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Characterization of recharge and flow behaviour of different water sources in Gunung Kidul and its impact on water quality based on hydrochemical and physico-chemical monitoring

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Abstract Karst aquifers are important water resources but highly vulnerable due to their heterogeneous and complex characteristics. Various hydrological aspects (recharge, flow behaviour) have to be known in detail to develop a sustainable concept for water collection, distribution and treatment. In the karst area of Gunung Sewu (Java, Indonesia) such a concept was to be implemented within a German–Indonesian joint IWRM project. The basic hydrogeological conditions and water quality aspects were characterized on a regional scale through hydrochemical monitoring of springs, wells, subsurface and surface rivers. More detailed information about the recharge, flow and storage behaviour was obtained from high resolution monitoring of T, EC and discharge in one large underground river system. The water quality is well below any guideline values with regard to inorganic pollutants during dry season. During rainy season, dissolved Al concentrations are frequently above the Indonesian guideline value. Slow matrix flow is the most important recharge component during dry season, thus assuring the year-round water availability in the subsurface karst. During rainy season, quick infiltration of the surface water is a dominant recharge component. Rapid response of discharge, T and EC to heavy rain suggests the presence of point recharge that feeds a highly karstfied conduit system with fast conduit flow and short transit time of water. The strong variations in discharge and hydrochemistry are particularly challenging for technical water usage and treatment facilities. Piston flow is indicated to be the third important flow component and is induced by heavy rainfall.

Keywords Karst hydrology · Groundwater quality · Electrical conductivity · Gunung Sewu · Gunung Kidul · Indonesia

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Introduction

Carbonate rocks are globally distributed and cover an area of ~17–22 million km^2 which equals around 20 % of the land surface (Ford and Williams 2007; Pfeffer 2009). Already up to 25 % of the world's population depend on karst water supply (Ford and Williams 2007) and it is likely that this proportion will increase in future due to rapid population growth in some karstic areas like in Indonesia. Karst water aquifers are characterized by heterogeneous distribution of three types of porosity: intergranular pores, fractures and conduits (Goldscheider and Drew 2007). The range of porosity and permeability influences many aspects of karst aquifer characteristics like recharge, flow path and velocity, storage and retention capacity. Recharge in karst either takes place via slow diffuse infiltration which is mainly controlled by matrix dominated features like fractures, epikarst etc. or fast point infiltration via swallow holes or sinking streams which are often directly connected to a conduit system (White 2002; Ford and Williams 2007). Consequently, flow primarily takes place in the conduit system while matrix porosity is mainly responsible for storage in karst aquifers (e.g. Worthington et al. 2000).

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This heterogeneity and complexity of karst aquifers lead to a low retention capacity and a high temporal and regional variability of discharge and hydrochemistry. This makes karst aquifers a highly vulnerable resource and its usage and management extremely challenging (Ford and Williams 2007; Goldscheider and Drew 2007).

Access to clean water and sanitation; however, is a human right as declared by the United Nations in 2010 (Resolution 64/292, UN 2010). Apart from quality and amount this also includes physical accessibility (within 1 km) and affordability (≤ 3 % of household income). In addition, states and international organizations are explicitly called upon to provide financial resources, capacity-development and technology transfer in particular to developing countries to scale up efforts to provide sufficient and affordable clean drinking water (OHCHR 2010). These considerations are also important aspects of the integrated water resources management concept (IWRM) that was developed and refined since the summit on sustainable development in 1992 in Rio de Janeiro (UNESCO 2009).

Since 2008, an IWRM concept that focuses on the implementation of adapted technologies and technology transfer has been implemented in Gunung Kidul, Indonesia, in the framework of a collaborative research project funded by the German Federal Ministry for Education and Research (BMBF) (Nestmann et al. 2010). The district of Gunung Kidul which is situated in the southeast of Yogyakarta is considered as one of the poorest regions in Indonesia and included in the list of the most disadvantaged regions by the Indonesian Ministry for Development of Disadvantaged Regions (KEMENNEG PDT 2005). During dry season people regularly suffer from water scarcity and poor water quality. One major reason is the fact that Gunung Kidul is located above a large carbonate rock formation which is highly karstified. As a consequence, surface water rapidly infiltrates without sufficient contaminant retention which explains the poor water quality (Matthies et al. 2014). One major achievement of the IWRM project was the installation of a hydropower plant which allows using underground water resources (Nestmann et al. 2009) and which is implemented into an integrated water management plan for the whole region.

To develop such an adapted water resource management which secures a safe, sustainable and long-term water supply in a karstic area like Gunung Kidul, a clear understanding of the processes causing and controlling variations in groundwater chemistry (including contaminants) and discharge is necessary (e.g. McConnell and Hacke 1993; Plummer et al. 1998; Birk et al. 2004; Katz 2004). The required information can be gained through a comprehensive hydrogeological characterization of a karst

system on a local or regional basis. The high degree of anisotropy in karst aquifers requires a multidisciplinary approach. This can include, for example, hydrological techniques (e.g. spring hydrographs, rainwater gauges), hydraulic methods (e.g. piezometric maps, hydraulic tests) and the application of natural (e.g. hydrochemistry, D-/O-isotopy) or artificial tracers (e.g. fluorescent dyes) (Goldscheider and Drew 2007).

Hydrochemical investigations are often primarily done to assess water quality and detect contamination problems. In combination with isotopic parameters like H-/O-isotopy, however, it can provide further valuable information, for example about the origin of water, its residence time or water–rock interactions. Monitoring of natural tracers, especially during storm events, in combination with rainfall data is particularly suitable to get insight into structure and dynamics of karst aquifers and allows the separation of distinct water masses (Baena et al. 2009; Mudarra et al. 2014). In this context continuous monitoring of electrical conductivity (EC), temperature (T) and discharge (Q) in spring or subsurface water sources has proven to be very useful. Variations of these parameters as response on recorded rainfall events give information about the amount and residence time of infiltrating surface water. Furthermore, it allows delineating varying contributions of different masses of water moving through the system under different flow conditions (e.g. Massei et al. 2003; Birk et al. 2004; Baena et al. 2009). In karst aquifers, EC is assumed to be mainly controlled by the calcium-carbonate equilibrium. Base flow values of EC are, consequently, a measure of slow matrix flow which allows equilibration with calcite, whereas sharp dips in EC are typically indicative for surface water intrusion through point sources (Birk et al. 2004).

The aim of this present study was a basic hydrogeological characterization of Gunung Kidul based on temporal and spatial variation of hydrochemistry in different water sources. This allows, on the one hand, drawing conclusions about water quality, contaminant sources and flow dynamics of different water resources in the area. On the other hand, it serves as a basis for the development of a regional water management plan. To get more detailed information about short term variations of flow and recharge behaviour of the karst system, high resolution monitoring of discharge, EC and T was additionally carried out for 1 month during rainy season (February 2012) in one of the focused underground rivers called Seropan River which flows through Gua Seropan (Gua is Indonesian for cave). Information about flow and hydrochemical variations and possible extreme events is necessary for an optimal dimensioning of the hydropower plant, the choice of technical equipment and subsequent water treatment planning.

Study area

Gunung Kidul, which is a district of the Yogyakarta Special Province, stretches along the south central coast of Java with an elevation range between 0 and 600 m above sea level (Flathe and Pfeiffer 1965; Haryono and Day 2004). Along the coast steep cliffs with heights of 25–100 m are often present (Uhlig 1980; Haryono and Day 2004).

Gunung Kidul has a warm and moist tropical monsoon climate with a mean annual temperature of 27 °C, a mean annual high humidity of $\sim$80 % and an annual precipitation of around 2000 mm (Flathe and Pfeiffer 1965; Haryono and Day 2004). The amount of precipitation is determined by the Australian-Indonesian Summer Monsoon and its seasonal movements which leads to an alternation of wet seasons (150–350 mm precipitation per month) from November to April and dry seasons from May to October (24–150 mm per month) (Brunsch et al. 2011). El Niño-Southern Oscillation (ENSO) events have a considerable impact on the rainfall amount in Gunung Kidul with dryer conditions during El Niño and more rainfall during La Niña years (Brunsch et al. 2011).

Based on its geology Gunung Kidul is commonly separated into three different landscapes. The mountain ranges of Baturagung in the north and Panggung in the north–east mainly consist of sediments and volcanic deposits of Eocene to early Miocene age. Further to the south, Miocene limestone of the Wonosari formation is present. The Wonosari plateau, which is an intermontane basin, mainly consists of bedded chalky limestone and is only weakly karstified. Along the coast strongly karstified massive coral reef-limestone, with intercalated clay and volcanic ash lenses, is present (van Bemmelen 1949; Flathe and Pfeiffer 1965; Waltham et al. 1983; Haryono and Day 2004).

This southernmost part of the Wonosari formation, called Gunung Sewu ("land of thousand hills"), is considered as type example of cone- or kegelkarst with around 30 cones per km^2 (Lehmann 1936; Flathe and Pfeiffer 1965). It has developed since the Pleistocene in response to the regional uplifting in combination with strong chemical weathering (Flathe and Pfeiffer 1965; Haryono and Day 2004). It stretches $\sim$85 km in EW and 10–25 km in SN direction. In total, it covers an area of around 1400 km^2. As a result of the regional lifting the Wonosari formation gently dips southwards with a gradient of $\sim$2 % (Uhlig 1980; Haryono and Day 2004). The valleys and depressions between the individual cones are filled with residues from limestone weathering, deeply weathered clay and layers of volcanic ash with a thickness of up to 10 m (Uhlig 1980 ; Waltham et al. 1983).

Due to ongoing strong karstification a typical karst landscape has developed within the Gunung Sewu with characteristic surface (sink and swallow holes, sinking streams, dry valleys, springs etc.) and underground (caves, vadose/phreatic conduits etc.) karst landforms which are connected by a sometimes extended epikarst zone. Karstification also led to high porosity. Consequently, rainfall can quickly infiltrate leading to a lack of surface runoff. On the surface, rainwater can only be accumulated in clay sealed karst depressions. The resulting small lakes, so-called Telagas, can remain for several weeks to months. In the subsurface, however, hundreds of caves have developed, many of which are water bearing and connected by a complex subsurface conduit network. These perennial rivers flow towards the coast where they eventually discharge through surface or submarine springs into the Indian Ocean. The major underground river network in the Gunung Sewu known so far is the Bribin-Baron system, which has an outlet discharge of up to 8000 L/s (Adji 2012). Apart from infiltrating rain, the Gunung Sewu aquifer is fed by different sinking streams which are located at the north edge towards the Wonosari Plateau. Three of them have sufficient discharge also during dry season (Kali Serepeng, Kali Tegoan, Kali Suci). The largest perennial surface river of the area, the Kali Oyo, flows through Gunung Kidul towards the Indian Ocean at the northern fringe of the Wonosari Plateau. Throughout Gunung Kidul, perennial underground rivers are widespread (Fig. 1). One of them, the Bribin River, was used to develop and implement a hydropower plant containing a full dam (Nestmann et al. 2009). The river water in Gua Seropan (Fig. 1, which was only discovered in the mid-1990s), a cave which is only 1.5 km away from Bribin, is currently extracted by conventional electric pumps. Within the IWRM-project this river was considered as optional construction site for the implementation of another concept of an underground hydropower plant which utilizes a wood-stave pipeline as the penstock instead of a dam.

Methods

Sampling

To characterize different kinds of water sources in Gunung Kidul, samples were taken in wells (mainly Wonosari Plateau), springs, subsurface and surface rivers (Fig. 1). The sampling locations were distributed in the *Kecamatan* of Wonosari, Ponjong, Semanu and Karangmojo. Water samples for cations, anions and H-/O-isotopy were taken in August 2009 (dry season), February 2010 (El Niño, wet season) and March 2012 (La Niña, extremely wet season). Directly in the field, physico-chemical parameters [pH value (SeniTix®41-3), electrical conductivity (TetraCon®),
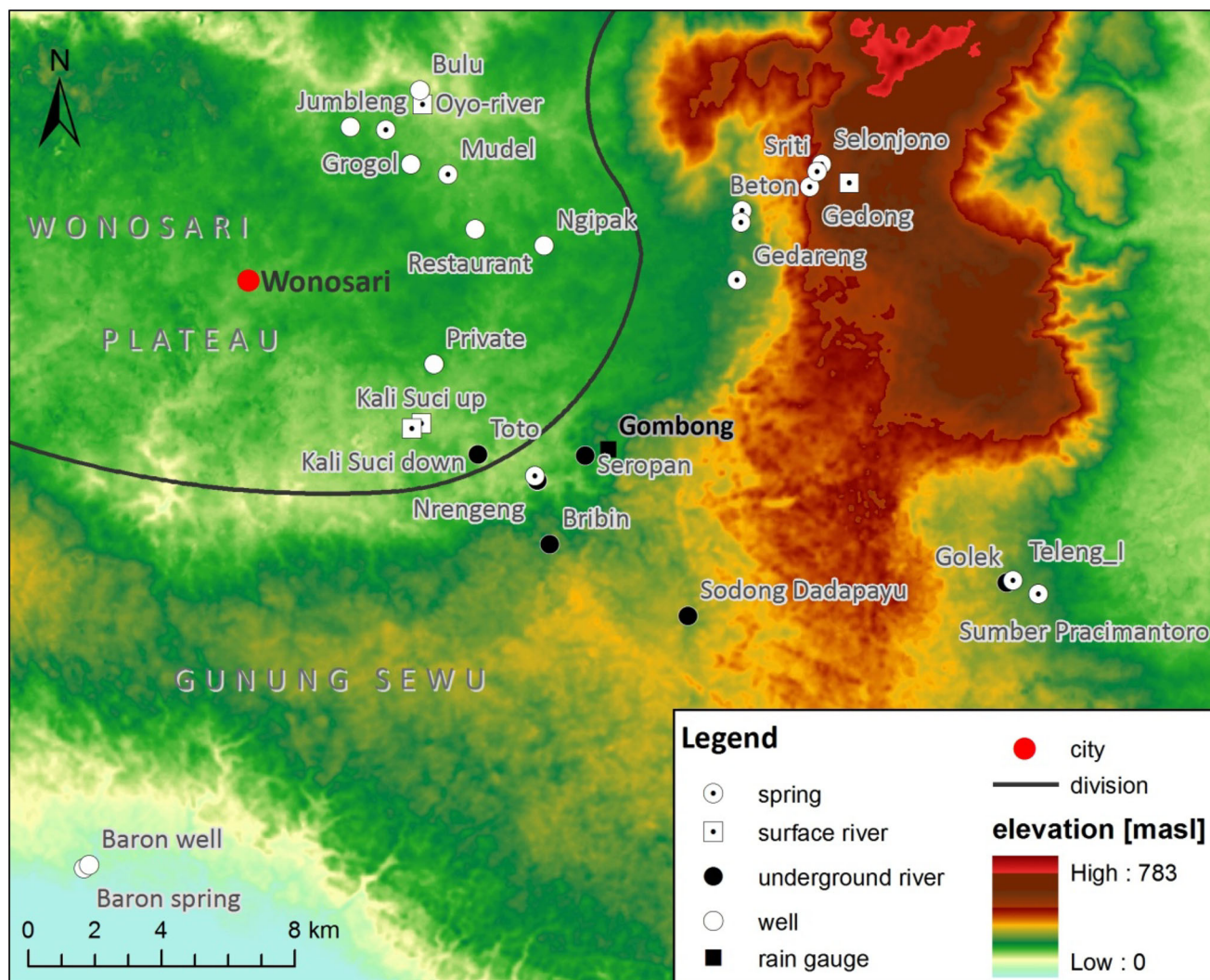
Fig. 1 Map of Gunung Kidul including location of the rain gauge in Gombang and locations of different water resources that were sampled in 2009, 2010 and 2012

and temperature] were determined using a WTW multiprobe (mulitline P4). Due to high relative humidity, the pH and EC probes failed several times. Therefore, these values are missing for some locations. Water samples were filtered (0.45 μm, cellulose acetate, Satorius Biolab Products) and stabilized using HNO_3 (65 %, suboiled) for cations and NaN_3 (1 g/L, Merck) for anions. All samples were kept cool until further analysis. The alkalinity was determined directly in the field using a titration quick test kit (Merck, 1.11109.0001). Due to heavy flooding, not all samples could be taken in 2012.

Hydrochemical monitoring in underground Seropan River

To get a detailed knowledge of the recharge characteristics of one of the larger underground river systems, a

hydrological and physico-chemical monitoring was carried out at Seropan River during rainy season in February 2012. Apart from its importance for the regional hydrogeology, the Seropan River was chosen because it played an important role for the IWRM project as mentioned above. Temperature and EC were recorded every 5 minutes using a combined T and EC probe (STS DL/N 70). The probe was installed about 5 metres in front of an artificial weir next to the cave's entrance in ~ 1 m depth. According to the manufacturer's specification, the resolution for T and EC is 0.1 °C and 1 μS/cm, respectively. The precision is ± 0.25 °C for T and ± 2 % full scale of EC.

Precipitation was recorded every hour using rain gauges from onset (HOBO RGB-M002). For this study the recorded precipitation from the rain gauge which is located in Gombong, ~ 1 km east of Gua Seropan, was used (Fig. 1). Discharge was measured at the weir in Seropan

River using STS air pressure and water level sensors (STS DL/N).

Water analysis

Major and trace element concentrations were analysed from the acidified water samples using an X-Series 2 ICP-MS (Thermo Fisher Scientific Inc.) in collision cell mode to eliminate polyatomic clusters. The accuracy was tested by repeatedly measuring the certified standard CRMTMDW-A (High Purity Standards, USA). Concentrations of all elements were within 7 % of the reference value. Additionally, ^{103}Rh, ^{115}In and ^{169}Tm were used as internal standards. Anion concentrations (Cl, NO$_3$, SO$_4$) were measured with ion chromatography [Dionex ICS-1000, IonPac AS4A-SC (2009), AS14 (2010/2012)] using a Na$_2$CO$_3$/NaHCO$_3$-Eluent with a flow rate of 2 ml/min. ICP multi-element standard solution IV (Merck KGaA, CertiPUR) and multi-ion IC standard (Alfa Aeser, specpure) were used for calibration and cross-check throughout the analysis procedure.

Results

Hydrochemistry

River water

Two different rivers (Betung, Oyo River) and one sinking stream (Kali Suci) have been investigated. Even though all are Ca–HCO$_3$-dominated (Fig. 2), the specific hydrochemistry varies between the different sampling campaigns but also between each river. All rivers have in common, that most trace elements that were analysed as well as nitrate, sulphate and chloride concentrations are relatively low and far below any threshold values during all seasons (Table 1; supplementary). In dry season, Betung and Oyo River, which have their source in the volcanoclastic rocks of the northern mountain ranges, have a relatively low mineralisation (343, 410 μS/cm) compared to the Kali Suci (519, 527 μS/cm) which mainly passes the limestone of the Wonosari Plateau. This difference is also expressed in the Ca and HCO$_3$ concentration with 55–74 mg Ca/L and 238–250 mg HCO$_3$/L for Betung and Oyo River, respectively, and 103–104 mg/L Ca and 329-348 mg HCO$_3^-$/L for Kali Suci. During dry season river waters are mainly supersaturated with respect to calcite.

During rainy season and especially during the flood events in 2012, the mineralization is sometimes considerable lower due to dilution effect. The dilution is especially pronounced in Kali Suci and expressed, for example, in a slight to considerable decline in Ca-, Mg- and HCO$_3$-concentrations. During extremely high discharge events in 2012 a five times lower electrical conductivity (107 μS/cm), four to five times less Ca (18 mg/L), Mg (0.9 mg/L) and HCO$_3$ concentrations (73 mg/L) were detected in contrast to 2009 and 2010 (Table 1; supplementary). In contrast, Al and Fe concentrations considerably increase with increasing discharge from 6.3 to 4400 μg Al/L and 9.5 to 1760 μg Fe/L in Kali Suci. In 2010, all river waters are subsaturated vs calcite whereas during the flood time in 2012 only the Kali Suci was clearly subsaturated.

Underground river water

In general, all underground rivers are Ca–HCO$_3$-dominated (Fig. 2). The mineralization is comparable to Kali Suci with 480 μS/cm, on average, during dry season (Table 1). Slightly higher values were found in Gua Golek (610 μS/cm) and Gua Toto (540 μS/cm). In Sodong Dedapayu, which has the lowest mineralization (EC 79–275 μS/cm), Ca (15–73 mg/L) and HCO$_3$ (43–250 mg/L) concentration in all seasons, the sampled water body had contact to the underground river but was not actively flowing. That's why this cave has to be considered as sinkhole rather than a river. In all other underground rivers, the Ca and HCO$_3$ concentration is considerably higher with 93 and 310 mg/L, respectively, on average. In contrast to surface water, the Ca and HCO$_3$ concentration and, hence, also the mineralization is nearly constant or only slightly decreasing throughout the three sampling periods. Again, Sodong Dedapayu is behaving differently, with a decline of Ca and HCO$_3$ concentration as well as mineralization by a factor four to five during the flood in 2012. An increase in Al and Fe concentration is only detectable during the flood event in 2012 in some of the underground rivers like in Golek River (increase 9.1–220 μg Al/L, 7.5–102 μg Fe/L, respectively) or in Sodong Dedapayu (increase 28–3260 μg Al/L, 14–1230 μg Fe/L). The calcite saturation varies from slightly sub- to slightly supersaturated with no detectable dependence on season (Table 1).

Springs

In total, 12 different springs have been investigated and can again be described as Ca/HCO$_3$ dominated (Fig. 2). On average, the mineralization of all springs (2009: 543 ± 76 μS/cm) is higher compared to surface and subsurface river waters and more or less constant over all seasons with slightly lower values during rainy season 2010. Only in Baron Spring, the mineralization (EC) as well as Ca and HCO$_3$ concentrations are reduced by ~30 % during the extreme flood season in 2012 (Table 1). All other springs have average Ca concentrations of 105–118 mg/L and HCO$_3$ concentrations of 321–362 mg/L, respectively. Despite the more or less constant hydrochemistry with
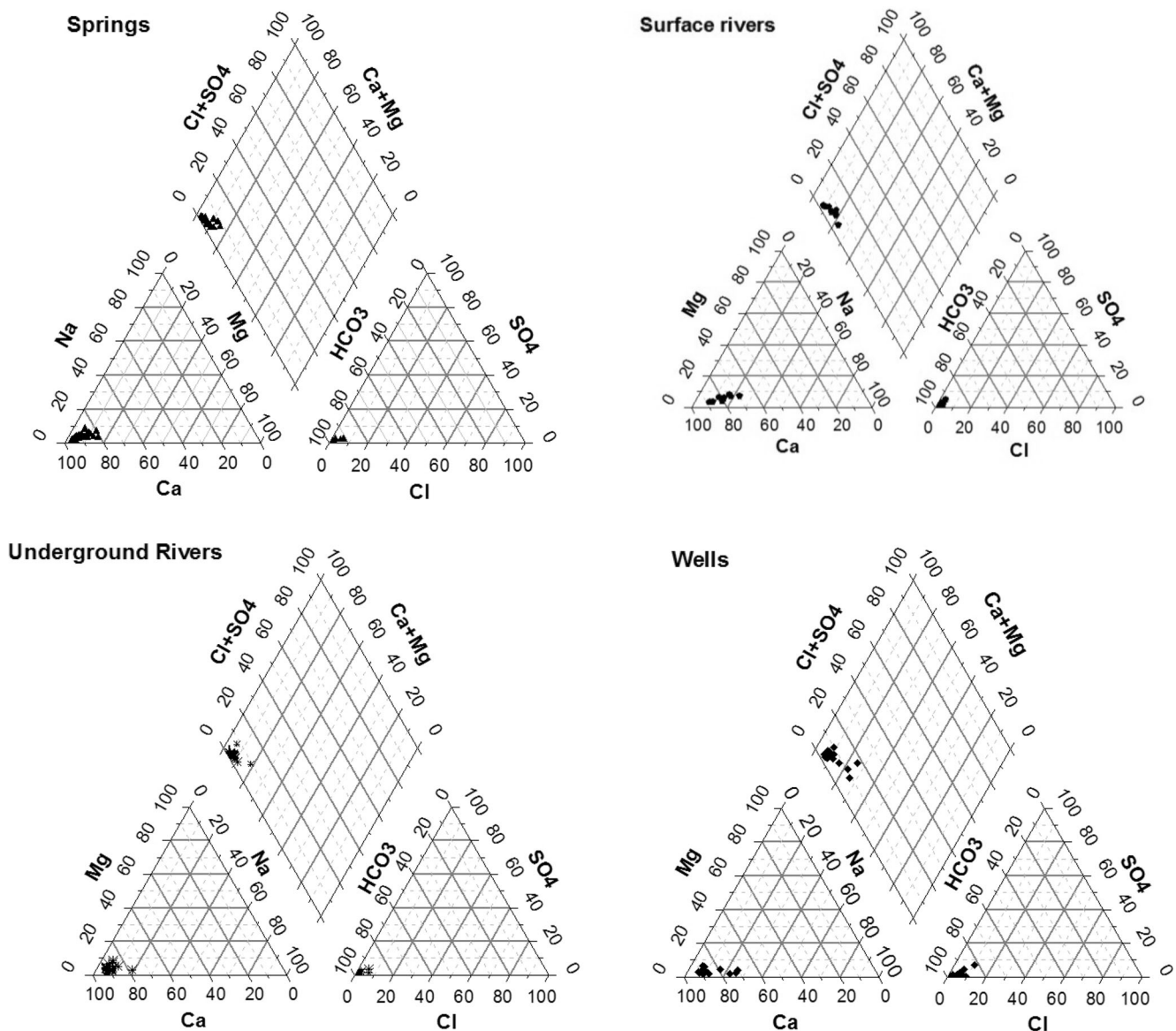
Fig. 2 Piper diagrams of springs, wells, surface and underground rivers including data of all sampling campaigns

regard to major anions and cations some springs (Gedareng, Grogol, Ngreneng) show again a slight to considerable increase in Al and Fe concentration while the others are constant with regard to these cations. In Baron Spring, Al but not the Fe concentration is increasing during rainy season. With exception of Gedareng (2009), Sriti (2010) and Ngreneng (2012) the water is supersaturated or more or less in equilibrium with respect to calcite (Table 1).

Wells

Due to strong karstification no wells are present in the Gunung Sewu. That is why nearly all sampled wells with exception of one well near Baron beach, are located on the Wonosari Plateau, where they are widespread. The amount

of water which is pumped varies considerably between each well. In comparison to the other investigated water resources, well water has the highest mineralization (EC), on average, over all seasons with 568–671 µS/cm. As a consequence, Ca (121–133 mg/L) and HCO_3 concentration (398–414 mg/L) is also highest on average (Table 1). The mineralization as well as the Ca and HCO_3 concentration in Jumbleng and the restaurant well show a dependence on the season with decreasing values during rainy season. In these wells and also in Baijharjo 2012, the Al but not the Fe concentration was increasing with amount of rainfall. Compared to other sources, chloride and/or nitrate concentrations are considerably higher in some wells like in the private well (NO_3 10–21 mg/L, Cl 20–40 mg/L), the restaurant well (Cl 25–42 mg/L) or Bulu (NO_3 16–28 mg/L).

Table 1 Hydrochemistry and calcite saturation index (SI_Cc) of different spring, surface, subsurface river and well water from August 2009 (dry season), February 2010 (rainy season) and March 2012 (extreme rainy season)

	EC (µS/cm)			Ca (mg/L)			HCO_3 (mg/L)			NO_3 (mg/L)			Al (µg/L)			Fe (µg/L)			SI_{Cc}		
	08/09	02/10	03/12	08/09	02/10	03/12	08/09	02/10	03/12	08/09	02/10	03/12	08/09	02/10	03/12	08/09	02/10	03/12	08/09	02/10	03/12
Springs																					
Beton	520	468	472	107	91	91	354	281	311	11	10	7.4	69	51	39	20	16	16	−0.1	−0.1	0.1
Baron	538	532	358	96	103	64	187	329	226	9.8	11	5.8	20	16	96	49	7.0	37	0.0	0.0	0.0
Gedareng	498	415	521	112	108	107	329	323	354		11	8.1	22	155	110	37	47	43	−0.3	0.2	0.3
Grogol	707	618	711	148	123	127	409	366	403	22	51	27	3.7	8.9	232	7	7	19	0.2	0.0	0.3
Mudel	595	588	634	122	125	122	409	390	415	8.8	9.1	8.8	2.5	23	8.9	8.5	12	11	0.1	0.1	0.2
Ngrengeng	490	459	598	104	107	98	336	311	348	9.8	11	8.1	6.1	44	203	7	17	299	0.1	0.0	−1.0
Sumb. Praci.	523	520	637	120	117	124	342	342	421	9.9	16	9.1	19	14	24	6.8	5.7	9.9	0.0	0.1	0.3
Teleng_I	470	435	590	105	95	114	314	299	372	6.6	5.5	8.4	20	36	13	14	14	6.9	0.3	0.0	0.6
Gedong		520	524		104	103		329	354	9.4		6.2	30		16		19	6.8		0.0	0.2
Selonjono		630	625		132	132		390	421	10		7.1	9.1		7.7		3.6	3.8		0.1	0.2
Sriti		308	332		50	58		177	232	4.2		2.8	309		275		85	95		−0.5	0.6
Teleng_II		515	540		98	112		317	354	10		7.7	24		41		8.4	13		0.0	0.1
Surface rivers																					
Betung	343	201	260	55	41	43	238	153	177	3.2	7.0	0.9	82	479	366	46	187	147	0.6	−0.7	0.5
Oyo	410	324	174	74	60	32	250	207	122	3.3	3.9	1.6	12	54	3350	18	28	1305	1.0	−0.4	0.1
Kali Suci down	519	501	107	103	92	18	329	268	73	8.8	7.3	1.8	6.3	23	4396	9.5	7	1761	−0.1	−0.1	−0.1
Kali Suci up	527	465		104	97		348	281		8.5	7.5		4.7	39		10	11		0.1	−0.1	
Underground rivers																					
Bribin	479		518	93	107	102	323	323	348	9.8	13	8.6	31	47	19	16	15	7.3	−0.3	0.0	0.2
Seropan	464		488	84	101	98	311	305	323	11	52	9.8	41	18	38	26	6	21	−0.1	−1.0	0.2
Golek	608	543	485	114	124	95	372	372	317	8.1	10	7.3	9.1	18	220	7.5	12	102	0.0	0.1	0.0
Sodong D.	275	334	79	73	67	15	250	207	43	3.2	8.3	1.9	28	50	3257	14	14	1234	−0.2	−0.4	−2.0
Toto	575	545	591	112	115	119	372	384	390	13	13	15	4.1	7.7	233	4.8	4.1	18	0.2	−0.3	0.2
Ngreneng_main	488	353		93	102		317	317		11	10		5.0	18		5.0	16		0.0	−0.1	
Ngreneng_side	489	489		93	102		275	311		12	11		14	77		9.1	32		0.0	0.0	
Wells																					
Bulu	684	675	626	147	161	127	427	409	397	23	28	16	5.8	10	78	6.1	5.5	8.4	0.3	0.3	0.0
Jumbleng	595	572	589	131	130	114	397	397	390	13	21	12	3.3	27	17	4.4	16	3.2	0.8	0.2	1.1
Restaurant well	701	660	607	144	115	100	421	336	348	11	14	8.7	4.2	98	141	6.2	14	12	0.6	0.0	0.6
Private well	717	606	707	136	120	132	391	384	421	21	10	21	6.0	7.3	6.4	5.0	4.7	4.2	0.2	0.1	0.2
Ngipak	538	348	568	115	109	108	354	530	372	7.6	8.1	8.2	6.6	18	12	5.0	4.7	4.2	−0.1	0.0	0.4
Baron		718	956		159	146		451	537		49	26		37	10		11	13		0.3	0.4
Tirtomulyo	575	564		124	121		397	378		8.1	9.2		5.8	0.6		6.5	1.1		0.0	0.1	
Bejiharjo		403	647		128	122		597	433		6.6	4.6		48	356		24	37		0.2	0.6

Sum. Praci Sumber Pracimantoro, *Sodong D* Sodong Dedapayu

Baron well shows a specific hydrochemistry with highest mineralization (EC 718–956 μS/cm), Ca (146–159 mg/L), Mg (8.4–9.2 mg/L) and especially Na (26–43 mg/L) and K (8.4–9.2 mg/L) concentrations. Furthermore, nitrate (26–49 mg/L) and chloride (26–41 mg/L) concentrations are partially higher compared to the other wells (Table 1; supplementary). Well water is mainly clearly supersaturated with respect to calcite (Table 1).

Time series of discharge, physico-chemical parameters and precipitation

In February 2012, the total monthly precipitation was 356 mm. The base flow of Seropan River was characterized by a base discharge of ~1.2 m^3/s, T of 27.3 °C and EC of 506 μS/cm, respectively. Base flow conditions are disrupted by two major and several smaller events (Fig. 3). After several days with very little rain (<6 mm/day), heavy rainfall was recorded on February 3rd and 4th with 85 and 46 mm/day, respectively. Based on hourly records several distinct rainfall events with up to 23 mm/h can be separated. Rainfall was followed by a major flood called Event_1 as indicated by a step-wise increase in discharge (Fig. 4). Seropan River responds quickly with a first increase in discharge (February 3rd; 20:30 p.m.) ~1.5 h after the rain starts. During Event_1 discharge is more than doubled from 1.2 to 2.8 m^3/s with two major peaks on February 4th (1:00 a.m., 3:10 a.m.) and one minor peak (12:40 p.m.).
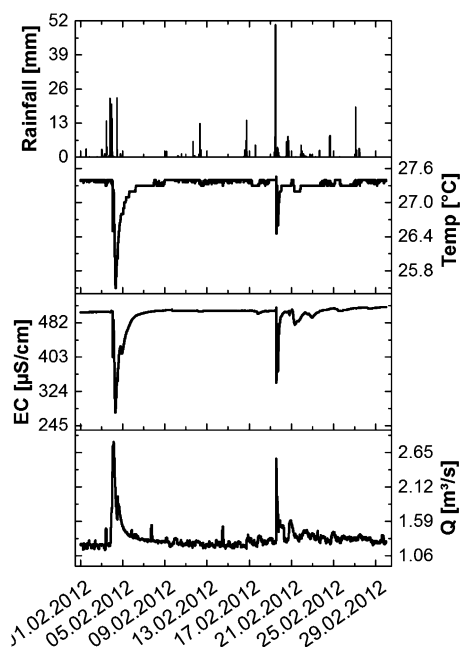
Based on the records of physico-chemical parameters, Event_1 can be separated into four periods (Fig. 4). Period A (till February 4th, 0:30 a.m.) is characterized by several hours of heavy rainfall, the 1st increase in discharge (2.0 m^2/s) but base flow values of T and EC. During period B (till 3:00 a.m.), T and EC dip to 26.4 °C and 395 μS/cm (1:20 a.m.), respectively, and rise again afterwards. Discharge increases to 2.8 m^3/s in two steps without further considerable precipitation (<2 mm/h). Within period C (till 11:00 a.m.), T and EC strongly decrease reaching a minimum of 25.5 °C and 275 μS/cm, respectively, at 7:00 a.m. No further rainfall was recorded leading to a continuous decrease in discharge during period C. At the beginning of period D a short interval of heavy rain (23 mm/h) was recorded which induced a simultaneous small dip in T and EC and a peak in discharge (12:40 p.m.) followed by a slow recession of all parameters. The recovery was disrupted by a small decline of EC only, peaking on 22:00 p.m.. Base flow conditions were reached again on February 7th at 4:00 a.m.
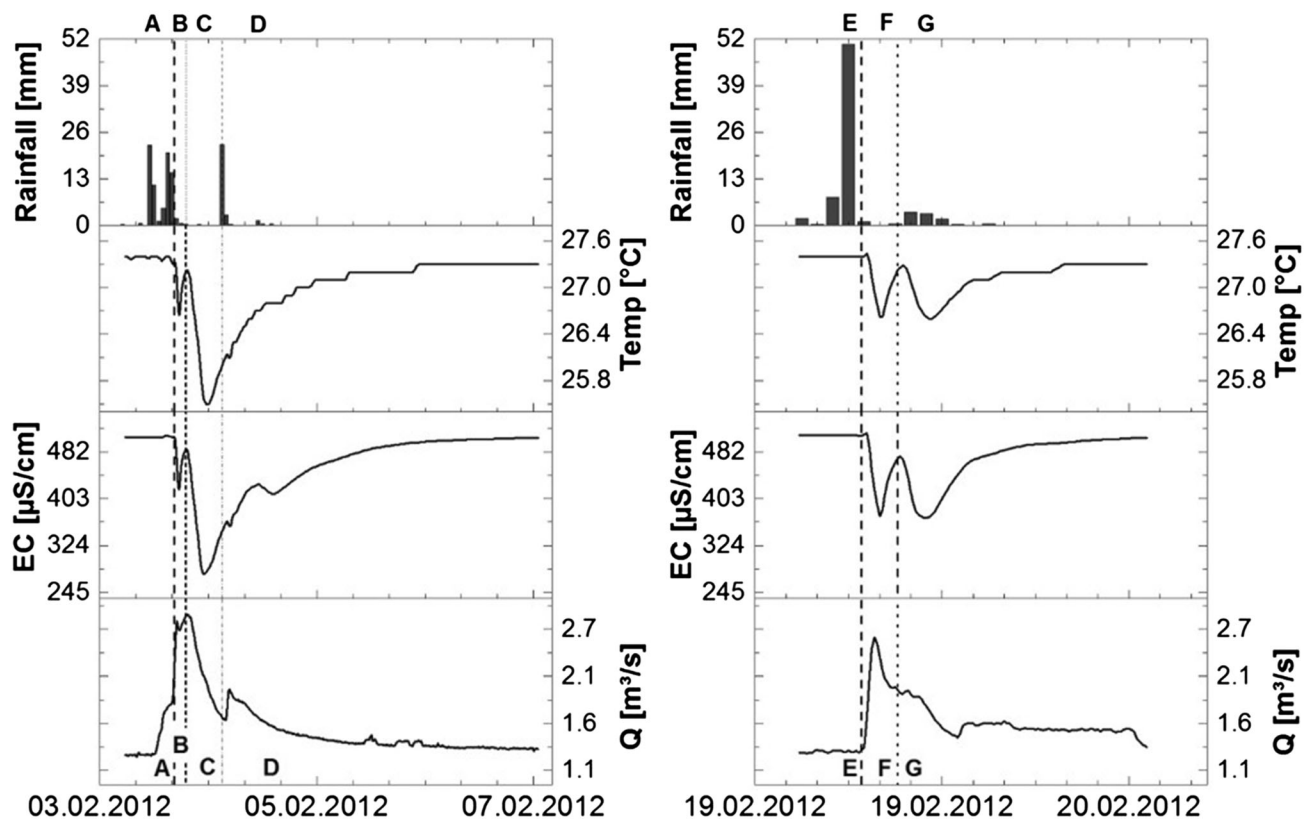
Following a second strong rain event on February 19th (12–1 p.m.) with 51 mm/h, a second major flood occurred (Event_2) (Fig. 4). In this case, the response of Seropan River was extremely quick with only 50 minutes between rainfall and increase in discharge (Period E). Following the rainfall event, all recorded parameters start reacting at the same time (12:50, Period F). Starting at 12:50 p.m., T and EC strongly decrease reaching lowest values of 26.4 °C and 328 μS/cm, respectively, only 1 hour later. The highest discharge was recorded with 2.6 m^3/s at 13:40 p.m., which means only 10 minutes earlier than T and EC. There was no rainfall during period F. In period G, starting at 15:10 p.m., T and EC dip again reaching similar minimum values at 16:50 pm compared to Period F. The continuous decline in discharge was slowed down in Period F. Both flood events were also accompanied by a strong increase in turbidity (visual observation). Event 2 was also characterized by a high water level due to backwater effects.

Discussion

Water quality aspects

Water quality is of great concern when using karst water resources due to rapid infiltration and low retention capacity of karstic aquifers (Ford and Williams, 2007). From 2009 to 2012 the concentrations of almost all investigated inorganic water constituents were well below any WHO advised guideline value (WHO 2011) in Gunung Kidul, indicating, that the usage and consumption of different water sources should be of no concern with regard to inorganic pollutants. Only in three cases (Grogol Spring,

Fig. 3 Time series of discharge (Q), electrical conductivity (EC) and temperature in Seropan River and hourly amount of precipitation in Gombang in February 2012

Fig. 4 Timer series of discharge (*Q*), electrical conductivity (EC), temperature in Seropan and hourly amount of precipitation in Gombang from Event_1 (*left*) and Event_2 (*right*)

Gua Seropan, the Private Well) nitrate concentrations were about equal to the guideline value of 50 mg/L (WHO 2011) in March 2010 (Table 1). Indonesian requirements for drinking water (Regulation of Indonesian Health Minister, No 492/Menkes/Per/IV/10) as well as the German drinking water guideline additionally have a limit for Al of 0.2 mg/L, a value which was exceeded in several of the investigated water resources during flood events in 2012 (Table 1).

In Gunung Kidul, like in many other karstic areas, the consumption of untreated water mainly poses severe health risks due to a strong microbiological contamination (e.g. coliform bacteria, *E-coli*; Matthies et al. 2014). This is not only caused by the local habit of dumping waste directly into karstic structures like swallow holes but also because of insufficient waste water collection and treatment (Fach et al. 2012). Due to the relatively low sample frequency and the typically high hydrochemical variability in karst, it can be assumed that some dissolved constituents, like nutrients from fertilizers or metals from burning of e.g. cans, might occasionally exceed guideline values especially during strong rain events. The possible influence and importance of these processes was indicated in the hydrochemistry of one spring (Grogol) and in some of the

investigated wells (e.g. Bulu, Baron, private and restaurant well). These locations, which are mainly located on the densely populated and agriculturally used Wonosari Plateau, show nitrate and/or chloride concentrations that are higher compared to most other water sources (Table 1).

Matthies et al. (2014) have highlighted that microbiological contamination of groundwater is especially high during rainy season. Our data indicates that this is also valid for inorganic pollutants. During the flood period in March 2012, Al and partly also Fe concentrations dramatically increased compared to dry season hydrochemistry of several water sources. As mentioned above, the Indonesian and German guideline value for Al of 0.2 mg/L is exceeded in many of these cases (DVGW, 2001). For example in Kali Suci, a sinking stream, Al concentrations are 730 times higher compared to the dry season and 20 times the guideline value (Table 1). This increase in Fe and Al concentration is probably caused by very fine (<0.45 μm) soil particles (e.g. clay or Fe minerals) or colloids and do not represent truly dissolved Al and Fe because both elements have a very low solubility in neutral and oxic environments. These ultrafine particles are rather washed in from fields during torrential rains and are so small that they can pass the 0.45 μm filter which was used

in the framework of the sampling protocol. Al and Fe concentrations are particularly high in all investigated rivers but also in many springs, subsurface rivers and to a minor extent also in some well waters. The data indicates that in case of high Al and Fe concentrations a point of quick infiltration of surface water, like a swallow hole, is nearby. In March 2012, for example, a constant stream of water from nearby fields was flowing into Gua Sodong Dedapayu leading to Al and Fe concentrations of 3.3 and 1.2 mg/L, respectively. High Al concentrations are mainly accompanied by high turbidity. Consequently, water will only be used after some kind of treatment which should remove large parts of Al. Even though Al itself is probably of minor concern due to its low solubility, fine particles can also sorb bacteria. Furthermore, several studies have shown that survival of microorganisms is enhanced when associated with particulates (Pommepuy et al. 1992; Palmateer et al. 1993). As a consequence, Al concentration and possible health implications should be further monitored.

Hydrogeological characteristics of Gunung Kidul Karst derived from hydrochemical monitoring

Surface water bodies are typically rare in karstic areas. In Gunung Kidul several perennial rivers are present, most of them, however, have their source in the volcanoclastic rocks of the northern mountain ranges. Still, the hydrochemistry of the rivers gets also clearly influenced by the carbonate bedrock during passage, which is indicated by the dominance of Ca and HCO_3 and their relatively high concentration (Ca 43–104 mg/L, HCO_3 153–348 mg/L), also leading to a supersaturation versus calcite during some of the sampling campaigns (Table 1; Fig. 2). A strong variation in hydrochemistry between the different seasons highlights the close connection between precipitation and river water chemistry. Especially during strong rain events, a considerable amount of water is washed in from nearby fields and villages carrying along soil constituents, pesticides, fertilizers, rubbish etc. As discussed above Al and Fe concentrations, which are particularly high in surface rivers during strong rainy seasons like in 2012 (Table 1, Al 0.36–4.4 mg/L, Fe 0.15–1.8 mg/L), are probably indicative of severe water input from the surrounding fields. This is of special interest because, through sinking streams like Kali Suci, these potentially hazardous components are also introduced into deeper karst feeding subsurface water resources like cave rivers, springs or wells.

Our study indicates that most well waters are mainly recharged by matrix flow which results from diffuse infiltration. The resulting long residence time buffers, on the one hand, the hydrochemistry so that most element concentrations only vary little between the different sampling periods. On the other hand, it allows equilibration with the calcite aquifer material leading to a slight oversaturation of well water versus calcite during all seasons (Table 1). As a consequence, well water also has by far the highest mineralization, on average, expressed by EC (Table 1). However, some wells (Bulu, restaurant well) also seem to be partly recharged by a quicker component during rainy season which is shown by clearly elevated Al concentrations (factor 13–33) compared to dry season hydrochemistry.

Underground rivers have an up to 30 % lower mineralization (EC), on average, compared to wells indicating a shorter residence time and/or a higher proportion of quickly infiltrating water especially after precipitation events. This explains the slightly lower Ca and HCO_3 concentration in most of the investigated underground rivers during the pronounced rainy season in 2012 in contrast to the dry season hydrochemistry. Enhanced Al and Fe concentrations in some subsurface rivers (Golek, Toto, Sodong Dedapayu) are probably the result of substantial surface water input (Table 1). In Sodong Dedapayu, a strong runoff from the fields was visually observable during sampling which also caused a considerable decline of most element concentrations due to dilution, and negative calcite saturation. In Toto River, however, all other parameters apart from Al and Fe remain similar compared to dry season. As a consequence, not dilution by infiltrating water but rather resuspension of previously deposited intrakarstic sediment is probably the dominating process causing the Al and Fe increase.

The mineralization of spring water (EC) is ~15 % lower than well water but ~15 % higher than subsurface river water, on average. This intermediate hydrochemistry can be explained by the fact that springs are typically the outlet of sometimes extended subsurface karst systems. As a consequence varying proportions of slow matrix flow like in the wells and quick conduit flow like in underground rivers are mixed together. The relatively high concentrations of Ca (mainly >100 mg/L) and HCO_3 (mainly >300 mg/L) throughout all seasons in addition to the fact that spring water is mainly supersaturated with regard to calcite (Table 1; Fig. 2) points towards a high contribution of a slowly flowing matrix component. Additionally, springs often have much larger catchment areas compared to most underground rivers. These two aspects explain why variations in hydrochemistry caused by rapid infiltration of rain or surface water are much smaller compared to cave rivers. This conclusion is supported by the lower maximum Al and Fe concentrations (Table 1) as indicator of quick surface water intrusion in most of the springs compared to subsurface rivers.

This, however, is not true for Baron Spring, the largest spring in Gunung Kidul, which shows the highest hydrochemical variations. After particularly strong rain events

(2012), the Ca concentration is nearly only half of that in normal rainy seasons. The Al and Fe concentrations, however, are five times higher during flood periods (Table 1). In this case, pulses of surface water intrusion are not compensated before reaching Baron. This could be due to a high proportion of water with a low residence time or considerable point infiltration at a site nearby. Enhanced Fe and Al concentrations are also present in some of the other springs (Gedareng, Grogol, Ngreneng) during the extreme rainy season in February 2012. In some cases (Gedareng, Grogol), resuspension of previously deposited fine material due to increased discharge is most likely the cause of these higher Al and Fe concentrations because of the supersaturation versus calcite and Ca/HCO_3 concentrations in the same range like dry (e.g. 2009) or normal rainy seasons (e.g. 2010).

Behaviour of the Seropan karst system derived from high resolution T, EC and discharge monitoring

Discontinuous measurements of hydrochemical parameters give important hints about the hydrological regime and the hydrochemistry in general, but are not sufficient to fully characterize various important aspects of the hydrogeology like residence time, type of flow and recharge etc. These parameters, however, are important for developing a sustainable concept for water extraction, distribution and treatment (Plummer et al. 1998; Birk et al. 2004; Katz 2004). As a consequence, T and EC in addition to discharge were monitored over a period of 1 month in Seropan River. This time series analysis allows determining basic hydrogeological characteristics. Additionally it is possible to delineate different types of water that make up the total discharge in Seropan. In this case it is assumed that each water mass has a distinct hydrochemical characteristic that results from different ways of recharge and storage (Fournier et al. 2007).

Seropan is a perennial river with an all-season discharge of $Q \geq 0.5$ m³/s despite the extended dry season without effective rainwater infiltration. The base flow in Seropan in February 2012 is characterized by an EC of 506 μS/cm which is about equal to the EC during dry season (data not shown). Because EC in karst systems is mainly controlled by the calcium-carbonate equilibrium (Fournier et al. 2007; Perrin et al. 2007), the constant and about 20 times higher EC compared to precipitation (20–30 μS/cm) indicates that base flow is continuously recharged by a water mass with sufficient long residence time in the limestone that allows equilibration with calcite (Hess and White 1988). This assumption is supported by a SI_{Cc} of around 0 in Seropan River water during dry season 2009 and the weak rainy season in 2010 (Table 1). This storage component is

characterized by a slow and diffusive matrix flow and recharged itself through diffusive surface water infiltration via epikarst or the vadose zone. Recharge to Seropan River from this storage component dominates during low water periods and is responsible for the year-round water flow also during dry season. Similar conditions of karst aquifers in low water periods were described for the Sierra de las Nieves aquifer in southern Spain by Baena et al. (2009).

During rainy season like in February 2012, however, discharge, T and EC in Seropan rapidly respond to strong and/or persistent rainfall events as shown by their considerable variation (Fig. 3). This indicates that Seropan River is connected to a highly karstified conduit system with fast conduit flow and short transit time of water (Birk et al. 2004; Moore et al. 2009; Mudarra et al. 2014). Furthermore, these large variations suggest point recharge in close distance (Moore et al. 2009). In this regard, especially the decrease in EC is reported to be a good indicator of surface water arrival (Massei et al. 2003; Birk et al. 2004). Nevertheless, not all rainfall events are rapidly transmitted to Seropan which is illustrated during the time period from February 12th to 18th (Fig. 3). Single rainfall events of up to 14 mm/h do not necessarily lead to significant variations in discharge and physico-chemical parameters in Seropan River. This, once again, goes in line with the existence of a large storage component in the Seropan system. Here, infiltrating water is slowed down and retained to a certain extent until a hydraulic saturation is reached. The observation of slow and rapid flow components in Seropan highlights that karst systems typically modulate incoming signals from rain events in different ways (Mudarra et al. 2014).

The investigation of heavy rainfall events allows a more detailed characterization of flow and storage behaviour of the Seropan system. During Period A (Fig. 4), discharge responds within 1.5 h to the first considerable rainfall illustrating again the quick response and close connection of the Seropan system to surface water intrusion. Temperature and EC are still characterized by their base flow values in Period A which shows that discharge responds quicker to the recharge event than the physico-chemical properties a phenomena which was reported by other studies (Ryan and Meiman 1996; Birk et al. 2004; Mudarra et al. 2014). The decoupling can be explained by the fact that the increase in hydraulic pressure due to heavy rainfall is almost instantaneously transmitted to the conduits. The induced increase in water heads first pushes "old" mineralized water stored in the matrix or poorly connected voids to the conduits. This so called piston flow (Ford and Williams 1989) is a typical feature of karst aquifers and was reported from several other studies (e.g. Hess and White 1988; Birk et al. 2004; Genthon et al. 2005; Massei et al. 2007; Perrin et al. 2007; Baena et al. 2009). The physico-

chemical properties change only after the actual recharge water consisting of "new" surface water arrives at the observation site in Gua Seropan during Period B. According to Birk et al. (2004) the lag time between the hydraulic and physico-chemical response, in this case 4.5 h (Period A/B), corresponds to the travel time of the infiltrating water through the conduit system.

The two strong dips in physico-chemical parameters (Period B/C, Fig. 4) stand for the actual arrival of infiltrated surface water which leads to a dilution of the base flow (e.g. Massei et al. 2003; Fournier et al. 2007; Barberá and Andreo 2012). Due to the rapid flow, the thermodynamic equilibrium with respect to calcite is not reached which explains the low EC during floods (Perrin et al. 2007). The relatively small and distinct peaks are indicative of concentrated infiltration close to Seropan. Travel time is not sufficient to allow a considerable mixing with the base flow so that the initial physico-chemical characteristics of the infiltrating water are still dominant. In Period B and C one distinct, nearly Gaussian shaped drop in T and EC is present. According to Massei et al. (2007) this can be interpreted as two different, chemically homogeneous masses of water that reach Seropan consecutively. Thus, Period B and C can be interpreted as two pulses of surface water infiltrating (1) at the same spot but at different times (Birk et al. 2004) or through different flow routes (Massei et al. 2007), (2) at different locations with different distance to Seropan or (3) as arrival times of water from different tributaries entering the main conduit (Hess and White 1988). The fact that two major rainfall events are followed by two major phases with increasing discharge in A and B points towards two pulses that infiltrate at the same spot. The higher discharge (Period B) and lower T and EC (Period C) of the second compared to the first pulse, is not related to a higher amount of precipitation recorded in Gombang. This, however, would rather point towards infiltration at two different sites.

Period D is preceded by a 1 h rain event (23 mm/h) which triggers a concurrent small increase in discharge and dip in T and EC with a time lag of only 1 h 40 min. The much quicker response time compared to Period B and C indicates that the system was already hydraulically saturated after ongoing rainfall so that no further water can be retained as matrix component. The lack of piston flow shows that voids and matrix pores that are accessible to infiltrating water have not been recharged with highly mineralized matrix water since Period A which points towards a similar infiltration location. 8 h after the rain event a sole dip of EC is visible in Period D (Fig. 4). The broad peak and concurrent lack of reactions of the other parameters suggest that another distinct pulse of water infiltrating in larger distance to Seropan arrives at the observation point. The longer travel time leads to a higher

degree of mixing which levels out differences between base flow and recharge hydrochemistry. Due to the smaller maximum drop in T of only 1.8 °C, differences between recharge and base flow are smoothed out much quicker so that only a dip in EC is maintained. The slow recovery of all recorded parameters, illustrated by the positive skewness of the peaks, indicates that the mixing ratio is consecutively changing towards a dominance of matrix flow. This is probably caused by temporary storage of infiltrated water in the epikarst, in small pools or matrix porosity followed by a slow and delayed release (Birk et al. 2004; Moore et al. 2009; Barberá and Andreo 2012).

Like in Period D, discharge, T and EC simultaneously respond to a very strong rainfall event of 51 mm/h during Event_2 (Fig. 4). Likewise, there seems to be no significant contribution from matrix flow in contrast to Period A. However, a very small increase in T and EC just before the major dip indicates that at least a small amount of highly mineralized water is pushed out from the matrix. Due to the intense rainfall, pores can be emptied that were not accessible during Event_1. The much shorter response time of all parameters compared to Event_1 is probably due to the higher rain intensity which increases flow velocity. Period G is again characterized by a strong dip of the physico-chemical parameters, however, without further rain event and no peak in discharge. This might be explained by a strong infiltration as reaction on a rain event in greater distance that was not recorded in Gombong. This assumption can be supported by the broader peak form compared to Period F which results from the longer travel time of water. Another possible explanation might be that more water enters Seropan that can drain again, leading to a backwater effect; a phenomenon which was visually observed in March 2012. As a consequence, the distinct water mass from Period F would be pushed back and recorded again without considerable mixing with the base flow.

The less strong maximum dip of T and EC in Event_2 compared to Event_1 highlights that apart from the rain intensity also the total amount of precipitation, which was more than twice as high during Episode_1, seems to be of importance in controlling the hydrogeology of Seropan Cave. This goes in line with Barberá and Andreo (2012) which showed in their study that higher volumes of infiltrating rain water will lead to greater dilution indicated by lower EC. Furthermore, it can be concluded that flow velocity in Seropan River highly depends on the rain intensity whereas the amount of infiltrating water is rather controlled by the total amount of rain. Our observations go in line with other studies (e.g. Mudarra et al. 2014) showing that type and amount of recharge is strongly influenced by the amount and intensity of rainfall, the type of karst forms and the previous hydrological situation.

Implications of flow characteristics for water usage

The regional hydrogeological characterization of Gunung Kidul has shown that during dry season all water resources are suitable for drinking water exploitation that is followed by an adapted treatment which mainly has to focus on microbiological contamination. The high variability in discharge, groundwater composition and turbidity (as indicated by Al/Fe concentrations) during rainy season, however, will represent a significant challenge for technical groundwater exploitation and treatment. Based on our study, spring and well water seems to be most suitable for the installation of groundwater extraction facilities because of the relatively constant hydrochemistry and low turbidity compared to surface and subsurface rivers. However, a successful installation of wells and boreholes in highly karstified aquifers is challenging and might fail due to subsurface heterogeneity. In Gunung Kidul, this will only be possible on a large scale basis on the Wonosari Plateau, where wells are already widespread. Springs in Gunung Kidul are not evenly distributed. To assure short distances between groundwater exploitation and treatment on the one side, and consumers on the other side, also subsurface rivers will have to be considered for groundwater extraction despite the sometimes extremely high hydrochemical and hydrological variations. In this case, the hydrogeological characteristics of the respective water source, especially during extreme events, have to be determined in advance.

In this context, monitoring of Seropan River can serve as an example. The results have both positive as well as negative implications with regard to a potential water exploitation. The high and constant mineralization of the base flow indicates a large proportion of matrix flow and hence, a long residence time of infiltrating water in the karst. Consequently, the retention capacity will be relatively high so that a considerable proportion of contaminants can be retained leading to a relatively clean base flow which can easily be treated especially with regard to microbial load. Furthermore, this high proportion of matrix flow assures sufficient water for constant exploitation also during dry season. During rainy season; however, frequent and rapid infiltration of surface water without considerable retention processes is a dominant feature. This results, on the one hand, in strong discharge variations which will be a challenge especially for hydropower driven water pumping systems (e.g. in terms of varying operating conditions and concerning a proper protection against flood-induced damages, Nestmann et al. 2015). Pulses of surface water also significantly increase the turbidity of water which might enhance wear and tear of pumps and turbines. Strong variations in groundwater chemistry and turbidity also severely complicate water treatment processes. Because of the often relatively short duration of extreme events in Seropan River, followed by return to base flow conditions (Figs. 3, 4), the installation of an alert system, which shortly interrupts water pumping for the time of flooding, has to be considered. Such an alert system might be coupled to an EC probe because our monitoring in Seropan River has proven that EC is a good indicator of surface water intrusion. Probes for electrical conductivity are easy to install and relatively robust.

Conclusions

To summarize it can be said that the hydrochemistry of all water sources in Gunung Kidul is strongly impacted by the equilibration with the carbonate rocks. During dry season all subsurface water sources are clearly dominated by matrix flow as indicated by the relatively high mineralization. Heavy rainfall during rainy season leads to a substantial input of surface water into the subsurface karst system which is accompanied by an increase in turbidity and a deterioration of water quality in many cave rivers and some springs. During these events technical groundwater exploitation and optimal water treatment will be challenging so that short time interruptions during floods would be advisable.

Based on the hydrogeological investigations in Seropan it is possible to distinguish three major types of flow which are related to a certain way of recharge. Throughout the whole year Seropan River is clearly dominated by the recharge from slow matrix flow indicating the existence of a large active storage component. The indicated large volume of this component is highly important for water management in Gunung Kidul, because it secures the perennial water flow of Seropan River and probably also of other underground rivers as indicated by the regional characterization. The relatively long residence time of matrix flow improves the retention of contaminants and, thus, the water quality at least during dry season when base flow is the sole flow component. During the rainy season strong rain events induce point recharge from surface water through fast conduit flow. In the case of Seropan River, concentrated infiltration occurs in close distance probably from more than one preferential infiltration site. As a consequence, the degree of mixing between surface water and base flow is very low. Considerable retention of particles or contaminants is, thus, not expectable leading to a poor water quality at least for some time during heavy rainfall events. This is of particular concern because water is currently pumped directly from the sump that is dammed by the artificial weir. Piston flow, as special case of matrix flow, is indicated to be the third important flow component and is preferentially induced by strong rainfall events.

References

Adji TN (2012) Wet season hydrochemistry of Bribin Cave in Gunung Sewu Karst, Indonesia. Environ Earth Sci 67:1563–1572

Baena CL, Andreo B, Mudry J, Carrasco Canots F (2009) Groundwater temperature and electrical conductivity as tools to characterize flow patterns in carbonate aquifers: the Sierra de las Nieves karst aquifer, southern Spain. Hydrogeol J 17:843–853

Barberá JA, Andreo B (2012) Functioning of a karst aquifer from S Spain under highly variable climate conditions, deduced from hydrochemical records. Environ Earth Sci 65:2337–2349

Birk S, Liedl R, Sauter M (2004) Identification of localized recharge and conduit flow by combined analysis of hydraulic and physicochemical spring responses (Urenbrunnen, SW-Germany). J Hydrol 286:179–193

Brunsch, A., Adji, T.N., Stoffel, D., Ikhwan, M., Oberle, P. and Nestmann, F. (2011): Hydrological assessment of a karst area in southern Java with respect to climate phenomena. In: Asian Trans-Discip Karst Conf Yogyak Indones, pp 55–68

Fach S, Kaiser M, Fuchs S (2012) Development and evaluation of appropriate concepts for sewage disposal and treatment in a rural area, central Java, Indonesia on the example of the village pucanganom. Hydrol Curr Res S 1:002. doi:10.4172/2157-7587.S1-002

Flathe H, Pfeiffer D (1965) Grundzüge der Morphologie, Geologie und Hydrogeologie im Karstgebiet Gunung Sewu/Java (Indonesien). Geol Jahrb 83:533–562

Ford DC, Williams PW (1989) Karst geomorphology and hydrology, 1st edn. Unwin Hyman, London

Ford DC, Williams PW (2007) Karst hydrology and geomorphology, 2nd edn. Whiley, Chichester

Fournier M, Massei N, Bakalowicz M, Dupont J-P (2007) Use of univariate clustering to identify transport modalities in karst aquifers. C R Geosci 339:622–631

Genthon P, Bataille A, Fromant A, D'Hulst D, Bourges F (2005) Temperature as a marker for karstic waters hydrodynamics. Inferences from 1 year recording at La Peyrére cave (Ariège, France). J Hydrol 311:157–171

Golscheider N, Drew D (2007) Methods in karst hydrogeology. Taylor and Francis, London

Haryono E, Day M (2004) Landform differentiation within the Gunung Kidul Kegelkarst, Java, Indonesia. J Cave Karst Stud 66:62–69

Hess JW, White WB (1988) Storm response of the karstic carbonate aquifer of south central Kentucky. J Hydrol 99:235–252

Katz BG (2004) Sources of nitrate contamination and age of water in large karstic springs of Florida. Environ Geol 26:689–706

KEMENNEG PDT: State Ministry for Development of Disadvantaged Regions (2005) Decree of the Minister 001/KEP/M-PDT/I/2005. National development strategic for disadvantaged regions

Lehmann H (1936) Morphologische Studien auf Java: geographische Abhandlungen. Series 3:1–114

Massei N, Wang HQ, Dupont J-P, Rodet J, Laignel B (2003) Assessment of direct transfer and resuspension of particles during turbid flood s at a karstic spring. J Hydrol 275:109–121

Massei N, Mahler BJ, Bakalowicz M, Fournier M, Dupont J-P (2007) Quantitative interpretation of specific conductance frequency distributions in karst. Gr Water 45:288–293

Matthies K, Mendes de Oliveira M, Obst U (2014) Field laboratory for an appropriate water treatment in a tropical karst region. Water Pract Technol 9:483–490

McConnell J., Hacke CM (1993) Hydrogeology, water quality, and water resources development potential of the Upper Floridan aquifer in the Valdosta area, south-central Georgia. US Geological Survey Water-Research Investigations Report 93-4044

Moore PJ, Martin JB, Screaton EJ (2009) Geochemical and statistical evidence of recharge, mixing, and controls on spring discharge in an eogenetic karst aquifer. J Hydrol 376:443–455

Mudarra M, Andreo B, Marín AI, Vadillo I, Barberá JA (2014) Combined use of natural and artificial tracers to determine the hydrogeological functioning of a karst aquifer: the Villanueva del Rosario system (Andalusia, southern Spain). Hydrogeol J 22:1027–1039

Nestmann F, Oberle P, Ikhwan M, Lux T, Scholz U (2009) Bewirtschaftung unterirdischer Fließgewässer in Karstgebieten—Pilotstudie auf Java, Indonesien. WasserWirtschaft 7–8:12–18

Nestmann F., Oberle P., Ikhwan M. and Stoffel D. (2010) Adaptive water resources management under extreme climatic and hydrogeological conditions: interdisciplinary research activities in Karst Regios of South East Asia. In: Proceedings of the IWRM Karlsruhe 2010, Karlsruhe, pp 300–307

Nestmann F, Oberle P, Ikhwan M, Stoffel D (2016) Development of an Innovative underground waterconveying plant in a Karst Region of Indonesia: Concept, Implementation, Operation and Optimization.Appl W Sci (this issue).

OHCHR—UN Office of the High Commissioner for Human Rights (2010) Fact sheet no. 35—The right to water. http://www.refworld.org/docid/4ca45fed2.html. Accessed 16 March 2015

Palmateer G, MacLean D, Kutas W, Meissner S (1993) Investigations of suspended particulate/bacterial interaction in agricultural drains. In: Rao SS (ed) Particulate matter and aquatic contaminants, chap 1: 1–40

Perrin J, Jeannin PY, Cornaton F (2007) The role of tributary mixing in chemical variations at a karst spring, Milandre. Switzerland. J. Hydrol. 332:158–173

Pfeffer K-H (2009) Wassermangel—ein globales Problem in Karstlandschaften. WasserWirtschaft 7–8:19–23

Plummer LN, Busenberg E, McConell JB, Denkard S, Schlosser P, Michel RL (1998) Flow of river water into a Karstic limestone aquifer: 1. Tracing young fraction in groundwater mixtures in the Upper Floridan aquifer near Valdosta Georgia. Appl Geochem 13:995–1015

Pommepuy M, Guillaud J, Derrien A, Le Guyader F, Cormier F (1992) Enteric bacteria survival factors. Water Sci Technol 25:93–103

Ryan M, Meiman J (1996) An examination of short-term variations in water quality at a karst spring in Kentucky. Gr Water 34:23–30

Uhlig H (1980) Man and tropical karst in Southeast Asia. GeoJournal 4(1):31–44

UN General Assembly (2010) The human right to water and sanitation: resolution A/RES/64/292 (adopted by the General Assembly, 3 August 2010). http://www.refworld.org/docid/4cc926b02.html. Accessed 16 March 2015

UNESCO (2009) The united nations world water development report 3: water in a changing world. integrated water resources management in action. dialogue paper. http://unesdoc.unesco.org/images/0018/001818/181891E.pdf. Accessed 16 March 2015

van Bemmelen RW (1949) The geology of Indonesia. In: Chapter 5—geological evolution of the physiographic units—Java Vol IA. Government Printing Office, The Hague, pp 554–559

Waltham AC, Smart PL, Friederich H, Eavis AJ, Atkinson TC (1983) The caves of Gunung Sewu, Java. Cave Sci 10:55–96

White WB (2002) Karst hydrology: recent developments and open questions. Eng Geol 65:85–105

World Health Organisation (WHO) (2011) Guidelines for drinking-water quality, 4th edn. WHO, Geneva

Worthington SRH, Ford DC, Cavies GJ (2000) Matrix, fracture and channel components of storage and flow in a Paleozoic limestone aquifer. In: Sasowsky ID, Wicks CM (eds) Groundwater flow and contaminant transport in carbonate aquifers. A.A. Balkema, Rotterdam, pp 13–128