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Management Tools for Sustainable Ground Water Protection in Mega Urban Areas – Small Scale Land use and Ground Water Vulnerability Analyses in Guangzhou, China

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ABSTRACT: In developing and newly industrialized countries, population growth and migration contribute immensely to the development of megacities and mega urban areas. In most cases, the rapid development of cities has far-reaching consequences for the ecosystem in general and the hydrological cycle in particular. The developments in China within the last decades show an interesting, but complex setting. Massive and rapidly occurring land use changes in the economically booming South-Chinese Pearl River Delta result in rising hazards and risks for the urban water resources and often in a severe deterioration of water quality. The quantity and quality of local groundwater sources is, however, much less investigated than the situation of the surface waters. In order to supporting a better protection of the urban groundwater resources, the aims of this article are to analyze the vulnerability of the groundwater and the potential hazards and risks for groundwater resulting from land use changes – taking Guangzhou as a case study area.

Key words: Land use, Urban units, Groundwater vulnerability, Risk mapping, Megacity, Guangzhou, China

INTRODUCTION

In the ongoing discourse of global, climatic and environmental change – today's vast fields of research – environmental degradation as well as environmental behaviour and awareness should play a central role. The most serious environmental problems include air , land- and water pollution. Next to solid waste management, water quality and quantity issues dominate the environmental issues debate. Research that deals with the interactions between urban structures and environmental conditions increasingly focuses on these processes in cities being located in transformational and developing countries. The ongoing rapid and dynamic urbanization in China shows an interesting, but complex setting in which hazards and risks arise for water resources in general and groundwater resources in particular.

In developing and newly industrialized countries, population growth and migration contribute immensely to the development of megacities and mega urban areas. Megacities are quantitatively defined as cities having a population of more than five (Bronger, 1996), eight (UN, 1987; Fuchs, 1994; Chen and Heligman, 1994) or ten million people (Mertins, 1992). However, the criterion 'population size' is only one of many factors which represent major challenges for the water management in a megacity. The city's settlement rate, infrastructural requirements and land use are some of the other important factors. With this in mind attention should be given to the ever increasing number of factors and complexity, which is revealed by coordination and steering problems (Heinrichs, 2009). Megacities growing at the rate of, for instance Berlin with a population of 3.5 million every few years have to face big challenges in terms of water supply, sanitation and water quality (Baier and Strohschön, 2012). A loss of ability to govern also coincides with a growing informality (Kraas, 2009). Furthermore, the divide between the poor and the wealthy population is widening. This is accompanied by the manifestation and intensification of inequalities as well as fragmentation of infrastructure and environments throughout the cityscapes (Coy and Kraas, 2003; Tibaijuka, 2006). Water quality is increasingly under threat, because of surface water and groundwater

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pollution, due to seepage and leakages from the sewerage systems as well as from the discharge of untreated water from non-existent or malfunctioning treatment facilities (e.g. Foster *et al.*, 1993; Morris et al., 1994; Azzam et al., 2009; Strohschön et al., 2013). The effects can already be seen as they are affecting the health of the people living in the cities (Vira and Vira, 2004; Maiti and Agrawal, 2005; Aggarwal and Butsch, 2012). The exceptional growth rates, a development which favours larger cities lacking institutional capability, the relationship between the increasing numbers of inhabitants and the condition of the environment with all its (health) implications could not be a more pressing topic.

Since 1978, Chinese megacities as well as smaller urban centers have been subjected to far-reaching changes due to the politico-economic reforms and the accompanying economic growth. The urbanization level of the country rose continuously between 1978 and 1999 with an annual increase of about 0.61 %: from 17.92 % to 30.89 % and by 2008 to 45.68 % (Liu *et al.*, 2003; People's Daily Online, 2009). In this context, the South-Chinese Zhujiang Delta, commonly called Pearl River Delta, became one of the most dynamic regions of China and one of the most densely populated areas on earth. In a few years, former small cities like Guangzhou, Dongguan and Shenzhen became internationally integrated industrial markets and megacities with more than five million inhabitants (Wehrhahn *et al.*, 2008). The consequences of this development were massive changes in land use on the one hand, and severe deterioration of water quality. The situation of the Delta's main rivers is already quite well examined: He (2005) and Ouyang *et al.* (2005), for instance, studied the deterioration of surface waters due to agricultural run-off; Ouyang *et al.* (2006) and Song *et al.* (2011) examined its degradation resulting from untreated industrial discharges; Gan (2008) analyzed the concentration of heavy metals in surface waters and explained their measuring values by the increasing traffic in frame of the urbanization and industrialization processes. In contrast, the quantity and quality of the Delta's groundwater sources is much less investigated until now (see e.g. Mu *et al.*, 2005; Chen *et al*,. 2006; Liu *et al.*, 2011; Baier and Strohschön, 2012).

Mostly, land use changes first took place in already existing core areas of megacities. There, they can be seen as clearly visible signs of urban change and urban renewal, such as the rising of modern business quarters or apartment tower complexes. With time, land use changes started along the bordering areas of the megacities. Currently, these are the most important zones of urban land use change within the framework of progressive urbanization, since potential building and development areas often still exist there (Strohschön *et al.*, 2009). In most cases, these massive and rapidly occurring land use changes have drastic affects on the ecosystem in general and the hydrological cycle in particular (Azzam *et al.*, 2008). It is therefore all the more important to develop and apply adequate protection strategies against (ground) water contamination. That is especially true for morphological complex mega urban areas where the remediation of aquifers is very time-intensive and its success often uncertain (Rukumbuja and Mato 2002). Therefore the set up of sustainable prevention measures of groundwater contamination in mega urban areas can be seen to be more appropriate and logical. For this, groundwater vulnerability and risk mapping methods are well suited management tools providing valuable information for the planning of prevention of (further) quality deterioration (Umer *et al.*, 2009). Because of the high rate of change of reactions between groundwater and surface water sources and sewage water in urban systems – particularly in areas with large river systems – the knowledge of the sensitivity of the groundwater to contamination is indispensable for a sustainable resource protection (Baier *et al.*, 2011). In this context, the aims of this article are to analyze the vulnerability of the groundwater in general and to analyze potential hazards and risks for groundwater resulting from land use changes in particular. With respect to the reliance of relevant research referring to the South China region and its water quality, this article contributes to groundwater research in Guangzhou.

Due to the economic transformation in China and the associated involvement in various globalization processes, some Chinese cities have undergone radical changes. In the last few years they have developed with the highest dynamic and the highest growth rate worldwide. The growth of industry, economic power and inhabitants in the Pearl River Delta (PRD) has led to extreme changes in land use and urban morphology (Wu *et al.*, 2007; Wehrhahn *et al.*, 2008). Some of the (industrial) megacities located in the PRD emerged from rural structures in just ten years. Within the net of Chinese megacities and special economic zones, the PRD with the megacity Guangzhou and the special economic zone Shenzhen plays a decisive role.

Guangzhou, the area being researched, lies about 120 km North West of Hong Kong in the center of the PRD. At present, it has a total area of 7 434 km² and a population of some 15 million inhabitants (Huang and Keyton, 2010, note that this population estimate does not distinguish between registered and unregistered residents). Due to the geographical location and the proximity to the South China Sea, Guangzhou has a sub-tropical Monsoon climate. The topography of the central parts of the city is distinguished by the Baiyun Mountains (Baiyunshan) in the north and the Pearl River and its tributaries flowing through the central city area. The Pearl River itself is divided into a northern and a southern tributary and divides the still sparsely populated southern/ south western districts of Guangzhou from the central and northern, densely populated districts. The relief falls from the north-west (highest elevation 382 m NN) towards south-east in the flood plain of the Pearl River at sea level. The central districts are flat with elevations of 0.3-1.3 m NN (He, 2005), with some exceptions of hilly areas (39.1-61.3 m NN).

Remote sensing investigations of the research area show that the surface covered by high-density urban areas has increased by about 368.52 km² in the period from 1990-2005 (Lu *et al.*, 2009). This increase has a close relation with the economic development and the growing number of migrant workers due to the need of additional living space. With the acceleration of economic development large areas of arable land and low-density urban area were converted into high-density areas. The rate of change of low-density urban area differs considerably during the periods of 1990-2000 and 2000-2005. For example, in the period 1990-2000 the area covered by low-density urban regions decreased by 286.13 km². This development is driven by population growth and economic development, which are associated processes of urbanization. From 2000 to 2005 low-density urban areas increased by further growth of population and economy. In this period large agricultural area and other land use types were converted to this type of land use (Lu *et al.*, 2011). The increasing population pressure and the accompanying uncontrolled urbanization led and still lead to extreme land use changes and serious environmental problems. These processes are therefore difficult challenges for Guangzhou's water management. Measures for groundwater management exist; however they seem to be rudimentary and are poorly known at the international level. This is a particular crucial point since the quality of protection systems for the natural framework conditions are low. But, it also needs to be taken into consideration that for some municipal wastewater parameters the framework conditions are quite good (cf. Baier *et al.*, 2011; Baier and Strohschön, 2012).

MATERIAL & METHODS

In regard to Guangzhou's high mega urban dynamic, disciplinary methodologies are not sufficient for supporting a sustainable protection of the cities' groundwater resources. Because of this urban planning must interact with approaches form hydrogeology. But also common urban planning tools are not useful to completely describe the dynamic development. Against this background and in frame of the German Research Foundation's priority program 'Megacities: Informal dynamics of global change', a tool was developed by an interdisciplinary working group[1], that describes and helps to understand mega urban land use structures and changes at a small scale basis (cf. Wehrhahn *et al.*, 2008; Strohschön *et al.*, 2009; Wiethoff *et al.*, 2011; Strohschön *et al.*, 2013). Moreover, these so called 'urban units' seem to be suitable to describe the potential hazards for groundwater resources resulting from different land use forms and to evaluate the risk of each land use form on water quality. In combination with hydrogeological vulnerability analyses as well as hazard and risk mapping it provides a new observation and planning approach for protecting groundwater resources in high dynamic megacities. The interdisciplinary working group with staff of the Department of Engineering Geology and Hydrogeology and the Institute of Landscape Architecture, both RWTH Aachen University, as well as of the Chair of Human Geography, Kiel University (all Germany) was set up in frame of the project „Analysis of informal dynamics in mega urban areas – based on spatial structures and steering mechanisms focused on water in the Pearl River Delta", which belongs to the above mentioned priority program.

In the context of the analysis of mega urban agglomerations and their specific dynamics, different levels of consideration constitute a high challenge in complex aggregations of mega-urban centers. The investigation of the whole area or large administrative units does not provide the necessary differentiation, while the complexity on the smallest level – for example single buildings, is not manageable anymore. For understanding the complex system of mega-urban centers it is therefore necessary to classify the large agglomeration areas into smaller units (Wehrhahn *et al.*, 2008). For that reason repetitive urban micro structures, such as single types of buildings and their contiguous surface broaching, are merged into clusters with respectively uniform and homogenous characteristics (Strohschön *et al.*, 2009). With such urban units it becomes possible to reduce the complex and confusing system of a megacity to its important and significant major constituents that allow investigating the development. The different types of urban units have characteristic features like ecological, economic and social specific values but also physical features like population density or economic power.

Respective changes in the extent or transformations of such urban units act as indicators for the overall system of a megacity. For its definition and classification structures are offered, which originate from traditional and current settlement development and which are based on growing sub units below the level of the settlement complex as a whole (cf. Wiethoff and Strohschön, 2009). In Guangzhou it is possible to easily identify such urban units by means of closed settlement structures due to social patterns and political planning. Thus, different types of urban units with their characteristics and dynamics can be described as basis structure of the system of megacity Guangzhou as a whole. A more detailed description of one of the reference areas, the urban unit Xincun, is given in Wehrhahn *et al.* (2008). Additional information related, for example, to the indicators analyzed on this small-scale basis can be found in Strohschön *et al.* (2013).

Intrinsic groundwater vulnerability

The intrinsic groundwater vulnerability for Guangzhou was assessed by the Hölting method – a classic system rating method (Hölting *et al.*, 1995). The method provides a separate assessment of attenuation processes for the soil and the subsoil layers. For the first meter of topsoil the protection value is calculated by:

$$S_1 = B \cdot W$$

Where S_1 = protection value of the topsoil layer, B = rating value for the effective field capacity, W = rating value for amount of percolation water by means of groundwater recharge rate.

Further every individual layer underneath the topsoil is evaluated separately. For unconsolidated rocks the protection potential is assessed by the cation exchange capacity. For the consolidated hard rocks it is assessed by the rock type and its texture (degree of karst and fracturing). These assessments lead to a rating value for each individual layer (G) that is multiplied with the layer's thickness (M) and the percolation rate (W). Where applicable, an extra value for perched groundwater or artesian aquifers is added. The protection value for the subsoil layers is expressed by:

$$S_2 = (G_1 \cdot M_1 + G_2 \cdot M_2 + \cdots + G_n \cdot M_n) \cdot W + Q + D$$

Where S_2 = protection value of the subsoil layer, G_{1-n} = rating values for the rock layers 1-n, M_{1-n} = thicknesses of groundwater overburden layers 1-n, W = rating value for the amount of percolation water, Q = additional value if perched groundwater is present, D = additional value if artesian aquifers are present.

The protection value for the entire groundwater cover (S_g) is the sum of S_1 and S_2 at every point in the study area. The values can be divided into five classes (very low to very high protection potential). For a detailed description of the method see Hölting *et al.* (1995) and for the intrinsic groundwater vulnerability assessment in Guangzhou see Baier *et al.* (2011).

To assess the risk of groundwater in a specific area, knowledge is important on two counts: about the grade of groundwater vulnerability and about the hazard resulting from different land uses. Thus, vulnerability maps and hazard maps are merged.

A hazard map comprises of potential contamination sources that result from urban land use and the appertaining human activities (Zwahlen, 2003). Four steps are necessary for a hazard assessment. First, the weighting of hazards, that allows to compare all different type of hazards (weighting value H). Second, set up of a ranking, that evaluates hazards according to the quantity of harmful substances released by each individual hazard (ranking factor Q_n). Third, determining the likelihood that a contaminant release takes place with regard to a hazard (reduction factor R_f). Fourth, calculating an index (HI), considering these three factors, which evaluates the potential degree of the hazards' harmfulness (Zwahlen, 2003). The hazard index is calculated as $HI = H \cdot Q_n \cdot R_f$. While the weighting value H is determined carefully by Zwahlen (2003) for several hazards, the ranking and the reduction factor is to be determined for each individual hazard in a specific study area. The hazard index provides the basis for the further risk assessment. The latter considers all possible impairing factors with regard to the hazard and the pathway to the target, which is the percolation way from the ground surface to the groundwater table. Having evaluated the groundwater vulnerability and the hazards, the risk can be assessed with a simple equation:

$$RII = 1/HI \cdot \pi$$

Where: RII = risk intensity index; HI = Hazard Index; π = PI-factor (index for intrinsic or specific vulnerability); π ranges from 1 (very high vulnerability) to 5 (very low vulnerability).

For a more detailed description of hazard and risk assessment see Zwahlen (2003). A combination of the three methods will promise detailed conclusions of the impact and risk of mega urban land use on groundwater resources and provides a powerful

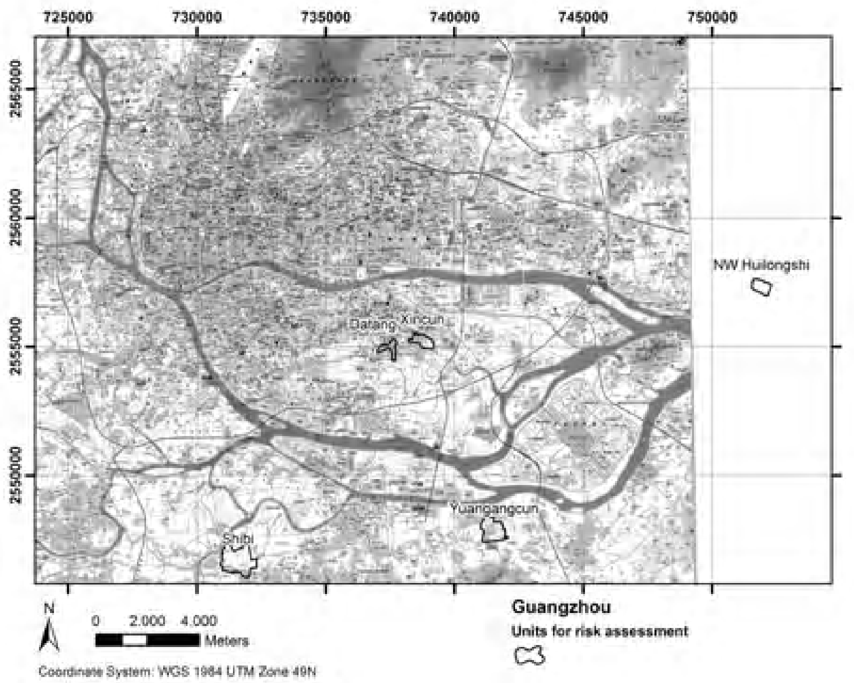

Fig. 1. Overview of the research areas

planning tool for sustainable protection of urban groundwater resources.

RESULTS & DISCUSSION

To work out the small spatial land use analyses, the following five study areas are investigated in detail: Xincun, Datangcun (in the following: Datang), Shibi, Yuangangcun and Huilongshi (see Fig. 1 for an overview of research areas). These urban units are also taken into account for the hazard and risk assessment.

•Xincun

Xincun is an urban village with settlement origins of about 2 100 years. It belongs to the centrally located Haizhu District, is close to the site of "Haizhu Artificial Lake" and situated at the core of the southern part of the new city axis. Hence, it is one of the targets of the real estate market looking for new areas suitable for the construction of housing and commercial infrastructure (Wehrhahn *et al.*, 2008). Xincun has undergone multiple transformation phases since 1990 and developed from an original village to an area, which is affected more and more by the current, internal and external, urbanization processes. For example, a creek and several fish ponds were filled up for becoming settlement area in recent years (cf. Strohschön *et al.*, 2013).

The population density is very high and the housing structure is confined and old. It seems that every household is connected to the public water supply and to the sanitation network. The latter consists of above-ground open drain pipes or underground sewer ditches. The predominant land use types are housing and, at the time of the early field investigation, fallow land (which has, until now, also been transformed into settlement area). A small contiguous sub-area can be considered as a recreational area (see Fig. 4).

•Datang

The urban village Datang lies about one kilometer west of Xincun. Its demographic composition, water supply and sewage disposal structures are similar to that of Xincun. The residential areas are supplied with drinking water pipes or, in some cases, with wells. In the main investigation period from 2007 to 2011, more and more open drain pipes were covered in order to ameliorate the areas. The Datong Chong is a river which crosses Datang with a flow direction from south to north. Its riverbanks undergo a process of modernization. Within the urban village and on its Western and Southern borders, numerous textile-processing businesses are located.

The inhabitants of Datang and Xincun are mainly members of the working class. Similar to Xincun, the main land use type is low to middle standard housing. Further land use types are commercial areas and fallow land (Fig. 5).

•Shibi

The village is located approximately 17 km south of the Guangzhou's city center in Panyu District. In 2008, it was inhabited by about 10,000 permanent residents and about 10,000 migrants from other Chinese provinces, working mainly in the secondary sector (esp. in garment manufacture). Shibi, especially the part of the village analyzed, is characterized by a comparatively rural way of life, an open structure and one to two storey houses with saddle roofs, arranged mainly in courtyard structure and adjacent to agricultural areas. The development of this village suggests that over time Shibi will change to an urbanized village with predominantly large-scale urban land use structures (Strohschön *et al.*, 2013). Transformation started, when several factories were established near the village by investors from Hong Kong amongst others, resulting from the new national economic development policies, industrialization and urbanization. As a consequence, rural workers from other provinces moved to Shibi searching for a job in one of the rising factories. Due to the increasing number of inhabitants, there is a growing demand for living space and changing demands concerning the functionality of the existent space, both resulting in various interacting processes.The construction of Guangzhou South Railway Station in Shibi, which has started in 2004 and which was opened in 2010, is one project of local, regional and even national importance (cf. Strohschön *et al.*, 2013). Related to the water resources, Shibi shows several signs of ecological vulnerability in the area of water quantity as well as water quality: i.e. deficient access to safe drinking water and sanitation, poor drainage with open sewers as well as unsecured dumps adjacent to agricultural land and fish ponds (Strohschön *et al.*, 2013). As shown in Fig. 6 the most important land use form in Shibi is agriculture. Further land use forms are commercial and industrial areas, fallow land and green spaces as well as residential areas. It can be expected that more land will be transformed because of the railway station mentioned above.

•Yuangangcun

In 1992 this former traditional 800 year old village located in Panyu District became part of Nansha Development Zone. This led to large-scale land use changes from agricultural to residential, industrial and trade areas such as for sewing, collecting points of plastic, harbor engineering and packaging. Direct domestic and industrial discharges are causing serious water quality deterioration. The residential buildings are kept rather simple. Some of the older ones are replaced by modern residential buildings. The inhabitants belong to the lower and middle classes population. Besides the large open spaces and agricultural areas, there are industrial areas in the West and in the South. The center of the village mainly consists of housing areas. In the West, Yuangangcun borders on a tributary of the Zhujiang (Pearl River). This small river drains fish ponds which are located in the South-West. Though the village seems to be fully connected to the water supply network some of the inhabitants are still using groundwater from private wells for their daily diet (cf. Strohschön *et al.*, 2013). Main land use forms of Yuangangcun are residential area, commercial and industrial areas as well as fallow land. Smaller areas can be found as agriculture; green space and surface water (Fig. 7).

•Huilongshi

Huilongshi village is situated in Guangzhou's eastern district Huangpu. In the course of urbanization, the village developed two areas with different structures: 1) newer buildings with the typical regular planning structure and small trade businesses at the areas' fringe and 2) heterogeneously grown old residential buildings with various informal building extensions, little distances between the houses, criss-crossing alleys as well as a mixture of open waste water gutters and canalized areas. In general, most of the villages' buildings seem to be at least partly being connected to the public water supply and sewerage network – though the untreated discharge of domestic effluent is clearly visible at many places. Stagnant and flowing surface waters are strongly polluted. The open spaces of the village are characterized by unused land. As shown in Fig. 8 the main land use form is residential area. Smaller spaces belong to commercial and industrial areas, green space, fallow land as well as road and traffic area. An enterprise producing body care products is located at the north-western fringe of the village directly adjacent to the Heng River (Heng Chong).

The *intrinsic groundwater vulnerability* of Guangzhou was assessed by using the method developed by Hölting *et al.* (1995). It shows a very high to high vulnerability in the largest part of the study area (Fig. 2). Only in areas with a high topographic elevation, the grade of vulnerability is low because there the groundwater table is lying deep to the surface. Where vulnerability is very high, the depth to the groundwater table is very low. In most parts there are no rocks overlying the groundwater because the groundwater table is within the soil in a depth < 1 m underneath the ground surface. The effective field capacity of the soil in general is favorable for the groundwater protection, but the high amount of

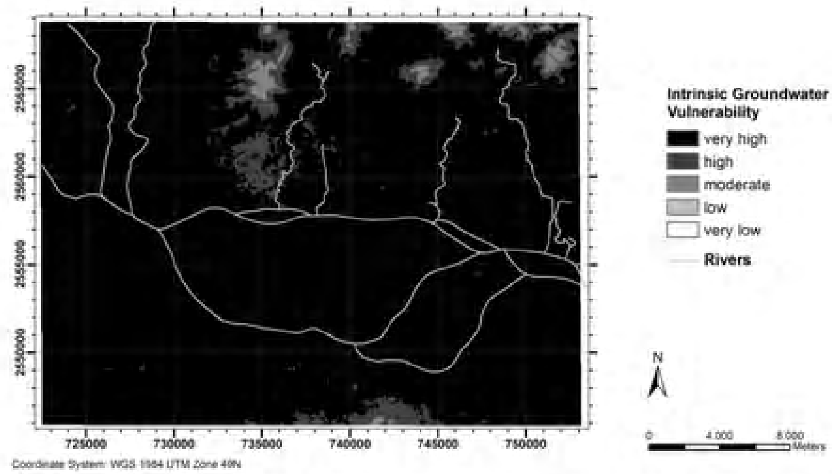

Fig. 2. Intrinsic groundwater vulnerability of Guangzhou (Baier *et al.* 2011: 89)

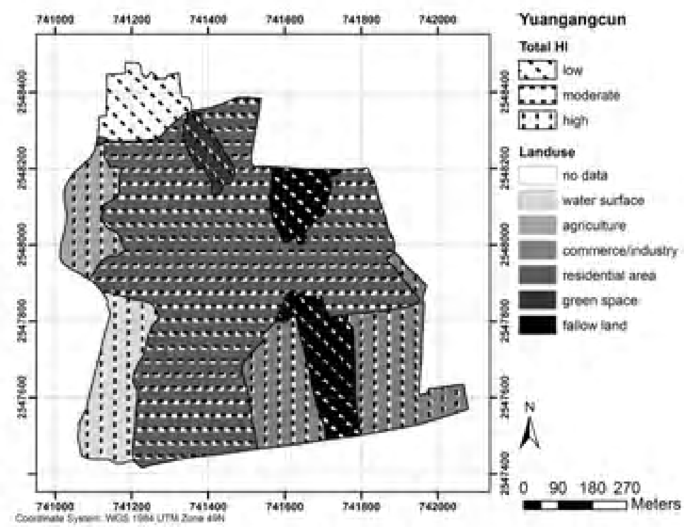

Fig. 3. Total hazard map of Yuangangcun

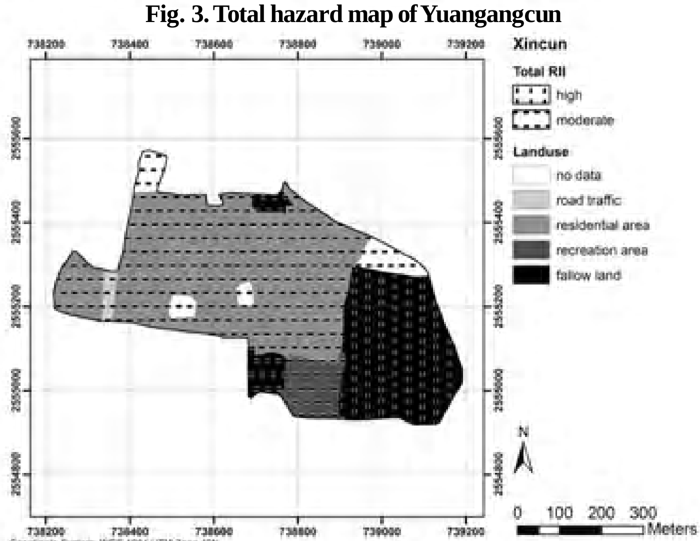

Fig. 4. Land use and risk map of Xincun

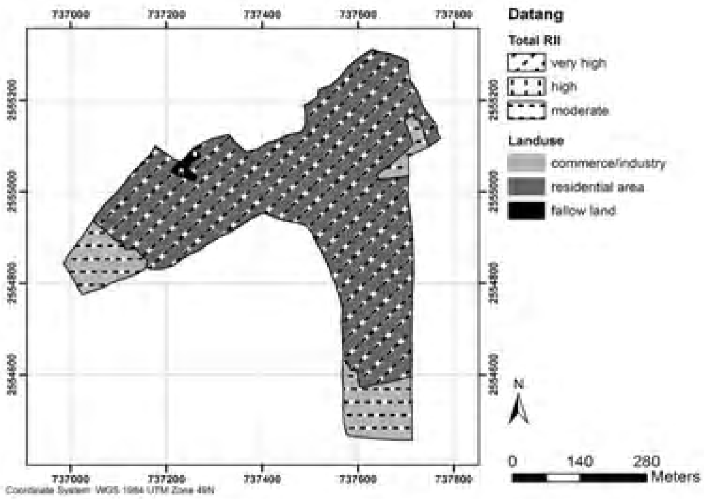

Fig. 5. Land use and risk map of Datang

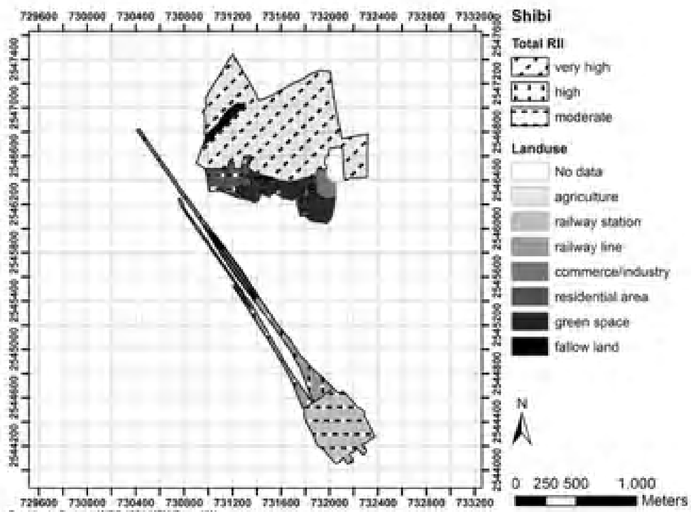

Fig. 6. Land use and risk map of Shibi

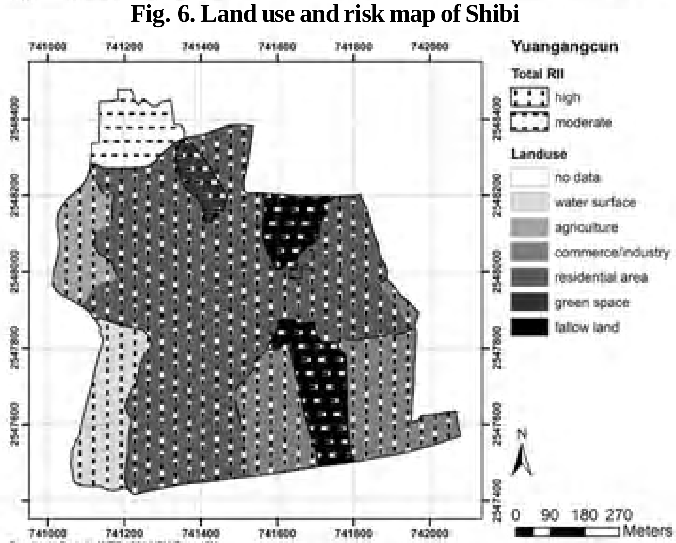

Fig. 7. Land use and risk map of Yuangangcun

Table 1. Individual weighting of the hazards according to the land use

Hazard No	Hazard	Units	Land use	Weighting value H	Ranking Value Q n	Reduction	Rr (√Reduction)	Hazard Index
1.1.1	Urbanization (leaking sewer pipes and sewer systems)	Xincun, Yuangangcun, Huilongshi, Datang	all	35	1	1	1,0	35,00
		Shibi	residential area, commerce/industry, station		0,8	0,8	0,894	25,04
1.1.2	urbanization without sewer systems	Shibi	agriculture	70	0,8	1	1,0	56,00
1.1.9	Waste water discharge into surface water courses	Datang, Yuangangcun, Shibi	residential area, recreation area, commerce/industry	45	0,8	0,8	0,894	32,20
		Huilongshi			1,2	1	1,0	54,00
1.2.1	Garbage dump, rubbish bin, litter bin	Shibi	agriculture	40	1	1	1,0	40,00
		Datang	fallow land + residential area					
1.2.4	Spoils and building rubble depository	Xincun	fallow land	35	1,2	0,9	0,949	39,84
1.4.4	Car parking area	Shibi	bus station	35	1	0,7	0,837	29,28
1.4.5	Railway line	Shibi	railway transportation	30	1,2	1	1,0	36,00
1.4.7	Railway station	Shibi	Railway station	35	1,2	0,7	0,837	35,14
2.2.1	Excavation and embankment for development	Shibi	fallow land	10	1	1	1,0	10,00
2.4.6	Chemical factory	Huilongshi	commerce/industry	65	1	1	1,0	65,00
2.4.8	Paper and pulp manufacture	Yuangangcun	commerce/industry	40	1	1	1,0	40,00
3.1.1	Animal barn	Shibi	agriculture	30	1	1	1,0	30,00
3.2.6	Greenhouse	Shibi	agriculture	20	1	1	1,0	20,00
3.2.7	Waste water irrigation	Shibi, Yuangangcun	agriculture + water surface	60	0,8	1	1,0	48,00

Table 2. Concentration of total coliform bacteria in the groundwater of Guangzhou

Urban Unit	Date of sampling	Coliform bacteria [MPN/ 100ml]
Xincun	2007-11-05	$3,3*10^4$
		$1,7*10^4$
		$3,3*10^4$
	2010-05-20	$5,0*10^3$
		$1,3*10^4$
		$3,3*10^5$
Datang	2007-11-05	$4,9*10^2$
		$4,9*10^3$
	2010-05-20	$2,3*10^4$
		$3,3*10^4$
		$8,0*10^4$
Shibi	2007-11-06	$3,3*10^2$
		$4,9*10^3$
		$4,9*10^4$
	2010-05-19	$1,3*10^3$
		$4,6*10^2$
		$1,3*10^4$
Yuangangcun	2008-09-27	$9,2*10^5$
		$3,5*10^5$
		$7,0*10^4$
	2010-05-19	$3,3*10^3$
		$1,3*10^4$
		$1,3*10^4$

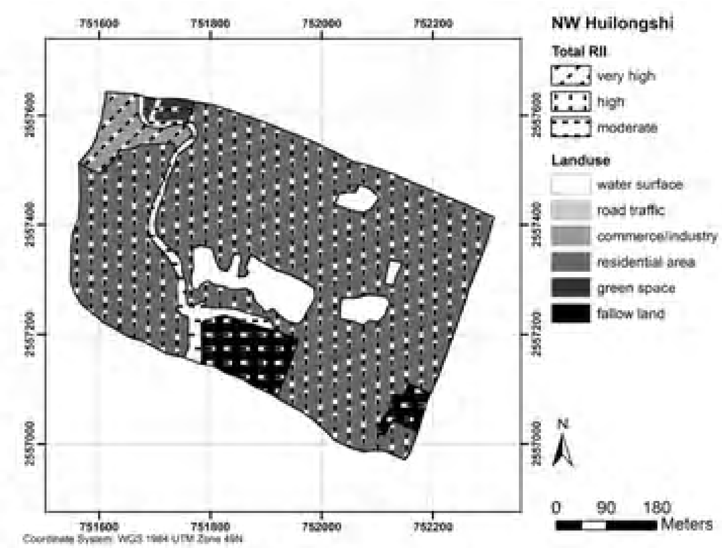

Table 2 .Concentration of total coliform bacteria in the groundwater of Guangzhou

percolating water has the most negative influence on the protection function resulting in very high vulnerability. A detailed description of the intrinsic and specific groundwater vulnerability modeling of Guangzhou is given in Baier *et al.* (2011).

In order to map the hazards, the individual hazards have to be weighted according to their actual land use. Table 1 shows a list of hazards that occur in the study units. The weighting value H is given by Zwahlen (2003) for each hazard. The values for Q_n and R_f are chosen individually for each unit. The hazard index is calculated as $HI = H \cdot Q_n \cdot R_f$. The results of the hazard assessment are, on the one hand hazard maps for each hazard in all chosen units, and, on the other hand, total hazard maps for each unit. The hazard maps for each single hazard show the spatial distribution of a specific hazard. The total hazard maps show the sum of all hazards caused by the land use impacting on a unit. An example of such total hazard maps is shown in Fig. 3 relating to the urban unit Yuangangcun. The total hazard of Yuangangcun is an addition of the hazards ‘leaking sewer pipes and sewer systems’ (1.1.1),’waste water discharge into surface water courses’ (1.1.9), ‘paper and pulp manufacture’ (2.4.8) and ‘waste water irrigation’ (3.2.7). The hazard is high where the land use is ‘water surface’, ‘agriculture’ or in commercial and industrial areas. It is predominantly moderate in residential areas and low in fallow land and green space. In general, agricultural areas show a high to very high total hazard, as well as the commercial and industrial areas. But these can be low hazardous if there is no involvement of specific heavy industry. Residential areas are predominantly low or moderate hazardous, but they can reach to a very high hazard – as e.g. in Datang, because there the grades of waste water discharge and garbage dump are especially high. The hazard of fallow land and water surfaces vary between low and high depending on their temporary use (fallow land) or the amount of waste water discharge (water surface). Very low hazards do not occur in this analysis.

“Risk” is the hazards’ influence on groundwater resources. It combines the hazard index with the groundwater vulnerability. Most of the analyzed areas in Guangzhou show a high or moderate risk index. Some parts have very high risk; low and very low risk do not occur because of the overall very high groundwater vulnerability ($\pi = 1$). As the vulnerability in general is very high, it is the hazard that makes the differences in the risk indices. Very high risk is the result of very high hazard in each case. A high risk can result from all hazard classes ranging between low (Shibi) to very high (Huilongshi). But in most cases high risks have high or moderate hazards. The differences have their origin in the values of the hazard index. These can vary although they are in the same hazard class. Additionally, same land use types can have different hazard because of two reasons: Firstly, because each land use is weighted and rated individually; secondly, because the same land use type can show different kinds and amounts of hazard. For instance, a residential area can either have a sewer system (hazard 1.1.1) or it has no sewer system (hazard 1.1.2).

Xincun shows a moderate risk in most parts and a high risk on the former fallow land site (cf. again Fig. 4). The whole area is covered with the hazard of general urbanization, including leaking sewer pipes and sewer systems. As it exhibits a sewer system, even if it is leaking, the risk is moderate and not high in the residential area. Thus, the risk in the residential area is moderate. The fallow land suffers additionally from spoils and building rubble depository. The addition of both hazards leads to the high risk in this area.

In *Datang* the residential area shows a very high risk because of the hazards of waste water discharge and garbage dumps additional to the general hazard of urbanization (cf. Fig. 5). On the other hand, the industry and commercial areas in this unit have only moderate risk. That indicates that a summation of moderate hazards can have more severe impact than one heavy hazard. High risk occurs on the fallow land because of garbage dumping.

A huge part of *Shibi* is agricultural area which has very high risk because of the presence of five different hazards (cf. Table 1). The railway lines are highly fraught with risk whereas the station shows only high risk because of the modern structure. The residential area is of high risk because of potentially leaking sewer pipes and untreated waste water discharge. In *Yuangangcun* the risk index in general is high because four different hazards occur in this unit (cf. Table 1), which partly overlie each other (Fig. 7). Green spaces, fallow land and areas where no land use data is available show moderate risk. These land use types are included in the general hazard of urbanization (No. 1.1.1). Most parts of the area in the North-west of Huilongshi are residentially used that have high risk to groundwater because of leaking sewer pipes and untreated waste water discharge (cf. Fig. 8). Commercial areas and industries have a very high risk, mainly due to the body care producing enterprise discharging its waste water untreated into the adjacent Heng Chong (Heng River). Green space, fallow land and water surface have moderate risk due to the general hazard of urbanization. The results show that a combination of the small-scale land use analyses in frame of the new developed „urban units"-approach and the methods of „intrinsic vulnerability modeling" and „hazard- and risk mapping" can provide useful information for an integrated groundwater management. Additionally, this can be a substantial contribution for an enhanced drinking water supply and thus of an improved protection of resources in general. All methods used in this paper are scientifically recognized and discussed. The integration of the small-spatial land use analyses into the existent vulnerability and risk hazard analyses represents a significant improvement of the risk analysis. With the help of this approach potential small-scale contamination sources can be taken into account.

The small scale land use analyses only implicate little uncertainties since it has been conducted majorly on site. Potential uncertainties could have been resulted when distinguishing urbanization pattern with and without a sewerage system. Although the social classes of buildings were rather good to be determined, it sometimes remains uncertain, if the respective buildings are really connected to adequate sewer system or not.

However, possible uncertainties have to be taken into account as there was a lack of existing data in regard to groundwater vulnerability modeling. Some of the data that is required for an accurate modeling of the intrinsic groundwater vulnerability was not available. Moreover, fundamental data such as topographic or hydrological maps can only be obtained on an inaccurate scale (e.g. 1:5,500,000); this resolution is too small for the size of area under investigation. Some data needed were found by an extensive literature review; so that the data which are used sometimes are secondary data (see Baier *et al.*, 2011; Baier and Strohschön 2012). Due to the problems described in data availability, data acquisition and due to the inaccuracy of the existing data, better and detailed results within the scope of intrinsic vulnerability modeling are not possible at the moment.

Though, the groundwater hazard evaluation shows good results by displaying a greater variety of hazards being carefully assessed concerning their contamination potential. In contrast to vulnerability parameters being intrinsic and relatively static, hazards are dynamic potential contamination sources posed by human activities. For hazard assessment, similarly to index models for vulnerability assessment, scores are assigned subjectively for specific land uses and the resulting contaminations. Hence, human activities are the determining factors as the results of the small-scale land use analyzes in frame of the urban unit-method show.

CONCLUSION

The risk intensity assessment shows mostly moderate, high and very high risks for Guangzhou's groundwater resources, depending on the classified land use and hazard evaluation. Particularly high hazards and risks are calculated for most of the residential areas because of non-existing or non-adequate sewer systems, industrial areas and also for fallow land and agricultural land use. Conducted groundwater analyses support this statement as especially high concentrations of total coliform bacteria could be detected (Table 2). Coliform bacteria resulting from domestic wastewater discharges belong to the most spread substances in Guangzhou's water cycle (Strohschön *et al.*, 2013).

It has to be taken into account that risk intensity assessment constitutes the product of the vulnerability and hazard assessment. Because of this, it transfers the above described uncertainties. For a total risk assessment literature states that risk intensity has to be complemented with risk sensitivity (consequences or socio-economic value). This has not been assessed in this study. Yet, it can be attended that the consequences of groundwater contamination are fatal. People belonging to the poorer population stratum are using groundwater directly by private or publicly accessible wells. At the moment raw water is mainly extracted from surface water (Baier and Strohschön 2012). But due to the increasing water demand caused by the population growth and the changing consumer behavior, the Guangdong province has plans for a development of groundwater resources (Baier and Strohschön, 2012). In this context it becomes clear that the risk assessment of potential groundwater contamination with regard to the natural protective function on the one side and to the small-scale land use on the other side should be an integral part of a sustainable management of Guangzhou's water resources.

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REFERENCES

Aggarwal, S. and Butsch, C. (2012). Environmental and Ecological Threats in Indian Mega-Cities. In: M. Richter, U. Weiland (Edss), Applied Urban Ecology: A Global Framework. Oxford, pp. 66-81.

Azzam, R., Post C., Baier, K., Real., A.and Ziefle, M. (2008). Water Supply and Sanitation Facilities in a Human-Centred Management Concept for Fast Growing Megacities. In: UN Habitat- United Nations Settlement Programs: Fourth session of the World Urban Forum, Nanjing, China, Documentations of Germany's Contribution to a Sustainable Urban Future.

Azzam, R., Baier, K., Neukum, C. and Post, C. (2009). Sauberes Trinkwasser für die Zukunft – Grundwasserschutz im Spannungsfeld zwischen Global Change und wachsendem Ressourcenbedarf. Umweltforum der RWTH Aachen – Themenheft Wasser, pp. 72-73.

Baier, K. and Strohschön, R. (2012) Die Grundwassersituation in der südchinesischen Megastadt Guangzhou. DVGW energie | wasser-praxis 4: pp. 18-23.

Baier, K., Strohschön, R. and Schmitz, K. S. (2011). Groundwater Vulnerability of Guangzhou Mega City, China. (In K. Baier, T.M. Fernandez-Steeger, K. Heinrichs, C. Neukum, C. Post (Eds.), Festschrift zum 60. Geburtstag von Univ.-Prof. Dr. Dr. h.c. Rafig Azzam. Mitteilungen zur Ingenieurgeologie und Hydrogeologie 104, pp. 81-94.

Bronger, D. (1996). Megastädte, Geographische Rundschau 2: pp. 74-81.

Chen, N. and Heligman, L. (1994). Growth of the World's Megalopolises. (In R.J. Fuchs, E. Brennan, J. Chamie, F.-C. Lo, J.I. Uitto (Eds.), Mega-city Growth and the Future. Tokyo, pp. 242-261.

Chen, J., Zhao, X. and Dong, Y. (2006). Impacts of urbanization on water quality in the Pearl River Delta, China. In J. Chen, M. Taniguchi, S.K. Jain (Eds.), Workshop on "Global Water System Hotspot in the Asian Region: Mega cities and Dams". 2nd GWSP Asia Network Meeting. Final report for APN project: ARCP2006-14NSY-Chen.

Coy, M. and Kraas, F. (2003). Probleme der Urbanisierung in den Entwicklungsländern. Petermanns Geographische Mitteilungen, **147**, 32-41.

Foster, S. S. D., Morris, B. L. and Lawrence, A. R. (1993). Effects of urbanization on groundwater recharge. (In W.B. Wilkinson (Ed.), Groundwater Problems in Urban Areas. Proceeding of Institution of Civil Engineers, June 1993, London, pp. 43-63.

Fuchs, R. J., Brennan, E., Chamie, .J, Lo, F. C. and Uitto, J. I. (1994). Mega-city Growth and the Future. Tokyo.

Gan, H., Zhou, M., Li, D. and Zhou, Y. (2008). Quality characterization and impact assessment of highway runoff in urban and rural area of Guangzhou, China. Environ. Monit. Assess., **140 (1-3)**, 147–159.

He, M. (2005). The water household as an example of ecology in the Pearl River Delta. In D. Ipsen, L. Yongning, H. Weichler (Eds.), The genesis of urban landscape: The Pearl River Delta in South China. Kassel: University of Kassel, pp. 77-84.

Heinrichs, D. (2009). Megacity mit Zukunft gesucht! Politische Ökologie, **27**, 44-46.

Hölting, B., Hartele, T., Hohberger, K. H., Nachtigall, K. H., Villinger, E., Wenzierl, W. and Wrobel, J. P. (1995).

Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung. Geologisches Jahrbuch, **63**, 5-24.

Huang, J. and Keyton, D. (2010). Guangzhou Population Closes to 15 million. Retrieved June 04, 2013, from http://www.lifeofguangzhou.com/node_10/node_37/node_85/2010/06/18/127683154477641.shtml.

Kraas, F. (2009). Globalisierungs- und Marginalisierungsprozesse in Megastädten. Praxis Geographie, 7-8, 4-8.

Liu, J. T., Sun, J. C., Lin, L. J., Zhang, Y. X. and Jing, J. H. (2011). A tentative discussion on nitrite, nitrate and ammonia (NNA) pollution of groundwater in typical urbanized areas of Guangzhou city. Geology in China, **38 (2)**, 489-494.

Liu, S., Li, X. and Zhang, M. (2003) Scenario-Analysis on Urbanization and Rural-Urban Migration in China. Interim Report IR-03-036. International Institute for Applied System Analysis, Laxenburg.

Lu, L., Baier, K. and Azzam, R. (2009) Analysis of Urban Land Use Types by Multispectral Satellite Image Analysis, Using the Example of the Megacity Guangzhou, China. In K. Baier, R. Strohschön (Eds.), Proceedings of Megacities – Interactions Between Land Use and Water Management. Mitteilungen zur Ingenieurgeologie und Hydrogeologie 99, pp. 31-40.

Lu, L., Baier, K. and Azzam, R. (2011). Die Analyse städtischer Landnutzungsformen durch multispektrale Satellitenbildanalyse am Beispiel der Megacity Guangzhou, China. In R. Strohschön, M. Romich, K. Baier (Eds.), Strukturen, Prozesse und Dynamiken der Mega-Urbanisierung in China – Landnutzung und Wasserressourcen. Aachener Studien zur Sozial-Ökonomischen Entwicklungsforschung 11, Internationales Zentrum für Vergleichende Sozial-Ökonomische Entwicklungsforschung, pp. 37-52.

Maiti, S. and Agrawal, P. K. (2005). Environmental Degradation in the Context of Growing Urbanization: A Focus on the Metropolitan Cities of India. Journal of Human Ecology, **4 (17)**, 277-287.

Mertins, G. (1992). Urbanisierung, Metropolisierung und Megastädte. Ursachen der Stadt"explosion" in der Dritten Welt – sozioökonomische und ökologische Problematik. (In Deutsche Gesellschaft für die Vereinten Nationen (Ed.), Mega-Städte – Zeitbombe mit globalen Folgen? Bonn. Dokumentationen, Informationen, Meinungen 44, pp. 7-21).

Morris, B. L., Lawrence, A. R. and Stuart, M. E. (1994). The impact of urbanization on groundwater quality (Project Summary Report), Technical Report WC/94/56, British Geological Survey.

Mu, R., Chen, R. and Ren, J. (2005). Water utilization and land use in the process of urbanization and industrialization: the case of Guangzhou. Agrifood Research Reports, **68**, 261-269.

Ouyang, T., Zhu, Z. and Kuang, Y. (2005). River water quality and pollution sources in the Pearl River Delta, China. J. Environ. Monit., **7**, 664-669.

Ouyang, T., Zhu, Z., Kuang, Y., Huang, N. S., Tan, J. J., Guo, G. Z., Gu, L. S. and Sun, B. (2006). Dissolved trace elements in river water: spatial distribution and the influencing factor, a study for the Pearl River Delta Economic Zone. Environ. Geol., **49**, 733-742.

Rukumbuja, R. and Mato, A. (2002). Groundwater Pollution in Urban Dar es Salam, Tanzania – Assessing Vulnerability and Protection Priorities. Eindhoven University of Technology, Eindhoven.

Song, M. W., Huang, P., Li, F., Zhang, H., Xie, K. Z., Wang, X. H. and He, G. X. (2011). Water quality of a tributary of the Pearl River, the Beijiang, Southern China: implications from multivariate statistical analyses. Environ. Monit. Assess., **172**, 589-603.

Strohschön, R., Baier, K. and Azzam, R. (2009). Urban Units as an Analysis Tool for Mega-Urban Development. The Case of Guangzhou, China. (In K. Baier, R. Strohschön (Eds.), Proceedings of Megacities – Interactions Between Land Use and Water Management. Mitteilungen zur Ingenieurgeologie und Hydrogeologie, **99**, 63-72.

Strohschön, R., Wiethoff, K., Baier, K., Lu, L., Bercht, A. L., Wehrhahn, R. and Azzam, R. (2013). Land use and water quality in Guangzhou, China: a survey of ecological and social vulnerability in four urban units of a rapidly developing megacity. In: International Journal of Environmental Research, **7 (2)**, 343-358.

Tibaijuka, A. (2006). Schwierige neue Welt. In: DGAP (ed.) Megastädte. Internationale Politik, **11 (61)**, 9-17.

Umar, R., Ahmed, I. and Alam, F. (2009). Mapping groundwater vulnerability zones using modified DRASTIC approach on an alluvial aquifer in parts of central Ganga plain, Western Uttar Pradesh. Journal of Geological Society of India, **73**, 193-201.

UN, (1987). United Nations – Population Growth and Policies in Megacities: Bangkok. Population Policy Paper **10,** New York.

Vira, B. and Vira, S. (2004). India's Urban Environment: Current Knowledge and Future Possibilities. In T. Dyson, R. Classen, V.L. Dyson (Eds.), 21st Century India. Population, Economy, Human Development and the Environment. Oxford, pp. 292-311.

Wehrhahn, R., Bercht, A. L., Krause, C. L., Azzam, R., Kluge, F., Strohschön, R., Wiethoff, K. and Baier, K. (2008). Urban restructuring and social and water-related vulnerability in mega cities – the example of the urban village of Xincún, Guangzhou (China). Die Erde, **3**, 227-249.

Wiethoff, K., Baier, K. and Strohschön, R. (2011). Brachflächen: urbane Leerstellen der Megastadt –

Auswirkungen der Interimsnutzung von Brachflächen auf die lokale hydrologische Situation in Guangzhou, China. Cybergeo: European Journal of Geography, article 524. doi: 10.4000/cybergeo.23537.

Wiethoff, K. and Strohschön, R. (2009). Dokumentation von 30 urban units in Guangzhou - Untersuchungsphase III: September - Oktober 2008 (Forschungsdokumentation), Aachen.

Zwahlen, F. (2003). Cost Action 620. Vulnerability and Risk Mapping for the protection of Carbonate Aquifers, Cost Action 620.