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Deep groundwater flow as the main pathway for chemical outputs in a small headwater watershed (Mule Hole, South India)

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ABSTRACT

This study examined the water and chemical cycles of a small forested head catchment. Application of chloride mass balance lead to the identification of a groundwater baseflow located into the active zone of the crystalline aquifer, below the weir. These findings indicate that groundwater contributes to a large part of chemical outputs at the catchment scale. This study shows that groundwater should not be ignored in most small watershed studies because this flow path and associated solutes are strongly significant for chemical balance assessment.

Keywords: weathering rate, chloride mass balance, groundwater flow, silicate rock, geochemical cycle

1. INTRODUCTION

Mineral weathering rates in small catchments are commonly assessed from a mass balance between solute inputs and outputs (Paces 1983; White and Brantley, 1995). Most of these studies consider that the subsurface flow is negligible and that water flows out the basin mainly as surface runoff. Therefore, it is assumed that the measurements of the discharge rate and elements concentration in surface runoff at the watershed outlet weir are sufficient to estimate the total output fluxes of elements.

The output flux due to inter-basin groundwater flow corresponds to water loss from the watershed via groundwater flow below the weir and therefore not measured at the outlet. This component of the water balance is usually poorly defined (Nichols and Verry, 2001) or even “frequently ignored altogether in catchment studies in the quiet hope that it is, in fact, zero” (Penman, 1963).

This assumption means that the limits of the hydrogeological basin correspond to those of the topographic drainage watershed, neglecting inter-basin groundwater flows. In most cases, especially in large watersheds (>100 km^2), this assumption is correct as an average. Cross-boundary inflows and outflows statistically nullify each other. For small head catchments, this assumption is not always true. As stated in a recent special volume of *Ground Water* journal on the issue of small head watersheds: “Researchers studying small watersheds need to be aware that ground water flow divides do not underlie surface divides in

many settings" (Winter et al., 2003). Moreover, ground water divides may move in response to dynamic recharge and discharge conditions.

In this paper, an extended hydrogeological analysis is performed on one small watershed located on a fractured crystalline aquifer in tropical conditions. Chloride mass balance method is implemented in order to compute groundwater flows and fluxes. In particular, we focused on the contribution of groundwater fluxes to the mass balance of weathering indicators and compared it to surface fluxes.

2. FIELD SETTINGS

The Mule Hole experimental watershed (4.1 km^2) is located in the Western Ghâts, in South India (Figure 1) at 11° 44' N and 76° 27' E (Karnataka state, Chamrajnagar district). The study site is located in the climatic semi-humid transition area with recurrent but non-periodic droughts, depending on monsoon rainfalls. The substratum belongs to the Precambrian Dharwar supergroup and consists of gneiss with amphibolites and quartz dykes. The elevation of the watershed ranges from 820 to 910 m ASL. The relief is mostly undulating with gentle slopes. It is covered by a dry deciduous forest (Barbiero et al., 2010; Barbiero et al., 2007). The thickness of the immature regolith explored by coupling geophysical, geochemical and mineralogical investigations is, on average, 17 m at the watershed scale, including 15 m of saprolite and 2 meters of soils (Braun et al., 2009).Thirteen observation wells (named P1 - P13) were drilled in the area in 2003-2004. Rainfall and runoff have been measured and sampled at a meteorological station located at Mule Hole checkpost and at the outlet (Figure 1). The stream is highly ephemeral (approximately 40 days of flow per year) with very fast recession periods and flows only in response to heavy rainfall events.

3. RESULTS

The measurements done in the observation wells indicate that the water table is 8 to 40 m deep. This is due to the high rate of evapotranspiration in this forested area (Maréchal et al., 2009). As a result, recharge rate is very low. The water table is located below the river bed during the whole year and is disconnected from the stream. The stream loses water recharging the aquifer (indirect recharge), and is similar to previous work on disconnected losing streams (Peterson and Wilson, 1988).

Recharge results from direct recharge through the regolith (Ruiz et al., 2010) and indirect recharge from the stream (Descloitres et al., 2008). The groundwater flows towards the southwest, with a baseflow identified below the weir into the saprolite and fractured shallow aquifer (Descloitres et al., 2008). The total recharge of the aquifer has been estimated using the chloride mass balance technique (Maréchal et al., 2009). Given that the water table is disconnected and there is no long-term water level fluctuation, we assume that the groundwater baseflow is equal to the natural recharge. Then, the chemical groundwater output can be determined at each observation well by multiplying element concentrations by recharge rate (Table 1). We compared these values to surface water chemical output calculated while multiplying discharge rate by element concentrations at the outlet.

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	Well	Cl GW (mmol/l)	Recharge (mm/yr)	Chemical output (mol/hectare/year)				
				Na	**K**	**Ca**	**Mg**	**SiO2**
Groundwater	P11	98	250	748	267	1798	1334	695
	P1	114	215	613	152	1195	913	1364
	P7	138	178	1367	232	2141	2357	603
	P13	164	150	1032	173	1111	957	1108
	P12	202	122	813	116	1103	803	666
	P8	303	81	942	82	1716	843	317
	P10	477	52	857	31	181	140	437
	P2	533	46	799	229	520	716	178
	P6	450	55	727	132	572	981	333
	P5	528	47	582	100	726	482	351
	P3	913	27	400	119	259	442	252
	Average			**807**	**148**	**1029**	**906**	**573**
Surface water	Outlet		Runoff = 80 mm/yr	**30**	**79**	**74**	**52**	**109**

Table 1: mass balance of the Mule Hole watershed.

The results show the high variability of chemical groundwater outputs according to wells located on various groundwater flow paths. As an average, the chemical groundwater output is much higher than the chemical output through surface runoff at the outlet: export by groundwater accounts for more than 95 % of sodium, 93% of calcium, 95% of magnesium, 84% of silica. The potassium is the only tracer for which the surface export is significant, approximately 35 % of the total output.

4. DISCUSSION

A recent study on 32 small watersheds shows that the average flow of groundwater out of the watershed is 45 % of streamflow (Verry, 2003). Sometimes, this flow can be due to specific geological conditions like the existence of faults or a sedimentary basin structure. However, it can also appear in a flat crystalline aquifer where flows predominantly occur in a shallow higher-permeability zone - “active” zone - that overlies a deeper lower permeability zone hosting little flow - “inactive” zone (Maréchal, 2010). Figure 2 shows where the groundwater flow is constituted by a hierarchical pattern of flow systems within the active zone: local, intermediate, and regional according to Toth theory (Toth, 1963). Groundwater flows from recharge areas, which are associated with high groundwater levels, to discharge areas, which are associated with low groundwater levels. A local flow system develops between a topographic high (recharge area) and an adjacent topographic low (discharge area). An intermediate flow system consists of several topographic lows intervening between recharge and discharge areas. A regional flow system has its recharge area at the highest part of the groundwater basin and its discharge area at the lowest part of the basin.

The study of the mass balance of a small drainage watershed located at the head of the system (Figure 2b) necessitates to consider an extra flux corresponding to the output flux by groundwater flow $Q_{i,gw}$. Even if the flow velocities in local flow systems are often much faster

than the flow velocity in a regional system, the flux of elements, which is highly dependent on the concentration in groundwater, may be non-negligible.

The scale effect of the problem is illustrated at Figure 2. Larger basins are statistically less subject to inter-basin groundwater flows, which generally occur in small head catchments. Therefore, groundwater should not be ignored in most small watershed studies because groundwater flow and associated solutes are significant to many of the local physical, chemical and biological processes (Rosenberry, 2003).

In such a case, the mass balance used to determine the chemical weathering fluxes for a species i must be corrected to:

$$Q_{i,w} = Q_{i,r} + Q_{i,gw} - Q_{i,p} - Q_{i,d} \mp Q_{i,b} \mp Q_{i,e}$$

Where $Q_{i,r}$ = runoff flux
$Q_{i,w}$ = net chemical weathering flux from bedrock, saprolite and soil layers
$Q_{i,p}$ = input flux due to atmospheric wet deposition
$Q_{i,d}$ = input flux due to atmospheric dry deposition
$Q_{i,b}$ = source/sink flux due to biomass activity
$Q_{i,e}$ = source/sink flux due to exchange by sorption/desorption in weathering profiles
$Q_{i,gw}$ = output flux due to inter-basin groundwater flow

This study has strong implications for modeling watershed scale processes - eg (Violette et al., 2010).

5. CONCLUSION

The study demonstrates that forest cover has impacted the water cycle and associated solute balances of this crystalline watershed. The high rate of evapotranspiration induces low recharge rate to the aquifer. Consequently, the water table is deep and disconnected from the stream. It results in deep groundwater flows below the weir which contributes for more than 90 % of the total chemical outputs, and for less than 10 % through surface runoff. The conclusion is that groundwater should not be ignored in most small watershed studies because groundwater flow and associated solutes are significant, if not dominant.

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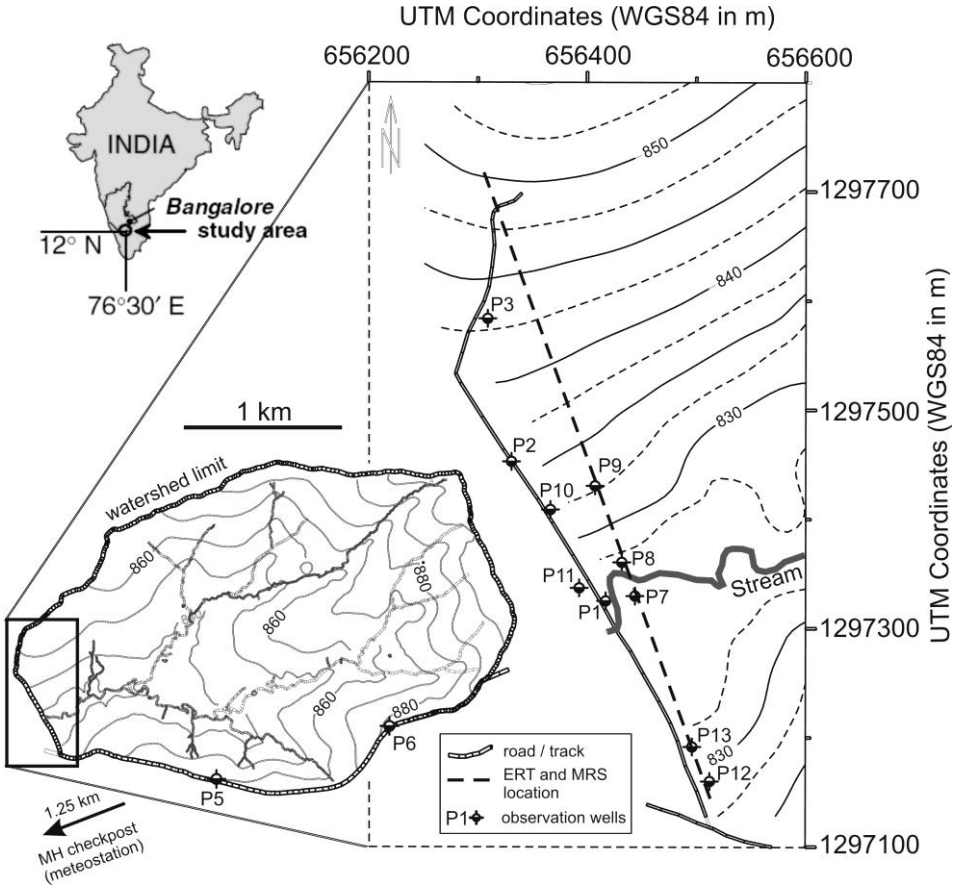

Figure 1: location map of the experimental site at the outlet of the Mule Hole watershed.

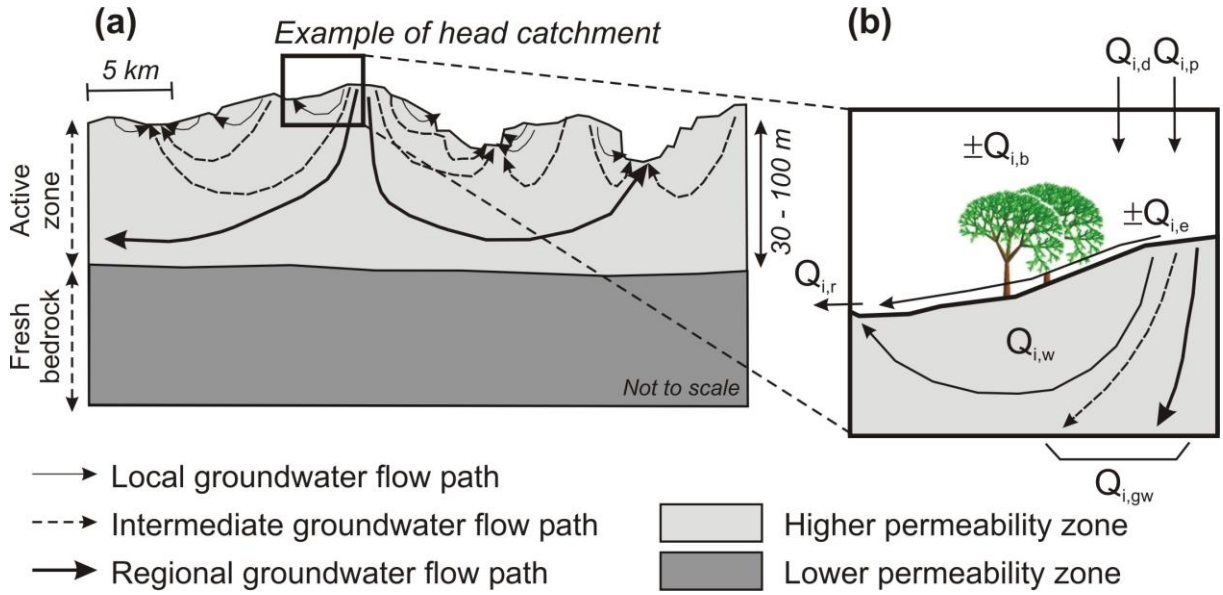

Figure 2: (a) Crystalline aquifer system showing flow paths associated with local, intermediate, and regional flow systems (modified from Toth, 1963). (b) Major fluxes of element i; symbols refer to the mass balance equation.