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ORIGINAL ARTICLE

Identifying potential groundwater contamination by mining influenced water (MIW) using flow measurements in a sub-catchment of the "Cradle of Humankind" UNESCO World Heritage Site, South Africa

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Abstract
To assess the potential risk of Mining Influenced Water (MIW) contaminating the "Cradle of Humankind" UNESCO World Heritage site ("Fossil Hominid Sites of South Africa"), flow measurements were conducted in the Tweelopiespruit, a stream influenced by treated mine water from abandoned gold mines in the Witwatersrand gold fields (South Africa). A possible negative influence of the caves by MIW infiltrating into the dolostone aquifer was investigated by conducting flow measurements at different stream locations between June 2014 and February 2019 using the salt dilution method via sudden injection ('gulp method'). Both logging approaches, the manual method using a multi-meter and the automatic device using probes connected to a data-logger, show reasonable and comparable results in the turbulent flow regime. The general flow increases along the course of the Tweelopiespruit rivulet and only minor localized discharge losses can be observed. An immediate danger for the caves of the "Fossil Hominid Sites of South Africa" from infiltrating polluted mine water cannot be postulated, though smaller amounts of the stream water seem to infiltrate into the dolomitic aquifer.

Keywords UNESCO World Heritage Site · Flow measurement · Discharge · Salt dilution method · Tracer · AMD · MIW · Mine water · Witwatersrand · South Africa

Introduction

Identifying the infiltration of mining influenced water (MIW) into aquifers is important in areas where groundwater is used as a drinking water resource or where stream loss into the subsurface is critical for other reasons. Besides protecting drinking water resources, it might also be necessary to protect archaeological sites or heritage sites that are connected to water-bearing aquifers. One of the world's most prominent archaeological sites are the Sterkfontein caves in South Africa, where paleoanthropological investigations identified hundreds of hominid bones and skull remnants (Stratford 2018).

In this area, there has consequently been a growing research interest in the mine water discharging from the Western Pool of the abandoned Witwatersrand gold fields, South Africa, during the past decade (Coetzee et al. 2013; Durand 2012; Mashishi et al. 2022; Tlowana et al. 2013; Turton 2015; van Wyk et al. 2013). This is predominantly due to the hypothesis that MIW might negatively affect the integrity of the caves in the "Cradle of Humankind" UNESCO World Heritage site (Bradley et al. 2010; Durand et al. 2010; Hobbs and Mills 2012; Leonard and Langton 2016), the correct name in the World Heritage list being "Fossil Hominid Sites of South Africa". Geologically, all the caves are situated within the 1200 m thick Malmani Subgroup of the Transvaal Supergroup, which has been studied and mapped substantially during gold exploitation. This carbonate subgroup is composed of dolostone, limestone, chert and shale as well as breccias (Eriksson

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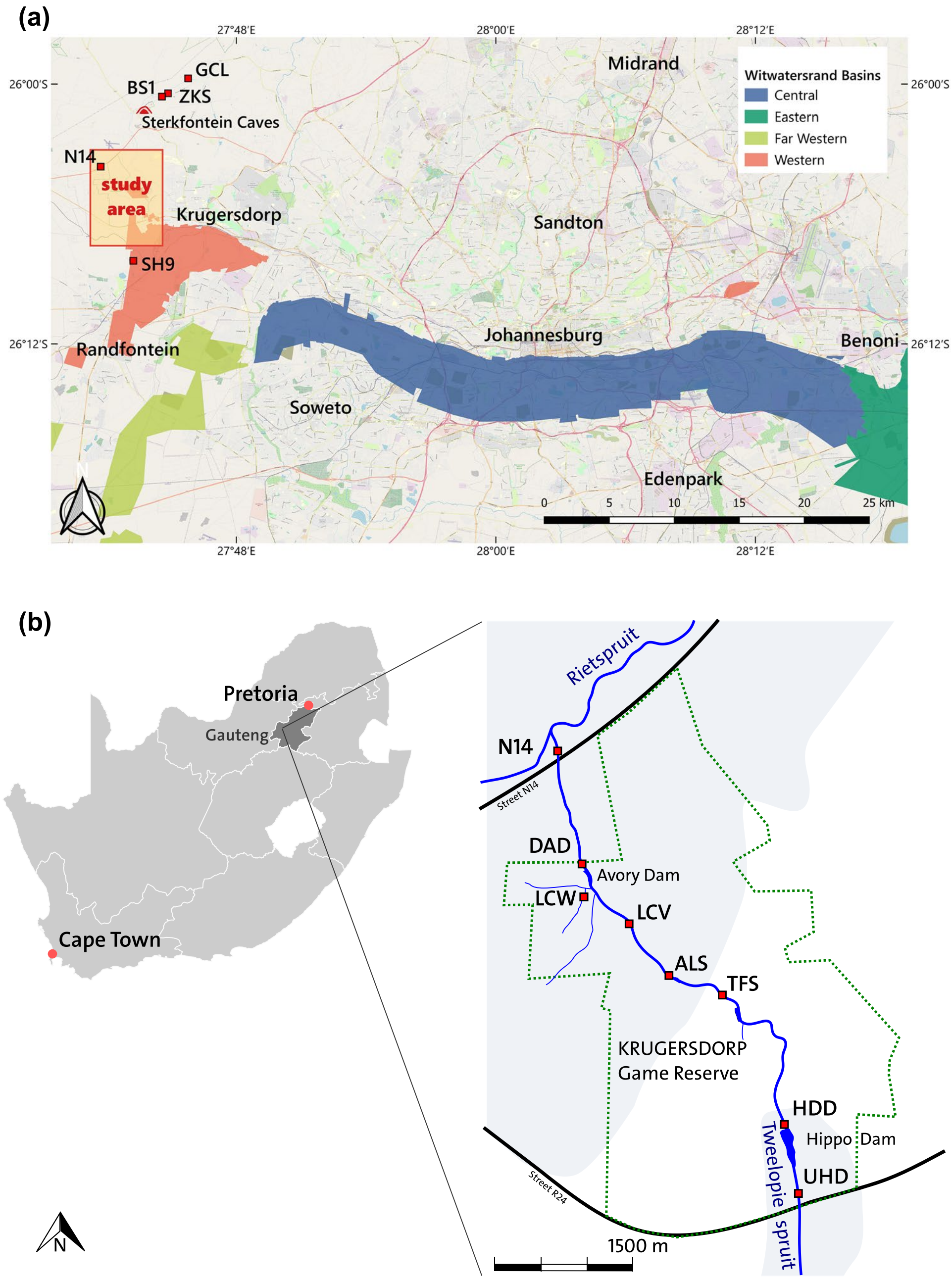

Fig. 1 Location map of the study area depicting the southern part of the UNESCO World Heritage Site and the Witwatersrand gold fields. Eight sampling sites (squares) at the Tweelopiespruit within and in the surroundings of the Krugersdorp Game Reserve and four additional sites used for exemplifying the chemical data outside the closer study area. Simplified outcrops of the Malmani Subgroup dolostones are shaded in grayish blue

and Altermann 1998) and shows characteristic weathering features as well as a typical dolomitic groundwater chemistry (Hobbs and de Meillon 2017; Vegter 1996; Vegter and Foster 1992). Hydrogeologically, the investigation area lies within the dolomitic aquifer of the Zwartkrans Compartment. Within the reach of the World Heritage site, there are numerous fossil caves with more than 500 *Australopithecus* finds (including "Mrs. Ples" and "Little Foot"). This makes these caves prominent *Australopithecus* sites that have an outstanding scientific importance (Martini et al. 2003; Stratford 2015, 2018). Therefore, it is imperative to protect these caves under all circumstances.

After flooding some of the abandoned Witwatersrand gold mines, the first acid mine drainage (AMD) discharges took place in late August 2002 (Coetzee et al. 2003). Subsequent calculations by Coetzee (2011) indicated that daily average mine water discharge rates in the area are about 27.5×10^3 m^3, of which 10.4 m^3/min are treated by the Rand Uranium treatment plant (Kolver 2013), now called Sibanye Gold Water Project. The Tweelopiespruit, a small stream that flows from south to north across outcrops of dolomitic aquifers (Fig. 1), is predominantly recharged by treated mine water (Table 1) and, consequently, is highly influenced by this source (Hobbs and Cobbing 2007).

Table 1 Average chemical composition of treated mine water discharged into the Tweelopiesspruit for the years, in which flow was measured

Year	n	pH, –	Fe, mg/L	Mn, mg/L	SO_4, mg/L	EC, µS/cm	Acidity, mg/L $CaCO_3$	Alkalinity, mg/L $CaCO_3$	Turbidity, NTU
2014	181–221	7.6	0.6	4.5	n.a	3920	33.7	32.7	3.6
2016	77–265	8.5	0.1	2.9	2335	3560	10.0	41.0	9.6
2017	239–243	9.0	0.1	1.9	2161	3120	10.0	47.0	9.5
2019	144–150	8.8	0.3	1.1	2690	3730	10.0	49.5	7.7

Data provided by DWS and CGS

n.a. not analysed

Table 2 Selected physico-chemical and chemical data of MIW (No. 19 shaft: SH9), the Tweelopiesspruit (N14), Bloubankspruit (BS1), dolomite aquifer spring (ZKS) and Grobler's Cave (GCL)

Parameter	SH9	N14	BS1	ZKS	GCL
pH, –	5.96	4.70	7.46	7.34	7.14
Temp, °C	20.4	22.1	22.0	21.6	20.4
TDS, mg/L	4128	2976	1032	1308	366
EC, µS/cm	3780	3010	1310	1420	605
O_2, %	25.6	94.3	73.2	61.8	83.5
HCO_3, mg/L	151	< 5	166	185	205
SO_4, mg/L	2591	2043	408	560	105
Ca, mg/L	529	808	128	159	54
Fe, mg/L	276	0.1	0.1	< 0.03	< 0.03

Sampling dates 2019-01-28/30, locations in Fig. 1a

TDS total dissolved solids (gravimetrically, 180 °C), *EC* electrical conductivity

There is a concern that the stream water partly infiltrates into the dolomitic aquifer while it flows over its outcrops in the Krugersdorp Game Reserve and negatively affects the "Cradle of Humankind" area. Previous studies in the catchment focused mainly on the pH values, temperatures, the chemical composition of the stream water (Holland and Witthüser 2009) and the general hydrogeological conditions before the discharge occurred (Vegter and Foster 1992). Very low pH values and oxygen concentrations, as well as elevated water temperatures (conditions that are characteristic of AMD) were initially described in the upper part of the Tweelopiesspruit (Digby Wells & Associates (Pty) Ltd. Co 2012). However, since that time, oxygen saturation increased and pH conditions have improved to circumneutral values but can decrease to acid conditions resulting from hydrolysis of iron, especially when the mine water treatment plant is not operating as scheduled. The chemical analysis of karst water in the Sterkfontein cave and springs south of the Bloubankspruit (ZKS in Table 2) have shown increasing concentrations of calcium and sulfate in the water compared to the compartment north of the river (GCL in Table 2), therefore, raising concerns that the caves might be irrevocably damaged by the mine water.

Between 2005 and 2006, Krige (2006) measured flows in the Zwartkrans Compartment, thereunder at eight locations along the Tweelopiesspruit. At ten additional locations along the river, he could not measure the flow, and two were dry at the time of his visits. He writes that the "… flow in the streams had to be gauged in the streams using whatever methods were available to us" (Krige 2006), mainly by bucket and stopwatch and floating devices. While the use of a bucket and stopwatch usually can be considered very accurate, the floating device method only works when correction coefficients for velocity differences at different stream depths are considered (see section "Measurement comparison").

In February and April 2010, Hobbs et al. (2011) conducted mechanical impeller flow measurements with the cross-section flow method and cross-sectional pipe section method (in broader terms: area-velocity methods) to identify stream losses. This method works best under laminar flow conditions (Science Applications International Corporation 2001; U. S. Department of the Interior—Bureau of Reclamation 2001). However, the Tweelopiesspruit is a turbulent stream and, therefore, more suitable and accurate methods of measuring the discharge, such as the salt dilution method, are necessary to reliably evaluate water gains or losses. This method uses a water-soluble conservative tracer substance, which is injected into the water course, dilutes evenly with the water, flows at its velocity and measures the tracer's time dependent concentration until the tracer reaches background concentration (Day 1976; Gees 1990; I.S.O.—International Organization for Standardization 1992; Kite 1993). As the tracer is evenly dispersed on its course along the mixing distance within the stream, a relationship between the flow and the integrated mass concentration of the tracer can be established. Especially in turbulent conditions, the salt dilution method is the method of choice for flow measurements, but heavily vegetated stream sections should be avoided due to possible retention (Moore 2003). Though Allen and Taylor (1923) concluded in one of the earliest investigations of this method that "in a few years, its simplicity and accuracy will make it an accepted standard method of water measurement", it is not widely known as an *accurate* flow measurement method.

The aim of this study was to investigate potential stream losses of the Tweelopiespruit surface water into the subsurface and dolomitic aquifer. Because the receiving water courses Rietspruit and Bloubankspruit have elevations below the caves' water levels, gauging in them was omitted for this study. Other than mine drainage, the Tweelopiespruit does not receive substantial discharges from additional pollution sources since there is not much agriculture along the rivulet, and the Game Reserve was closed most of the time in the past years. This study also aims to quantify potential groundwater infiltration of the contaminated water at eight flow measurement sites at various times of the year and for a longer period between 2005 and 2019, thereunder five new measurements with the salt dilution method. In addition, the paper shows the advantages of the salt dilution method under certain conditions.

Methods

Location, geological and hydrogeological settings

The Tweelopiespruit flows west of Krugersdorp over a distance of approximately 10 km, and is located 30 km WNW of Johannesburg, South Africa. Originating at Robinson Lake, it eventually flows from south to north through the Krugersdorp Game Reserve and the dolomitic outcrops there (Figs. 1, 2). North of the N14 highway, the rivulet flows into the Rietspruit and further downstream into the Bloubankspruit, which is part of the upper Crocodile River Catchment (Department of Water Affairs 2013) and passes the sites of the World Heritage caves. On average, the stream's width is between 1 and 3 m and its depth between 0.3 and 1 m. No detailed soil characteristics in the reach of the Tweelopiespruit have been published, though Shapi et al. (2020) report that pedological data was collected by them. At most

Fig. 2 Malmani Dolomite outcrop near location LCW. Width of image 1 m

of the gauging stations described here, the stream's floor consisted of sand, gravel or loamy sand and the Malmani Dolomite could usually not be seen within the stream bed.

The underlying dolomitic strata (Fig. 2), an outlier within the Black Reef Formation quartzite, are platform carbonates that belong to the Malmani Subgroup (Eriksson and Altermann 1998; Eriksson et al. 2006). Due to its high porosity and the presence of large amounts of mixed iron-manganese oxides, the dolomite outlier is known as wad (Department of Water Affairs 2013; Hobbs and Cobbing 2007). Generally, the "[…] water supply of the Tweelopiespruit comes from a number of sources, [which] vary from groundwater flow, industrial, sewage and mine works discharge, urban runoff and input from nonperennial (*sic!*) tributaries " (Digby Wells & Associates (Pty) Ltd. Co 2012). The stream is mainly fed by treated mine water that discharges at various locations along the stream. Additionally, the Tweelopiespruit is assumed to be fed by dolomitic groundwater, which can be seen by the decreasing water temperature along the stream. Referring to the hydrogeological map "2526 Johannesburg" and Vegter and Foster (1992), a karst and fractured groundwater regime exists within the stream's course. In the vicinity of the stream, predominantly groundwater from the Malmani Subgroup is abundant (Hobbs and Cobbing 2007).

Measurements

The salt dilution method is also known as 'salt velocity method', 'relative salt dilution method' or 'conductance tracer method'. It is discussed in detail by Moore (2005), I.S.O.—International Organization for Standardization (1992) and I.S.O. – International Organization for Standardization (1994) and was used to measure the discharge at seven locations along the Tweelopiespruit and additionally in a small tributary (Fig. 1, Table 3). The procedure has a high accuracy of measurement under turbulent flow conditions provided there is thorough mixing along the mixing length between the injection and measuring sites. Commercial table salt (NaCl) was chosen as the tracer substance and used for on-site measurements of the electrical conductivity (EC) change during the study. Though Wood and Dykes (2002) found certain short-term effects on some taxa, they exclude long-term effects on the aquatic ecosystem when using the salt-tracer method for flow gaging. The salt dilution method is based on a calibrated linear relationship between the EC of the water and the concentration of the diluted salt. At each site, 504–4092 g of carefully weighted NaCl were dissolved in 10–20 L buckets of stream water from the Tweelopiespruit. This amount was chosen to increase the EC not more than necessary and to avoid potential negative effects on the aquatic ecosystem. To produce an appropriate tracer solution, all added salt was completely dissolved in the bucket before being injected into the stream. As a general

Table 3 Sampling sites, in downstream order, along the Tweelopiespruit thalweg, the mixing length and the distance between the sampling sites (locations in Fig. 1)

Measuring site	Description	Mixing length L_w, m	Distance, m
UHD	Upstream Hippo Dam	85	–
HDD	Downstream Hippo Dam	42	880
TFS	Next to feeding sites	64	1970
ALS	Above Lions Camp Site	30	730
LCV	Lions Camp Valley	56	690
LCW	Lions Camp West	38	–
DAD	Downstream Avory Dam	47	920
N14	Under and north of Highway N14	60–172	1330

N14 mixing length depending on vegetation intensity

rule, the mixing length L_w, which is the distance between the injection and measuring location, should be at least 25 times the width w of the stream (Day 1977), in which case the mixing distance is usually large enough to result in an evenly diluted salt tracer:

$$L_w = 25 \times w. \quad (1)$$

Fischer et al. (1979) provide more detailed equations for a "'complete mixing' from a centreline discharge", and Landesanstalt für Umweltschutz Baden-Württemberg (2002) recommends a factor of 50 to calculate the mixing distance. Yet, for practicability of field measurements, Eq. (1) can be considered sufficient.

Two different methods were used for evaluating the EC and consequently the discharge: a manual method with an HQ40d portable multi-meter (HACH Lange GmbH, Düsseldorf, Germany) using mathematical evaluation with the software TableCurve (Systat Software GmbH, Erkrath, Germany) and an automated method, Mobile Discharge Measurement System (TQ-Tracer) using its proprietary software TQ-Commander (Sommer Messtechnik, Koblach, Austria). In both cases, the probes were installed *ex aequo* approximately 60% below the water surface. Before injecting the tracer solution, the background EC was recorded.

The injection of the tracer into the stream water took place as quickly as possible with careful rinsing of the bucket to ensure all the tracer was injected (Figs. 3, 4). This is referred to as the "sudden injection ('gulp')" or "slug method" (Moore 2005; Wolkersdorfer 2008). Simultaneously, recording of the EC started. Manually measured values (multi-meter HQ40d) were recorded approximately every 5 s, and with the automated TQ-Tracer system every 1 s until the EC returned to background values. The automatically recorded data were evaluated with the software TQ-Commander (Version 1.1.1.1, Sommer Messtechnik, Koblach, Austria) and the manually measured data with MS Excel and TableCurve.

In addition to the flow data, on-site data were measured with the HQ40d at all dates. This included pH, EC, temperature, redox potential and oxygen saturation. These were primary recorded for quality control to ensure the water quality does not suddenly change due to changes in the operating parameters of the mine water treatment plant located upstream.

Fig. 3 Slug injection of the NaCl solution at sampling location TFS (courtesy H. Coetzee)

Measurement comparison

In 2014, at location N14, a comparison between the salt-tracer method and the standard flow measurement method used by the South African Council of Geoscience (CGS) at that time was conducted (Fig. 5). This "CGS-standard" method at that time consisted of a one-point-one-lamella measurement, which per se is known to give only "satisfactory results". In addition, the operator placed the impeller near the surface, where the water's velocity is close to its maximum velocity (Fig. 6). Yet, based on the specifications necessary for an accurately conducted one-point-one-lamella method, the impeller must be placed at "60% of the depth from the water surface" (Herschy 1995;

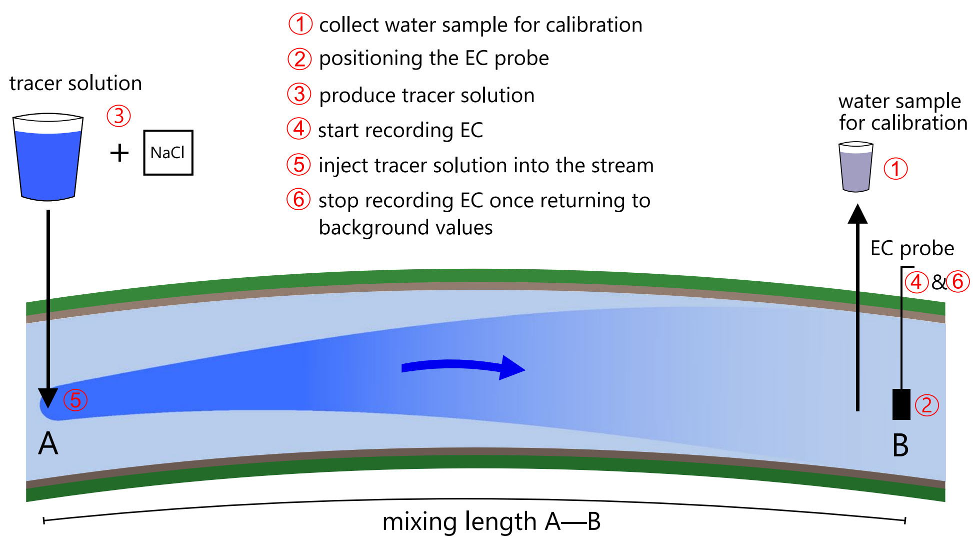

Fig. 4 Schematic model of a flow measurement using the salt dilution method ["sudden injection ('gulp') method"]. *EC* electrical conductivity

Fig. 5 Flow measurement with an impeller meter at the Tweelopiespruit (location N14) by the 2014 standard method of the CGS. Note that the impeller is placed incorrectly just below the water's surface. The water is flowing from right to left, meaning that the operator is not within the reach of disturbing the flow measurement

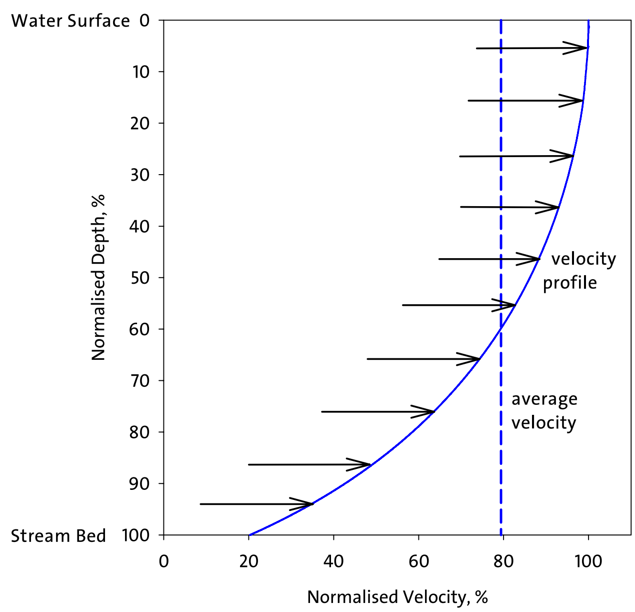

Fig. 6 Typical parabolic velocity profile for a natural stream flowing from left to right. The average velocity is reached in a depth of 60% from the water surface (modified after Fetter 2001)

U. S. Department of the Interior—Bureau of Reclamation 2001). The reading of the CGS impeller measurement was therefore higher than the real flow measured with the salt dilution method and would have had to be multiplied with a stream depth dependent factor of 0.7–0.8 to get the real flow rate (U. S. Department of the Interior—Bureau of Reclamation 2001). Consequently, it would be essential that the CGS is adjusting its standard method to a more sophisticated method in the future, using several depths and lamellas, and that operators are trained appropriately to conduct accurate flow measurements. Since 2014, the CGS revised its method and is now measuring the flow according to the prescribed standards for the impeller method or with the salt dilution method.

Calibration and breakthrough curves

The conductivity probes need to be calibrated with the same salt used for the tracer test and with water from the stream (Fig. 7). Calibration for the HQ40d multi-meter was done in the laboratory with water from sampling sites DAD and HDD. 2 mL of the calibration solution (concentration 10 g L^{-1}) were added stepwise 10 times into 480 mL of stream water. After mixing, the stabilized values of the EC

Fig. 7 Precise calibration of the stream water with NaCl of a predefined concentration (10 g L^{-1})

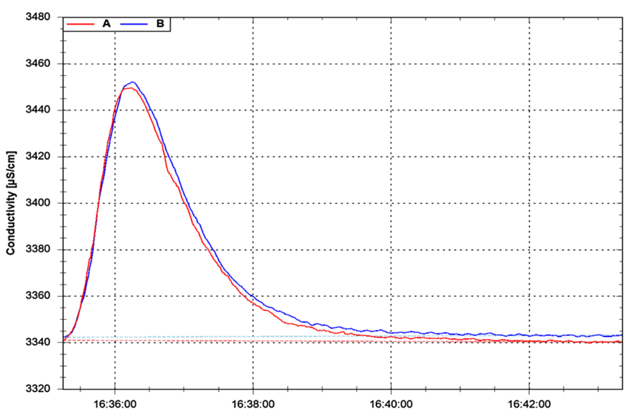

Fig. 8 Typical breakthrough curves of a flow measurement with two conductivity probes A and B at sampling location TFS on 2014-10-03. Individual flows are 389 L/s and 385 L/s, respectively, with an average of 387 L/s

were plotted against the produced salt concentration in the stream water, and then the calibration coefficient was calculated. It is common to use 5–10 calibration steps and report the calibration coefficient with 4 decimal places provided the correlation coefficient was better than 0.999.

In-situ calibration for the TQ-Tracer EC probes followed the same principle as described above. The calibration solution with a concentration of 10 g L^{-1} was prepared in the laboratory, the salt being dissolved in deionised water. By adding stepwise 10 times 0.5 mL of this calibration solution to 250 mL of stream water, a calibration coefficient was determined for each sampling site directly in the field. These values were then stored in the evaluation software's database.

The breakthrough curve reflects the relationship between EC and measuring time (Fig. 8). Using the calibration coefficient, the integral for the concentration over time, resulting from the linear relationship between EC and the dissolved salt content can be calculated. The discharge $\dot{V}$ is the quotient of the injected salt mass M divided by the integration of the salt concentration c over time t:

$$\dot{V} = \frac{M}{\int_{t_0}^{\infty} c_t \cdot dt} \tag{2}$$

The program TableCurve was used to determine the integral of the breakthrough curve for the manual measurements. Original values were detrended, and the curve was smoothed by the cubic constrained method.

Using TQ-Commander for the automatically measured data, a breakthrough curve was automatically generated during the measurement (Fig. 8). Directly after data acquisition, the discharge value $\dot{V}$ is calculated and reported by TQ-Commander. If necessary, a detailed adjustment of the starting and end point of the integration was done after the measurement.

Results and discussion

Similar calibration coefficients of 0.2725 for all sampling sites were determined with the manual calibration, concluding that the addition of the table salt caused similar physicochemical reactions in the stream water. Differences in the calibration coefficients might result from small impurities in the commercial table salt, such as iodine or anti-caking agents. The *in situ* calibration with the TQ-Tracer system ensured individual calibration coefficients for each sampling site and probe and provided very similar coefficients for each sampling location as well (2014: 0.5081–0.5155; $\sigma = 2.3 \cdot 10^{-3}$). This is once more an indication for similar chemical behaviour of the stream water towards the salt tracer.

Preliminary flow measurements in the area were conducted with bucket and stopwatch and floating devices between 2005 and 2006 by Krige (2006). Similarly, the first systematic, resilient flow measurements with impeller flow meters as well as the cross-section flow method and the cross-sectional pipe section method were carried out by Hobbs et al. (2011). Thereby, the measurement points TFS, DAD, and N14 of this study are approximately at the same location as those of Hobbs et al. (2011), and the locations of Krige (2006) were transposed to the closest locations of this study. A comparison of the flow data shows that the absolute flow is different between the various flow measurements (Table 4), which is partly due to seasonal changes of precipitation. A substantial difference exists between the Krige and the Hobbs as well as the recent flow measurements, possibly resulting from partly unsuitable flow measurement methods for this hydrologic regime.

Table 4 Discharges at the seven locations along the Tweelopiespruit and one of its tributaries (LCW)

Measuring site (*)	2019-02-01 L s^{-1}	2017-01-10 L s^{-1}	2016-04-07 L s^{-1}	2014-10-03 L s^{-1}	2014-06-02 L s^{-1}	2010-05-02* L s^{-1}	2010-04-01* L s^{-1}	2005/6 L s^{-1}
UHD	200	476	368	334	–	–	–	–
HDD	–	–	–	–	580	–	–	17
TFS (5)	225	480	365	387	687	–	602	29
ALS	218	449	345	370	589	–	–	50
LCV	221	–	–	–	–	–	–	58
LCW	8	7	–	–	–	–	–	6
DAD (6)	220	456	363	403	1251	370	394	59
N14 (7)	199	451	403	376	1042	405	463	–
Average	214	462	369	384	830	388	486	43

*Location numbers and measurements of Hobbs et al. (2011). The flow at UHD and HDD can be considered similar. On 2014-10-03 and 2016-04-07, the measurement site downstream the Hippo Dam (HDD) was not accessible, and therefore the flow was measured upstream the Hippo Dam (UHD) instead. The error of the first five result columns is about 5%. No errors are known for the results in the last three columns. Based on the literature, they might be between 10 and 30%; locations are listed in the flow direction. 2005/6 locations are listed under the locations closest to those of this study

–: no measurement conducted

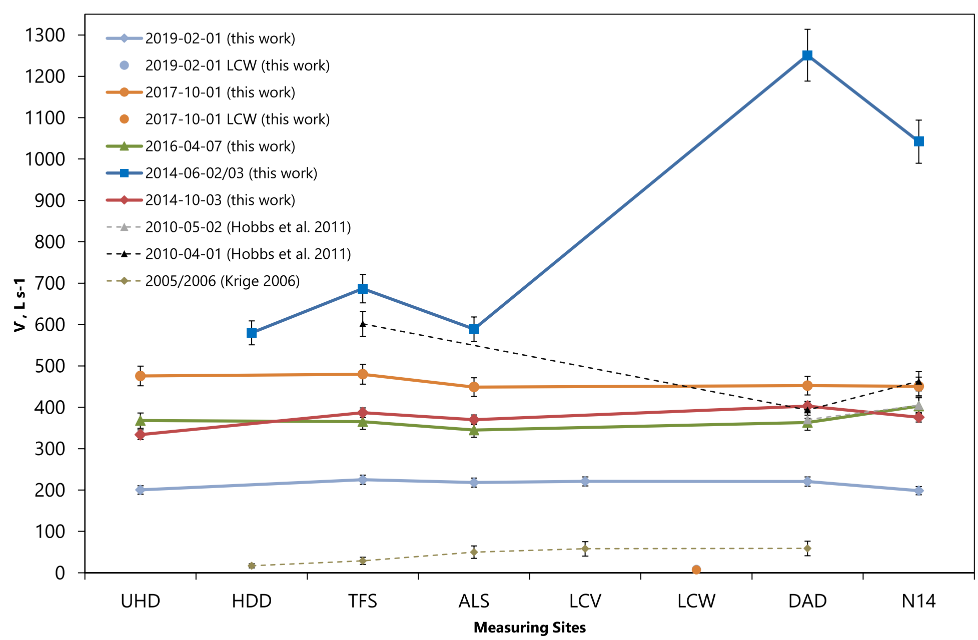

Fig. 9 Results of the five flow measurements (salt dilution method) along the Tweelopiespruit. Additional data from Hobbs et al. (2011) and Krige (2006). Flow at LCW for 2017-10-01 and 2019-02-01 is 7.2 and 8.4 L/s, respectively, and therefore plots on the same point

The error bars (Fig. 9) indicate an error range of ± 5%, which is the mean error range of the salt dilution method mentioned in Day (1976) and ± 30% for the uncorrected floating device results of Krige. Huge differences are shown by the mean values from 2014-06-02/03 (HQ40d measurement) and 2014-10-03 (TQ-Tracer measurement), which is similar to the 2016-04-07 measuring. In June 2014, a mean value of 830 ± 270 L s^{-1} (standard deviation) was recorded, whereas in October 2014, the mean value for the flow was less with 374 ± 23 L s^{-1}. Very similar values were encountered in April 2016 with a mean flow of 369 ± 19 L s^{-1} and in January 2017 the flow was 462 ± 13 L s^{-1}.

Yet, all the eight measurement campaigns reported here show a similar trend in the discharge along the stream. For nearly all measurement campaigns, a relative increase in the flow rate along the Tweelopiespruit can be observed. After the inflow into the game reserve, the total flow increases. A first peak is reached at measuring point TFS, whereafter the flow rate shows a substantial decrease. The increase in flow before TFS is in the same range as the decrease at this measurement point. This is clear in the June 2014 measurement. After measuring point ALS, the measured flow rates from June and October 2014/April 2016 differed substantially. In June 2014, the flow increased by more than 660 L s^{-1}

to 1251 L s^{-1}. Then, it decreased, with discharge values over 1000 L s^{-1}. The same trends are seen in the October and April measurements with flows being substantially lower. The results of Hobbs et al. (2011) are in the same range as the October 2014 and April 2016 salt dilution measurements, but that study had less measurement points and came to different conclusions than this study. Only after the water leaves the game reserve and enters farmland, and a dam used for irrigation water just before sampling point N14, the flow decreases again. Results of the individual sampling campaigns by this study and the previous ones cannot be compared with each other, because the individual flow situation results from precipitation influenced flow to base flow conditions.

The small flow loss between TFS and ALS in all but Krige's measurement by approximately the same discharge rate can be explained by some water infiltrating into the dolomite which outcrops in that area. At measuring points DAD and N14, the flow rates for June 2014 and October 2014/April 2016 were substantially different. In June 2014, the measurement was carried out at the beginning of the dry winter season, and the little feeder streams above point DAD may have been water bearing. Yet, a more detailed measurement in 2019 showed, that the contribution of these seems to be minor under normal circumstances. It is, therefore, unclear, where the substantial increase in flow in June 2014 originated. However, based on that measurement, during and after rain events, a strong flow increase into the Tweelopiespruit by these sources can be assumed.

The measurement in October 2014 was conducted towards the end of winter, after a long season with no precipitation and in April 2016 at the beginning of autumn with minor rainfall events before the day of measurement. Consequently, the small rivulet upstream of point DAD had dried up, and no increase in discharge was observed in the October 2014 measurement and only a minor increase in the April 2016, October 2017 and February 2019 measurements. This lack of precipitation is also likely to be responsible for the low mean discharge during the October and April measurements.

A common method to identify stream losses and inflows are temperature and EC measurements along the stream (Leibundgut et al. 2009; Ackman and Jones 1988). As can be seen from the EC measurements (Table 5), this on-site parameter shows a decreasing trend along the thalweg of the Tweelopiespruit. Similarly, the temperature decreases (Fig. 10) between UHD and N14. This is an indication of cooler and less mineralised water entering the Tweelopiespruit and proofs the results from the flow measurements showing an increase in the flow rate during the streams' course through the game reserve.

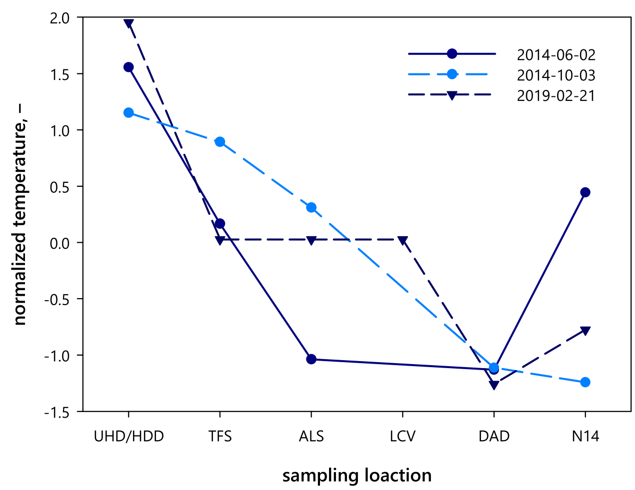

Fig. 10 Normalized temperature measurements along the Tweelopiespruit in 2014 and 2019. In general, the temperature decreases during the stream's thalweg indicating an inflow of colder water

Table 5 pH and electrical conductivities (μS/cm) at the flow measurement locations in the Tweelopiespruit

Measuring site	2014-06-02/3	2014-10-03	2016-03-15	2016-04-07	2017-01-10	2019-02-01
UHD	–	6.98 ǀ 4098	–	7.53 ǀ 3650	8.51 ǀ 3450	– ǀ 3740
HDD	3.56 ǀ 4026	–	–	–	–	–
TFS	3.37 ǀ 3599	6.67 ǀ 3388	–	5.87 ǀ 3176	4.94 ǀ 2990	– ǀ 3096
ALS	3.39 ǀ 3613	6.66 ǀ 3368	–	5.98 ǀ 3209	4.93 ǀ 2880	– ǀ 3104
LCV	–	–	–	–	–	– ǀ 3103
LCW	–	–	–	–	6.83 ǀ 269	– ǀ 294
DAD	3.56 ǀ 3414	6.63 ǀ 3244	–	6.44 ǀ 3097	5.75 ǀ 2840	– ǀ 2942
N14	3.53 ǀ 3285	7.31 ǀ 3117	5.83 ǀ 3099	6.12 ǀ 3093	5.82 ǀ 2820	4.70 ǀ 2978
Averages*	3.48 ǀ 3587	6.85 ǀ 3443	5.83 ǀ 3099	6.39 ǀ 3245	5.99 ǀ 2996	– ǀ 3161

*Averages without the tributary LCW

Conclusions

Two conclusions can be deduced from the results of this investigation. First, the investigation shows that the salt dilution method is an effective way for a precise flow measurement under turbulent flow conditions in mine water affected streams, as in the case of the Tweelopiespruit in the Gauteng Province/South Africa. Sodium chloride as a tracer substance is comparably cheap and easy to handle in addition to its nontoxicity in the concentrations commonly applied. Two different methods for measuring the EC were used in this study: manually and automatically. Using the automatic system, less personal expenditure is required and less measurement errors appear. In addition, the breakthrough curve can be evaluated more easily by factory-made software tools. Therefore, the automatic system is the method of choice for future flow measurements in mining influenced water, though the manual method is good enough for a use if appropriately handled.

Second, the flow measurements conducted in this study showed that the earlier hypothesis of the stream losing water to the underlying dolomite aquifer over its full course in the game reserve must be rejected. The measurements reflect that there is a small stream loss of 3–14% once the Tweelopiespruit crosses the dolomite outcrops, but once the water leaves the Game Reserve, the flow is close to when it entered it. Stream losses downstream the Game Reserve cannot always be observed but might result from agricultural use rather than exfiltration into the underlying dolomite. Because stream loss along the Tweelopiespruit thalweg can be neglected, a groundwater contamination by MIW in the Krugersdorp sub-catchment can be excluded.

Within the Tweelopiespruit, the strong increase of the flow rate in June 2014 at point DAD can be explained by an additional inflow upstream of the measuring point. Summing up the results of the flow, EC and temperature measurements in the Tweelopiespruit, it is concluded that the flow increases over the measuring distance resulting from the inflow of cooler and less mineralized water. Because the water is meanwhile circumneutral, as it emanates mainly from the Sibanye Gold mine water treatment plant, an immediate danger for the caves of the "Fossil Hominid Sites of South Africa" World Heritage Site from infiltrating, polluted mine water can, therefore, not be postulated, which was recently also shown from a geochemical point of view (Mashishi et al. 2022). A sampling program using stable isotopes and chemical analyses as well as a laboratory study to investigate the dissolution rate of the dolomite from the mining influenced water is currently underway.

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Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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