtene and Yoshitani 2005; GFDRR 2011; World Humanity Action 2000); their drinking-water supplies are also physically damaged and /or polluted.

When rescue operations secure an affected population, the most pressing priority is renewal of drinking-water services. Developing such a policy is inevitable in areas affected by recurrent cataclysmic hydrological (floods, storms, droughts) or geological (earthquakes, volcanic activities) events or by the effect of both (tsunamis, landslides, mud-flows). In such areas, timely investigation, assessment and development of groundwater resources resistant to disasters is of critical importance to secure drinking-water services in the post-disaster period. Groundwater that has been proven safe to natural disasters could replace, either temporarily or in the longer term, ordinary water supplies affected by disasters.

The following topics are proposed to strengthen efficiency of groundwater governance in emergencies, to decrease population exposure and vulnerability to drinking-water scarcity and to manage drinking-water services in emergencies in an integrated and equitable manner:

- Comprehensive and coherent action and accountability of governmental authorities at all levels to respond properly and to cope effectively with disaster impact on water supply facilities
- Clearly defined water rights in emergencies
- Integration of rescue teams into (1) restoration of damaged or polluted water supply facilities and (2) renewal of drinking-water services for affected populations
- Establishing the risk and demanding management of groundwater resources in disaster-prone areas, coordination and balancing of competing water demands in emergencies involving diverse sectors and water stakeholders
- Robust monitoring of groundwater and dependent ecosystems, and early warning systems oriented towards specific types of disasters
- Development of the technical and scientific capabilities to enhance effectiveness of groundwater governance in emergencies
- Delegating responsibility to and strengthening the position of local communities to self-manage water supply facilities during and after disasters
- Support for active participation of NGOs

Special attention in development of groundwater governance in emergencies should be given to developing countries. They often face insufficient knowledge of hydrogeological conditions and scarcity of reliable and consistent groundwater data sets in disaster-prone regions. Governmental water structures are often poorly developed and experienced professional human resources and advanced water technologies are scarce. International cooperation, solidarity and support of professional and voluntary organizations and individuals in developing countries should particularly focus on:

- Building groundwater governance structures in emergencies (institutional authorities, legal framework, rescue teams, professional and technical capacities)

- Education and training of water technicians and professionals focused on drinking-water management and services in emergencies
- Support and assistance from the international community with regard to expertise, partnerships and knowledge dissemination
- Community information, education and ability to cope effectively with the impact of disasters on drinking-water sources
- Raising investment means (national and international) and financial funding for (1) implementation of protective and mitigation measures against disaster risk and impact on drinking-water facilities, (2) identification, investigation and development of emergency groundwater resources and related water-supply services resistant to disaster impacts and (3) establishment and operation of groundwater-monitoring networks and early warning systems in disaster-prone areas.

Formulation of principles of groundwater governance in emergencies and their implementation in all phases of disaster events in countries regularly affected by disasters should be considered as crucial instruments which help to (1) manage effectively the risk and impact of disaster events on drinking-water services, (2) secure access of affected populations living in disaster-prone areas to safe drinking-water supplies and (3) support populations social, economic and environmental needs in emergencies.

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