Tracer Tests at Birohe Water Catchment, Gitega

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Project: Burundi - Management and Protection of Groundwater Resources

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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe</td>
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<tr>
<td>Δh</td>
<td>Groundwater level difference between the injection point and the spring in m</td>
</tr>
<tr>
<td>d°mm'ss.ss''</td>
<td>Degrees, minutes, seconds (geographic coordinates)</td>
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<tr>
<td>EC</td>
<td>Electrical conductivity (µS/cm)</td>
</tr>
<tr>
<td>IGEBU</td>
<td>Institute de Géographie du Burundi</td>
</tr>
<tr>
<td>I</td>
<td>Hydraulic gradient</td>
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<tr>
<td>K</td>
<td>Hydraulic conductivity in m/s</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>l</td>
<td>Liter</td>
</tr>
<tr>
<td>Lat</td>
<td>Geographic latitude (d°mm'ss.ss'')</td>
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<td>Lon</td>
<td>Geographic longitude (d°mm'ss.ss'')</td>
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<tr>
<td>m amsl</td>
<td>Meter above mean sea level</td>
</tr>
<tr>
<td>NaCl</td>
<td>Sodium chloride (common salt)</td>
</tr>
<tr>
<td>nₑ</td>
<td>Effective porosity (-)</td>
</tr>
<tr>
<td>t</td>
<td>Flow time in h</td>
</tr>
<tr>
<td>v</td>
<td>Flow velocity in m/h</td>
</tr>
<tr>
<td>x</td>
<td>Distance between the injection point and the spring in m</td>
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</table>
Summary

Authors: Dr.-Ing. Sara Vassolo, Torsten Krekeler
Title: Tracer Tests at Birohe Water Catchment, Gitega

Keywords: Hydrogeology, Burundi, water protection zones, tracer test

In April 2013 two tracer tests were conducted in the Birohe water catchment in Gitega, Burundi. Aim of the tests was to determine the average flow velocity of the groundwater. The results play a major role in the delineation of water protection zones.

Common salt was used as tracer material. The results showed an average groundwater flow velocity in the range of 1.8 m/h to 2 m/h, due to the very steep gradient. The estimated hydraulic conductivity varies from 1.5E-4 m/s to 2.5E-4 m/s.
Overview

One of the goals of the “Management and Protection of Groundwater” project is the delineation of protection zones for wells and springs that provide water to the villages. Water supply is managed by REGIDESO.

To start with, the protection zone for the springs located in the Birohe catchment had to be defined. The area is characterized by the presence of numerous springs. The REGIDESO captures water from the largest 10 springs. The volume of water provided by these springs represents some 10% to 15% of the total volume supplied to Gitega.

To comply with the definition of a protection zone for the Birohe water catchment, the BGR together with the partner IGEHU and a colleague from REGIDESO performed two tracer tests (Fig. 1). The aim of these tests was the evaluation of the flow velocity and indirectly the estimation of the hydraulic conductivity of the aquifer. The tracer tests were performed using common salt (NaCl) as tracer material.

Fig. 1 Map showing the Birohe water catchment
Characteristics of the catchment

The Birohe water catchment is located to the SW of Gitega. It is a small horseshoe-shaped catchment in a NW/SE direction within a hilly environment with an average slope of 18% (Fig. 2). Precipitation in the area is very high with a long-term annual mean average of 1,197 mm for the time period 1979-2009 and a long-term mean daily temperature of 21°C for the time period 1985-2012.

Fig. 2 Birohe valley view to N/E

Geologically, the catchment is mainly composed of jointed quartzite intercalated by schist layers and covered by loose colluvium. The lower part of the catchment is covered by lateritic clay deposits, a weathering product of the schist.

A cross section along the length axis of the catchment is presented as Fig. 3. It shows that in the SE the ground surface falls from 1702 m above mean sea level (amsl) to 1670 m amsl (32 m) over a distance of 40 m. Further, the clay layers at the bottom of the valley act as flow barriers and trigger the springs.
Objective of the tracer tests

The tracer tests were performed to determine the groundwater flow velocity. This parameter is of great importance for the delineation of protection zones, which is the final aim of the exercise.

Common salt (NaCl) was used as tracer material. This election was adopted to avoid the long process needed to obtain the permission for using dye tracers. A concentration of 200 g/l was chosen to ensure that the water at the spring would always be suitable for human consumption, even if all water injected would flow out of one of the springs. Along the underground passage, the high concentrated tracer water is diluted by the very low conductive background groundwater (about 29 µS/cm) leading to concentrations of Na and Cl at the spring that are far below the maximum concentrations of the WHO guidelines (200 mg/l and 250 mg/l, respectively).
First Test

Before the tracer was injected, it was necessary to determine the relationship between the electrical conductivity and the amount of salt tracer in the solution (Fig. 4). For this calibration, first small amounts of salt were dissolved in the water from the spring, where the tracer was expected to flow out, followed by the measurement of the corresponding electrical conductivity. The obtained relationship results in:

\[ C_{\text{NaCl}} \text{ (mg/l)} = 0.5363 \times \text{E.C. (µS/cm)} - 14.621 \]

The first test was started on the 16th April at 3 PM. For this test a hole (IP25) was specially excavated to be able to inject the tracer material in the underground without passage of the unsaturated zone (Fig. 5). Groundwater was found at a depth of 1.7 m. Before tracer injection, groundwater was removed from the hole to enhance infiltration of the tracer.
The tracer material was prepared dissolving 40 kg of NaCl in 200 l of water. The recovery of the tracer was monitored with WTW Multimeters 340i and 3430 and attached EC probes. They were installed in chamber 105 (Fig. 6) that receives water from two separated branches, one concerning spring C25 and another collecting water from C26 and C119 together.
The only spring where tracer outflow was detected was spring C25 (Fig. 1; Fig. 6). From springs C26 and C119 no tracer material was recovered during the first test. The first indication of tracer was detected 4 hours after injection, which seems to be very fast. This high flow velocity is due either to the very steep slope of the area (average of 18%) or to a very high hydraulic conductivity. The maximum concentration was obtained 28 hours after injection (Fig. 7).

A total of 56% of the tracer mass was recovered from spring C25 (Fig. 7) until the monitoring was stopped on the 24th April after eight days of measurement. According to SSH (2002), the amount of mass recovered can be classified as high recovery.

![Spring C25 Concentration of NaCl Tracer and Relative Recovery](image)

**Second Test**

For the second test, a mass of 300 kg of NaCl dissolved in 1,500 l of water was injected into the dug hole “IP2” that was excavated for this purpose within an abandoned quarry (Fig. 1). Here, it was not possible to reach the groundwater table due to the hardness of the underground (Fig. 8) and tracer was injected in the unsaturated zone at a depth of 1 m instead.

The test was started on the 24th of April at 10:00 AM. Unfortunately, it is not possible to access the outflows of springs C26 and C119 separately. Measurements were performed in chamber 105 that collects water from spring C25 through one pipe and springs C26 and C119 through another pipe (Fig. 6). Tracer was mainly recovered from these two last springs, but also some tracer material was found in spring C25 (Fig. 1).
The first indication of tracer at springs C26 + C119 was detected about 5.5 hours after injection. The flow velocity seems to be very fast, probably due either to the steep slope of the area (average 18%) and/or to an extremely high hydraulic conductivity. The maximum concentration was measured after 30 hours (Fig. 9).

The last measurement taken on the 28th of May showed a mass recovery of 14%. According to SSH (2202), an average recovery has been obtained. Mass recovery from C25 is very low and cannot be differentiated between the first and second test.
As already mentioned, spring C25 reacts slightly to the injection in IP2. This is indicated by a slight increase of the electrical conductivity measured in the outflow of the spring after the start of the second test (blue curve in Fig. 10).

The green line in Fig. 10 shows the recording of an EC meter installed in chamber 123 that collects water from springs C25, C26, C119, C121 and C122 (Fig. 6). As it is a collector, it is unclear, if the electrical conductivity peaks are caused by tracer material from springs C26 and C119 or if the other springs also account for some reaction. Because the green curve shows maxima and minima at the same time as the black curve for springs C26 and C119, it is likely that it only shows salt tracer from springs C26 and C119 diluted by water from C121 and C122 and an extremely small amount of salt tracer from spring C25.

![Fig. 10 Comparison of electrical conductivity values measured in outflow of springs C26 and C199 (black curve), C25 (blue curve) and collector 123 (green curve). A slight increase of the electrical conductivity was measured in spring C25 and collector 123 after the commencement of the second test](image)

**General results**

The coordinates and elevations for the injection points and the springs where tracer was recovered are presented in following Table 1.

<table>
<thead>
<tr>
<th>Point</th>
<th>Lat</th>
<th>Long</th>
<th>Elevation (m amsl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP25</td>
<td>3°25'50.72&quot;S</td>
<td>29°56'47.94&quot;E</td>
<td>1675.87</td>
</tr>
<tr>
<td>IP2</td>
<td>3°25'50.02&quot;S</td>
<td>29°56'46.54&quot;E</td>
<td>1687.24</td>
</tr>
<tr>
<td>C25</td>
<td>3°25'50.25&quot;S</td>
<td>29°56'49.06&quot;E</td>
<td>1667.38</td>
</tr>
<tr>
<td>C26</td>
<td>3°25'47.85&quot;S</td>
<td>29°56'47.78&quot;E</td>
<td>1668.22</td>
</tr>
<tr>
<td>C119</td>
<td>3°25'47.64&quot;S</td>
<td>29°56'48.19&quot;E</td>
<td>1665.85</td>
</tr>
</tbody>
</table>
When compared with daily precipitation measured at the airport in Gitega, it is evident that electrical conductivity curves rapidly respond to large precipitation events (Fig. 11). A first peak is seen in the curve corresponding to the spring C25 (blue curve) after the precipitation event from 23rd April with 15 mm. Later, all curves respond clearly to the large precipitation event from 28th April with 35.4 mm. The curves corresponding to the springs C26 + C119 (black curve) and 123 (green curve) show a large and rapid peak, while C25 responds with a delay of about half a day. Again, C26 + C199 respond rapidly to the event from 6th May with 6.7 mm and C25 with half a day delay.

The apparent lack of response of the curve for C25 to the rain events of 20th and 21st April could be the effect of local rainfall that did not reach the Birohe catchment area. Precipitation data belong to the Gitega airport station, which is located some 4 km to the WNW from the test site.

Spring discharges increase rather slowly after large precipitation events and do not reflect the changes of electrical conductivity. Further, tracer material was not rinsed with fresh water after injection. Therefore, it can be concluded that the increases in electrical conductivity after large precipitation events are caused by a renewed flushing of tracer salt that remained adhered to the aquifer material or in low-flow pores.

**Test evaluation**

The main goal of a tracer tests is the evaluation of the flow velocity. This can be calculated taking into account that \( v = \frac{x}{t} \)

with:

- \( v \): average flow velocity (m/h)
- \( x \): distance between injection point and spring (m)
- \( t \): flow time of the tracer (h)
The concentration curve measured in the spring allows for the estimation of flow velocities as follows:

- **Maximal effective flow velocity** for the shortest time needed by the tracer material to arrive at the spring
- **Peak effective flow velocity** for the time at which the peak is measured
- **Average effective flow velocity** for the average flow time. This time is calculated as the time for which the peak concentration has been reduced to 2/3 (SSH, 2002):

The corresponding breakthrough, peak and average flow times were calculated from the respective concentration graphs (Fig. 12). The results for the flow velocities are summarized in Table 2.

### Table 2 Summary of velocities calculated from the measured concentration curves

<table>
<thead>
<tr>
<th></th>
<th>First Test (C25)</th>
<th>Second Test (C26 + C119)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance injection-spring (m)</td>
<td>39</td>
<td>88</td>
</tr>
<tr>
<td>(T_{\text{breakthrough}}) (h)</td>
<td>4.00</td>
<td>5.50</td>
</tr>
<tr>
<td>(T_{\text{peak}}) (h)</td>
<td>28.33</td>
<td>30.48</td>
</tr>
<tr>
<td>(T_{\text{average}}) (h)</td>
<td>40.33</td>
<td>42.98</td>
</tr>
<tr>
<td>(V_{\text{breakthrough}}) (m/h)</td>
<td>9.64</td>
<td>16.02</td>
</tr>
<tr>
<td>(V_{\text{peak}}) (m/h)</td>
<td>1.36</td>
<td>2.89</td>
</tr>
<tr>
<td>(V_{\text{average}}) (m/h)</td>
<td>0.96</td>
<td>2.05</td>
</tr>
</tbody>
</table>

The average flow velocity of the second test appears to be double of the one calculated for the first test. Because the aquifer in both cases appears to be similar, it can be concluded that this difference is the result of a steeper slope of the flow path.

According to OFEG (2003), a heterogeneous aquifer composed of good interconnected fractures with high permeability is characterized by

- Flow times that do not increase significantly with distance to the injection
- High flow velocities of tenths or hundreds of meters per day
- The isochrones at the limits of the catchment shows flow times lower than 10 days
- A high mass recovery and curves showing a short peak of tracer

The tracer tests performed in the Birohe catchment show all these characteristics. Therefore, it can be concluded that the aquifer is heterogeneous and composed of good interconnected fractures with high permeability.
Due to the high interconnection of fractures, the aquifer can be represented by a porous media and the hydraulic conductivity can be estimated by means of the Darcy law with the calculated average flow velocities, as follows:

\[ K = \frac{\nu_{AV} \cdot n_e}{l} \]
with:
\( v_{av} \): average effective flow velocity (m/s)
\( n_e \): effective porosity (-), which has been estimated at 0.1 due to the jointed quartzite covered by loose colluviums (Castany, 1988)
\( I \): Hydraulic gradient (-)

The hydraulic gradient can be calculated from the first test as:

\[
I = \frac{\Delta h}{x}
\]

for which:
\( x \): Distance between injection and spring (m)
\( \Delta h \): difference in groundwater level height between the injection point and the spring (m)

Due to the fact that groundwater was only found in the first injection point (IP25), the hydraulic gradient can only be estimated for this test.

- The distance between the injection point (IP25) and the spring (C25) was measured at 39 m (Table 2)
- Assuming that the groundwater level at the spring coincides with the surface height at C25, it should be 1667.38 m amsl (Table 1)
- The groundwater level at the injection point can be calculated subtracting 1.7 m (groundwater depth) to the surface height, which means 1675.87 m amsl – 1.7 m = 1674.17 m amsl. The difference in groundwater height is \( \Delta h = 1674.17 – 1667.38 = 6.79 \) m.

Thus, the hydraulic gradient would result in:

\[
I = \frac{6.79}{38.56} = 0.176 \text{ or } 17.6\
\%
\]

Therefore, for the first injection test, the hydraulic conductivity results in:

\[
K = \frac{0.96 \cdot 0.1}{0.176} = 0.55 \frac{m}{h} = 1.5E - 4 \text{ m/s}
\]

In the second test, tracer material was injected in the unsaturated zone because groundwater was not reached during digging. Therefore, the hydraulic conductivity cannot be estimated directly as in the first test. However, the largest possible gradient for this test can be estimated considering the bottom of the dug hole (1 m from the surface) as the height of groundwater. This largest possible gradient leads to the smallest possible hydraulic conductivity.

- Distance from the injection point (IP2) to the spring (C26 + C119) was measured at 88 m (see Table 2)
- The difference in height can be calculated as the different in altitudes between that of the bottom of the injection dug hole and that of the spring C119. The bottom of IP2 can be calculated by subtracting 1 m from the altitude of the injection point of 1687.24, which means 1686.24 m amsl (Table 1). The altitude of the spring C119 was measured at 1665.85 m amsl. Therefore \( \Delta h = 20.39 \) m.

Thus, the largest possible gradient would result in:
And the lowest hydraulic conductivity for the second test is calculated as:

\[ K = \frac{2.05 \cdot 0.1}{0.232} \times \frac{m}{h} = 2.5E - 4 \, m/s \]

Both hydraulic conductivities are normal for jointed quartzite covered by loose colluviums, as it is found in the vicinities of the springs. Therefore, it can be concluded that the fast response of the tests is due to the extremely steep slope of the area (18% in average).

**Summary and conclusions**

Two tracer tests were performed in the Birohe water catchment aimed to determine the average flow velocity.

The results can be summarized as follows:

- The first test shows a high recovery of tracer material (56%), while an average recovery was obtained in the second test (14%)
- Both conductivity curves react to precipitation events. This is due to a flushing of tracer material adhered to the soil material by rain water
- The average effective flow velocities are calculated to 0.96 m/h for the first test and 2.05 m/h for the second. The difference is due to a steeper slope of the flow path in the second test that leads to a more rapid flow
- Assuming an effective porosity of 0.1, the hydraulic conductivity of the jointed quartzite covered by colluvium can be estimated between 1.5E-4 m/s and 2.5E-4 m/s, which are typical for that kind of media
- The apparent rapid response of the tracer test (first indication of tracer recovery after 4 h for the first test and after 5.5 h for the second) is due to the steep slope of the area

The results of the tests show high average effective groundwater flow velocities as the result of steep gradients. These velocities can be used for the estimation of the area that should be protected if groundwater of good quality is to be provided.

**References**


