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URANIUM CONTAMINATION OF FLUVIAL SYSTEMS - MECHANISMS AND PROCESSES

PARTII: DYNAMICS OF GROUNDWATER-STREAM INTERACTION - A CASE STUDY FROM THE KOEKEMOER SPRUIT (SOUTH AFRICA)

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ABSTRACT: Dissolved uranium from tailings-deposits of various gold - mines in South Africa was found to migrate via seepage and groundwater into adjacent fluvial systems. The extent of the associated non-point pollution depends not only on the concentration of uranium in the water but also on the volumes of polluted groundwater seeping into the stream channel. While the uranium concentration in the groundwater is rather constant and therefore comparably easy to determine, the same is not true for the water exchange at the groundwater-stream interface. In order to track the relevant hydraulic processes, in-situ data-logger controlled probes were placed within the system measuring gauging heights and electric conductivity (EC) in 10-minute intervals. As a result of a steep hydraulic gradient between water-saturated tailing-deposits and the receiving watercourse, exfiltration (baseflow) of contaminated groundwater generally dominates. However, short-term inversions of the direction of flow (infiltration of stream water into the groundwater) were also observed. They are attributed to the artificial flow-regime of the Koekemoer Spruit, which results from a pumping scheme that discharges dolomitic groundwater into the stream. Electricity costs-related differences of pumping rates lead to pronounced diurnal fluctuations of gauging heights in the stream, which in turn cause even higher fluctuations of the associated groundwater table (up to 90cm a day). The consequences and mechanisms of these man-made stream fluctuations for the hydraulic stream-groundwater interaction as well as implications for the solute transport of uranium are discussed.

RESUMEN: El uranio disuelto, procedente de escombreras de minas de oro de Sudáfrica, migra hacia sistemas fluviales adyacentes a través de *las aguas subterráneas.La importancia de la contaminación difusa depende no sólo de la concentración de uranio en el agua, sino también del volumen de agua subterránea contaminada que accede al cauce fluvial. Mientras que la concentración de uranio en el agua subterránea es constante y fácil de determinar, no sucede lo mismo con el intercambio de agua en la interfase agua subterránea-río. Con el fin de controlar los procesos hidráulicos más relevantes se colocaron sondas conectadas a data loggers para medir la altura del agua y la conductividad eléctrica en intervalos de 10 minutos. Como resultado de un fuerte gradiente hidráulico entre el agua saturada procedente de las escombreras y los cauces fluviales receptores, dominan procesos de exfiltración (flujo de base) de agua subterránea contaminada. No obstante, se han observado también inversiones en la dirección de flujo (infiltración de agua desde el cauce hacia las capas subterráneas). Se atribuyen al régimen artificial del Koekemoer Spruit, debido al sistema de bombeo que descarga agua subterránea de origen dolomítico en el cauce. Las diferencias en el ritmo de bombeo debido al coste de la electricidad conducen a pronunciadas fluctuaciones en la altura del agua del cauce, lo que a su vez causa importantes fluctuaciones en el nivel del agua subterránea (hasta 90 cm en un día). Se discuten las consecuencias de estas fluctuaciones en la interacción sistema hidráulico-agua subterránea así como las implicaciones para el transporte de uranio disuelto.*

Key-words: Water pollution, Uranium, Fluvial system, Groundwater, South Africa.

Palabras clave: Contaminación, Uranio, Sistema fluvial, Agua subterránea, Sudáfrica.

1. Introduction

Due to elevated concentrations of uranium and other heavy metals, seepage from tailing-deposits of uranium mining and milling often leads to diffuse contamination of nearby watercourses. The dissolved metals migrate into the underlying groundwater that finally seeps diffusely into the adjacent stream (Winde, 2000 and 2001). The extent of such non-point pollution depends on both the concentrations of dissolved contaminants in the groundwater and the volume (rate) with which the groundwater seeps into the watercourse.

Since the water-saturated tailings are often deposited tens of meters above stream level, extremely steeped hydraulic gradients cause accelerating subsurface seepage-flow towards the stream. Since those hydraulic gradients are maintained over long periods of time, exfiltration of contaminated groundwater (and thus the associated diffuse stream pollution) is commonly regarded as a continuous process with more or less constant intensity throughout the year.

Although exfiltration (which is also termed baseflow) under such conditions is likely to prevail during the course of the year, it cannot *a priori* be excluded that short-term variations in direction and intensity of water flow between stream water and associated groundwater occur. Since such variations would directly affect the water quality, they are vital for understanding the dynamics of fluvial uranium transfer.

By means of long-term *in situ*-measurements of gauging heights in the Koekemoer Spruit and the associated alluvial aquifer in ten-minute intervals, the dynamic of hydraulic interactions between both water-bodies was tracked.

2. Study area

The location of the Koekemoer Spruit catchment is shown in Figure 1. Despite a relatively large catchment area of about 860km^2, an average runoff of less than 2% of the annual rainfall allows for seasonal flow only. However, a pumping scheme at the closed Stilfontein goldmine, which prevents the adjacent (active) Buffelsfontein goldmine from being flooded, sustains a perennial flow between 150l/s and 450l/s. At Margret-shaft dolomitic groundwater from underground mine workings at a depth of 1000-1300m is pumped up to the surface where it is discharged into a concrete channel (Figure 1). After approximately 5km the channel flows into the Koekemoer Spruit some 10km upstream the gauging weir, where datalogger-sensors are installed.

The lower Koekemoer Spruit, adjacent to the Buffelsfontein Goldmine, was chosen as study area, since it presents a typical situation where uranium contamination is likely to occur. The focus area comprises of a cross section through the floodplain stretching from slimes dams of the Buffelsfontein goldmine on the right-hand stream bank to an evaporation dam on the left-hand side of the stream.

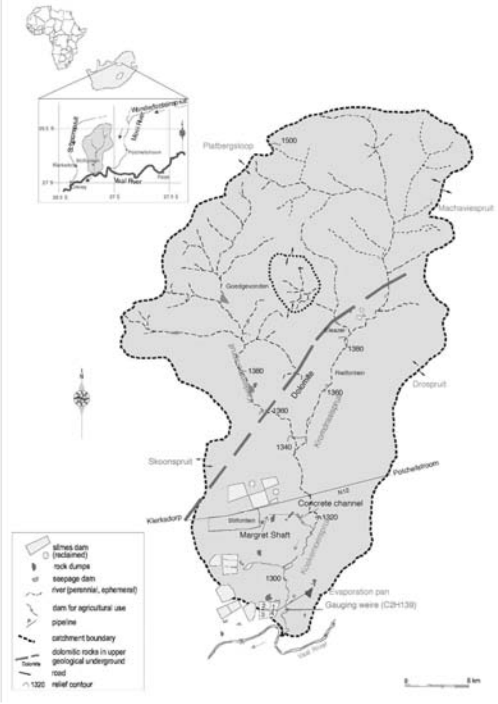

Figure 1. Location and catchment area of the Koekemoer Spruit.

The unlined slimes dams of the Buffelsfontein Goldmine are regarded as the most important sources of uranium contamination in the study area. A shallow alluvial aquifer in the floodplain constitutes a hydraulic link between the slimes dams and the Koekemoer Spruit. For slimes dam #3, which is some 38m high, the piezometric head is about 26m above the average water level in the Koekemoer Spruit (de Bruin, 2000). The resulting hydraulic gradient drives a permanent water flow to the stream, as high levels of groundwater with elevated electric conductivity (EC) in the floodplain suggest. The direction of flow is slightly modified by a weak down-valley gradient towards the Vaal River. Similar conditions were found on the left-hand side of the stream although the hydraulic gradient is less steep. Here an evaporation dam, which is designed for evaporating non-recyclable process-water from the gold mine, acts as source of groundwater contamination. Because of the highly permeable dolomitic underground, it has been estimated that <2% of the disposed water really evaporates, while the remaining balance seeps into the underground (Hearne & Bush 1996) (Figure 2).

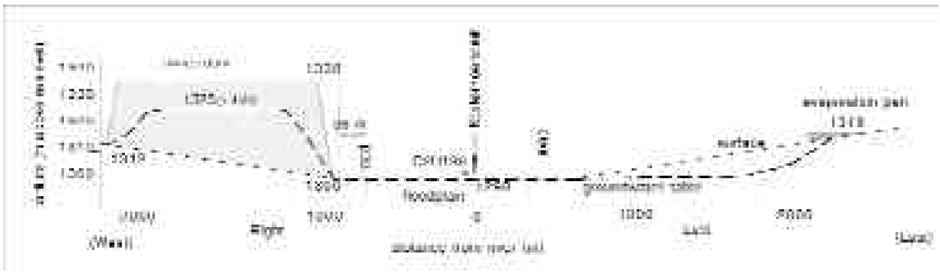

Figure 2. Hydraulic gradient between the slimes dams/evaporation dam and the Koekemoer Spruit.

3. Methods

All interpreted data were recorded at a computerised data logger station, which was installed at a gauging weir of the Department for Water Affairs and Forestry (DWAF), station C2H139 (for location see figure 1).

Apart from the sensors, which were used to track hydraulic interactions between the stream and the groundwater (gauging heights and electric conductivity) this station also was equipped with probes needed for hydrochemical studies (pH, redox-potential and water-temperature). In addition meteorological parameters like air-temperature, relative air-humidity and precipitation were recorded. All probes were wired to and controlled by a data-logger (Delta T, Dl2e) which was powered by a 12V battery. The location of the probes at the station is shown in Figure 3.

Gauging heights in the alluvial aquifer were measured in a groundwater-monitoring pipe (PET, 8cm diameter, 0.2mm slashed) which was installed 1m deep in the floodplain sediments, 15m distant from the right-bank of the stream. To protect the instruments from

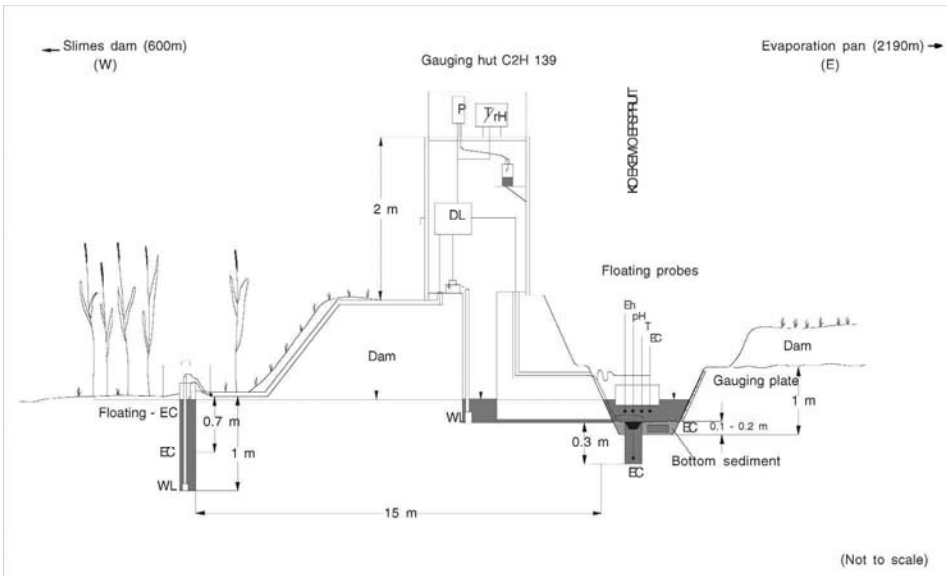

Figure 3. Cross section of the data logger station at the Koekemoer Spruit.

tampering, a cap of bricks (50cm x 50cm wide, 40cm high) was built around the top of the pipe. The water stage in the Koekemoer Spruit was measured in the gauging-well inside a concrete hut of station C2H139.

At both sites, data logger-controlled piezometers, recording data every ten minutes over a period of 7 months (groundwater) and 16 months (stream) respectively, measured gauging heights. Both piezometers were calibrated against the gauging plate of the weir and checked monthly.

Simultaneously, the electric conductivity (EC) in both systems was measured in the same time-interval. Both sensors were temperature-compensated. Rainfall was measured in ten-minute intervals by an electronic pluvial-meter (Hellman) on top of the gauging hut (2m above ground) which also was connected to the data-logger inside the hut. The rainwater was collected in a 3l-PET-bottle in the gauging hut for analyses of volumes (calibration) and quality. Air-temperature and relative air-humidity also were electronically measured on top of the hut in the same time interval (figure 3).

4. Results and discussion

4.1. Flow regime in the Koekemoer Spruit

Gauging records from the Koekemoer Spruit display pronounced diurnal and weekly fluctuations of the water level (between 20 and 50cm/day), which is mainly caused by a pumping scheme at the Magret shaft of Stilfontein gold mine. Because of cheaper off-peak prices of electricity, the pumping rates at night and during weekends are significantly higher than at daytime during the week (435l/s and 160l/s respectively - de Bruin, 2000).

The diurnal cycle of flow reaches the maximum of 435l/s during night-time (22:00–6:00), when electricity is less expensive and all seven pumps are switched on. During daytime only three pumps are in operation, pumping an average of 161l/s into the Koekemoer Spruit (de Bruin, 2000.). The varying flow rate results in water-level changes at the gauging weir from a minimum of about 20cm to a maximum of 45-50cm. The water level peaks there about 23-24h after switching to the maximum pumping rate (22:00 – 23:00). With a vertical distance of 1.3km from the underground to the surface at Margret shaft and another 15km from there to the gauging station, this gives an average flow velocity of >0.2m/s. The minimal flow at the gauging weir occurs round about noon (11:30-13:00). At weekends (Friday 22:00 – Monday 06:00) the reduced electricity price applies as well resulting in an uninterrupted high flow rate Saturdays and Sundays. The fact that no water is extracted for industrial purposes during nights and weekends, further increases the flow in the Koekemoer Spruit (figure 4). When increasing seepage in wet periods exceeds the storage capacity of the underground reservoirs at Margret shaft, maximum pumping rates are also applied during daytime. (de Bruin, 2000.).

It is due to these fluctuations that rain events in the catchment do not result in a typical hydrograph but often only in levelling the diurnal fluctuations. Since rainwater also recharges the dolomitic underground, a delayed impact on the stream was observed, resulting from higher pumping rates for several days after the rain event (Figure 5).

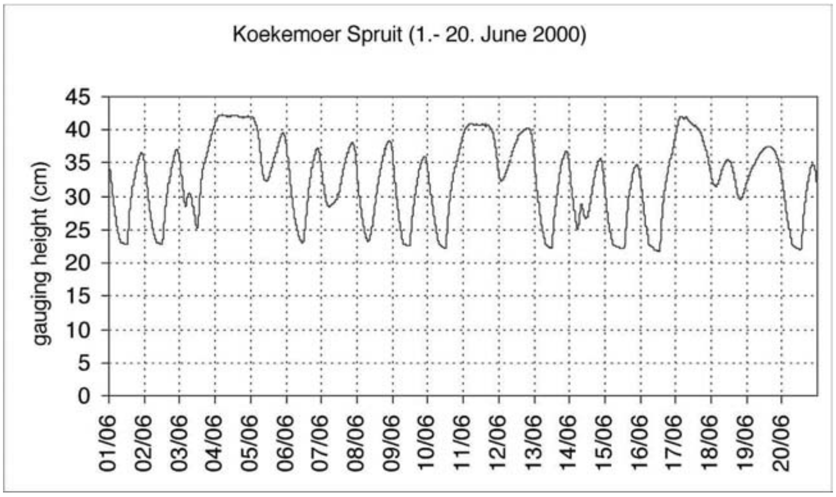

Figure 4. Gauging heights of the Koekemoer Spruit at station C2H139 (1.-29.06.2000) as typical example for the pumping scheme controlled flow –regime of the stream.

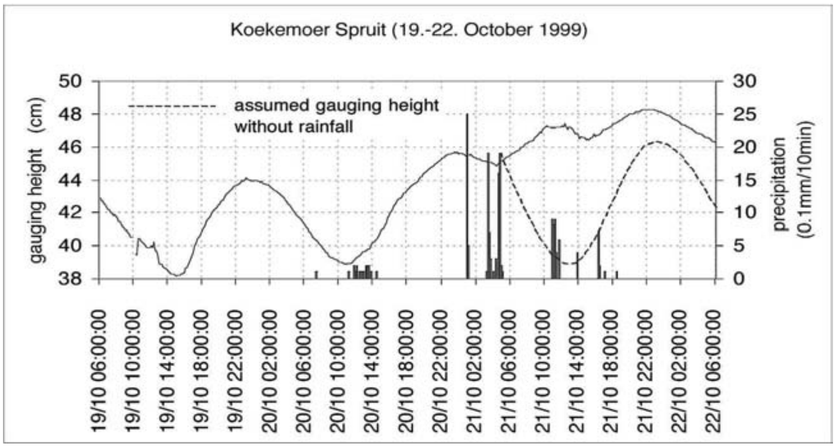

Figure 5. Response of the water level in the Koekemoer Spruit to a rain event .

4.2. Hydraulic interaction between stream and alluvial groundwater

4.2.1. Time delay and magnification factor of groundwater response to stream fluctuations

Time series of the gauging height in the stream and the alluvial groundwater display a high similarity suggesting a close hydraulic link between the two water-bodies (Figure 6).

In order to determine the controlling factor (thus the direction of the interaction), statistical time-series analyses was carried out by applying the software-package STATISTIKA. This program compares the correlation of both time series against each other by shifting one of them gradually along the time scale until the best correlation is found. In this case the stage fluctuations in the stream explain the variation of the groundwater-table best (75%) when the groundwater series is lagged against the stream by 3hours (Figure 7). This fits to the chart analysis, which yielded an average time-lag between the maxima of both time series of 3h (Figure 6).

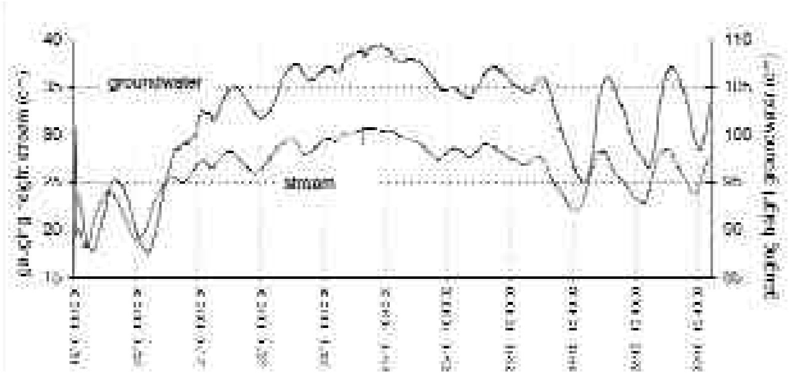

Figure 6. Gauging heights in the Koekemoer Spruit and the associated groundwater (19. –29.10.1999)

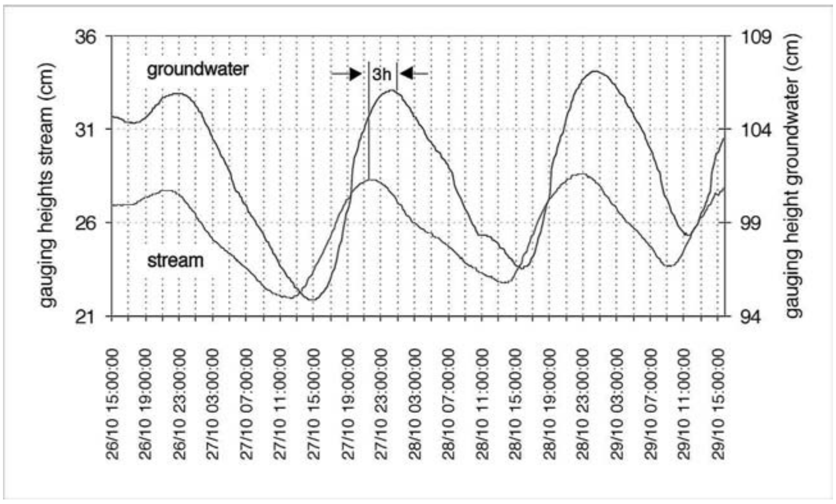

Figure 7: Time delay of the groundwater response to stream flow fluctuations in the Koekemoer Spruit.

Using a Boscop-transformation to ignore variations in the amplitude of changes, the stream level even explains 93% of the variation in groundwater gauging heights.

All attempts to find any statistical significant dependency of the diurnal groundwater fluctuations from relative air humidity - as inverse parameter for evapotranspiration – failed. It therefore can be concluded that the pumping-related variations of gauging heights in the Koekemoer Spruit are the main (and only?) cause for the pronounced diurnal fluctuations of the associated alluvial groundwater-table. The close statistical relationship could also be confirmed by correlating the maximal daily differences in gauging heights of both water-bodies. For a period of 12 days (19.-30.10.1999) a linear regression with R=0.9867 (95% confidence level) between both series was found. (Figure 8)

The ascent of the resulting straight line in figure 8 of 1.79 (see equation) indicates that the response of the alluvial groundwater to stream-flow oscillations is not only delayed by 3hours but also magnified. That means that in this case an increase of the stream-level by 10cm causes the groundwater table to rise by 17.9cm. The ratio between the gauging height changes in the groundwater and the stream is further termed “magnification factor”.

The “magnification-effect” can be explained partly by the space that is already taken up by sediment particles in the floodplain, which causes the water to rise higher than it did in the (sediment-free) stream channel. E.g. if a given volume of water is poured into a column where half the volume is occupied by sediment the water will rise double as high as it would do in a sediment-free column. This suggests that the magnification-factor only depends on the pore-volume (which is determined by the grain size distribution) of the floodplain sediments. Since those parameters are constant to a large degree, no significant changes of the magnification-factor are to be expected.

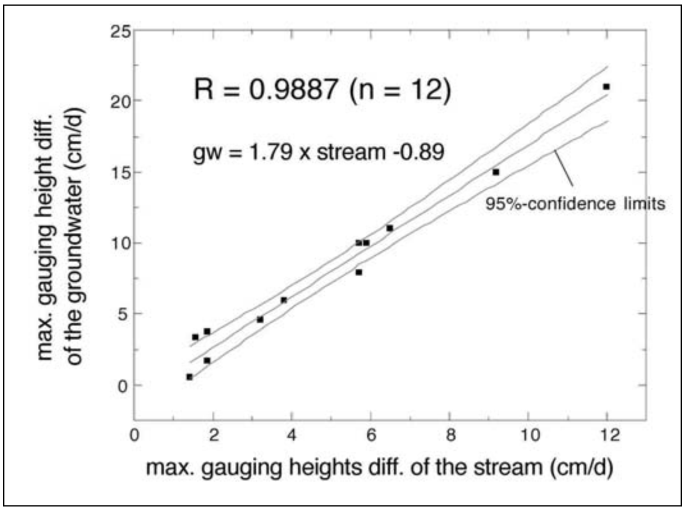

Figure 8. Relation between maximal diurnal gauging fluctuations of the Koekemoer Spruit and the associated alluvial aquifer (19.-30.10.1999).

However, it was found that the magnification-factor varies considerably over time. E.g. for December 1999 an average magnification-factor of 5.35 was found (compared to 1.79 in October). Stream fluctuations of only 4-15cm a day were causing groundwater-fluctuations of 10-80cm per day.

A major difference between the two months were significant higher gauging stages in December, which were almost twice as high as in October (40-50cm and 20-30cm respectively). It therefore was assumed that apart from the pore-volume of the sediments, also the level of gauging heights in the stream channel might influence the magnification-factor. No significant linear relationship between the latter and the gauging heights in the Koekemoer Spruit was found. However, this can be explained by the fact that with rising gauging heights in the stream channel, the volumes of through-flowing water increases not linear but exponentially (logarithmic rating curve). I.e. the volume of infiltrating water rises much stronger than the measured gauging height in the stream channel. If more water is seeping into the floodplain sediments, the groundwater table must rise. Thus the relationship between stream-gauging heights and magnification factor of the groundwater response cannot be linear. It rather is to be expected that the magnification factor rises exponentially with increasing gauging height and eventually approaches an upper maximum (similar to a rating curve). This would explain why the rises of the magnification factor from October to December (3 times: 1.79 to 5.3) was stronger than that of the average stream-level (2 times: 20cm to 40cm). No statistical significant relation between stream level and magnification factor could be established, but the reason for this might be the heavy rains during December, thereby superimposing runoff on the stream-groundwater interaction. Due to time-differences of the hydraulic response to the rain-events (quick surface run-off in the stream versus delayed groundwater recharge), the interaction between the two water-bodies were influenced by an additional factor, which disturbs the clear-cut relationship. This assumption is supported by a decreasing correlation between the maximal daily fluctuations in stream and groundwater from R=0.9867 in (dry) October to R=0.9037 in (wet) December 1999.

4.2.2. Water flow at the stream–groundwater interface (hydraulic gradient)

4.2.2.1. Dynamics

The direction and rate of water-flow between streams and alluvial aquifers are determined by the hydraulic conductivity of sediments at the groundwater-stream interface and the hydraulic gradient between the water tables. With the hydraulic conductivity of sediments being largely constant, the flow-rate depends exclusively on the hydraulic gradient, indicating direction and rate of water-flow between the systems. It was calculated as quotient of the height-difference between stream and groundwater table and the distance between the points of measuring (Figure 9). As shown in Figure 9, negative values therefore indicate flow of groundwater into the stream (exfiltration = baseflow conditions) while positive values indicate infiltration of stream water into the alluvial groundwater.

Using time series of gauging heights in the stream and in the groundwater respectively, the hydraulic gradient was calculated for each 10min-interval over a period of seven months. The resulting third time-series allowed continuos *in situ*-monitoring of

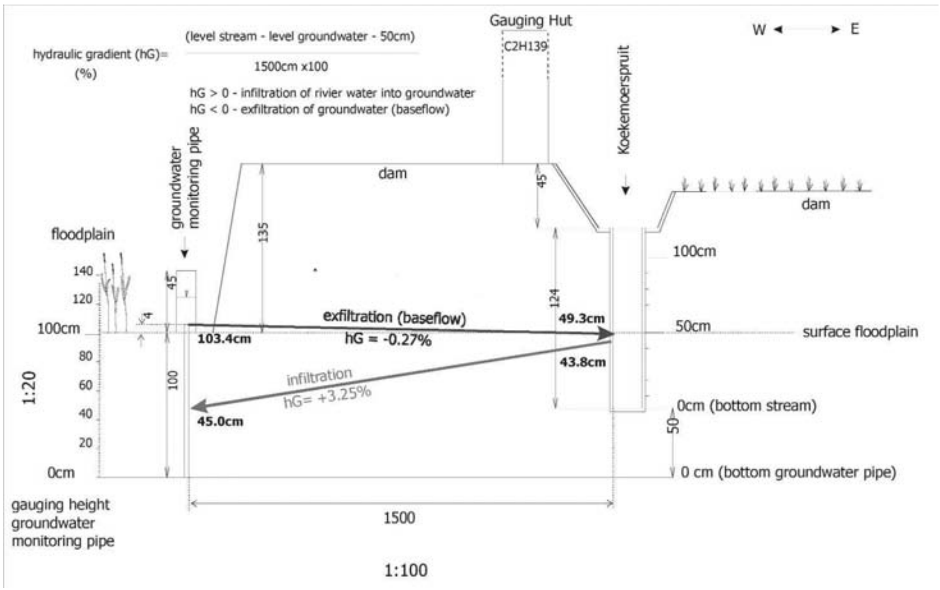

Figure 9. Examples for calculated hydraulic gradients at the Koekemoer Spruit indicating infiltration and exfiltration of groundwater.

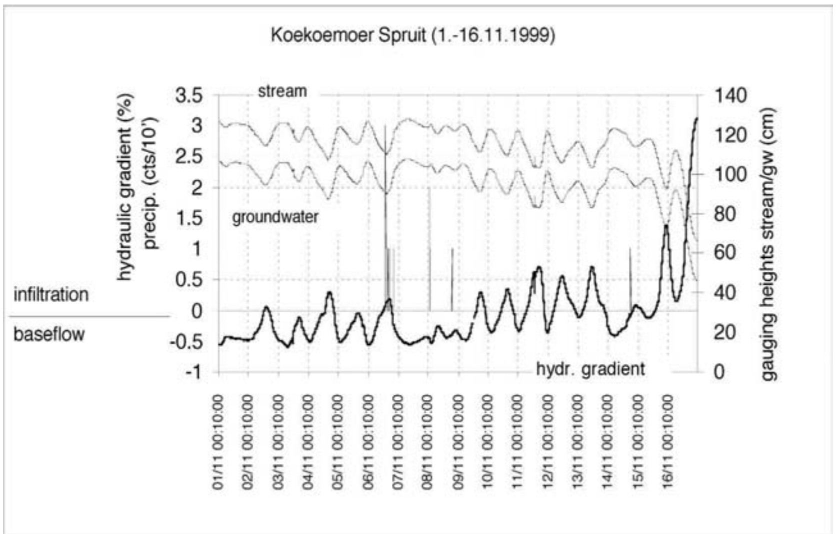

Figure 10. Hydraulic gradient 10 days November.

hydrodynamics between the stream and groundwater. An example is given in Figure 9, which displays a 10-day period in November 1999 where, after low-intense rainfall at the 7th and 8th , dry weather conditions continued to prevail (Figure 10).

The water level in the Koekemoer Spruit fluctuates between 3-13cm per day leading to groundwater fluctuations of 5 to 46cm/d. Due to those fluctuations, which are particular pronounced during dry weather periods, the hydraulic gradient changes daily between infiltrating conditions (positive values) and exfiltration (=baseflow conditions, negative values) (Figure 9). Stream water infiltrates into the groundwater mainly during high flow conditions (day time) while the reverse process - groundwater seeping into the stream channel - occurs almost exclusively during low flow conditions (night time) (Figure 11).

However, time-histories of the hydraulic gradient over a 7month-period (October–April) indicate that baseflow is the predominant process during the rainfall season (Figure 12). The data-gap between the end of December and end of February was caused by high groundwater levels, which exceeded the measuring-scale of the piezometer. That implies that the groundwater level was above 110cm during the whole period, hence suggesting that predominantly baseflow conditions prevailed during this period of time. However, flood events in the stream might have lead to sporadic reverses of the direction of water exchange with its aquifer.

Although it was expected that after rain events, short periods of infiltration would occur as a result of surface run-off causing the stream level to rise much quicker than the

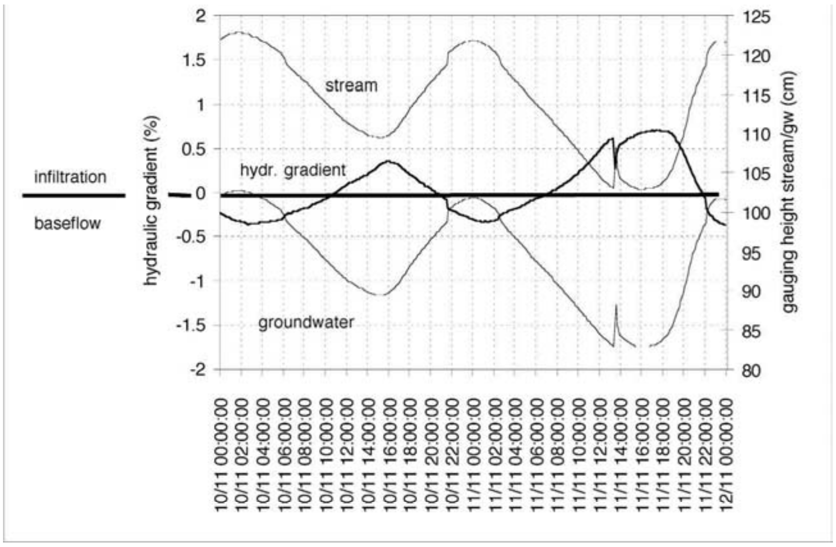

Figure 11. Hydraulic gradient between alluvial groundwater and the Koekemoer Spruit (2-day chart:10.-12.11.1999).

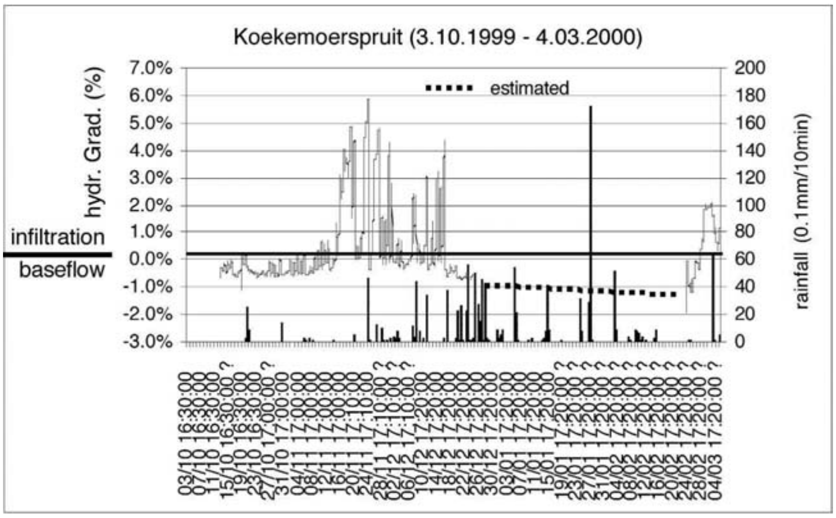

Figure 12. Hydraulic gradient at the Koekemoer Spruit in relation to rainfall (October 1999-April 2000).

groundwater table, such effects were hardly evident. In general, man-made stage height fluctuations had a significant higher impact on the stream-groundwater interaction than the rain events. This is mainly due to the comparably small contribution of rainwater to the total flow in the Koekemoer Spruit and the fact that the rainwater run-off frequently only levels stage fluctuations in the stream (Figure 12).

Although no direct dependency could be established, it is likely that seasonal changes of the vegetation cover of the floodplain also influence the hydraulic stream-groundwater interactions by changing rates of water consumption, transpiration and interception.

4.2.2.2. Mechanisms

Apart from fluctuating stream levels, resulting in infiltrating or exfiltrating conditions, also the absolute value of the hydraulic gradient (steepness) might have an impact on the stream and groundwater interactions. During October 1999 and March 2000, the statistical average of the hydraulic gradient was +0.4%, suggesting that infiltration was dominant during this period of time. However, the negative median (central value) of -0.1% indicates that more than half of the 11,871 values were negative, suggesting that baseflow conditions prevailed. The positive average mainly results from extreme high peaks of positive gradients in November and December during several flood events. Due to the fast rainwater run-off, the stream level rises much quicker than the groundwater table, resulting in short-term peaks of positive hydraulic gradients. With +5.9% such peaks are significant higher than the steepest baseflow-gradients (–1.9%).

A question arising from this is whether very steep hydraulic gradients really allow stream water to infiltrate far into the adjacent floodplain or whether the diurnal turn-around just recharges “old” stream water back into the stream channel? In order to assess this, the hydraulic conductivity of the floodplain/bank sediments has to be taken into account. Assuming that stream water would migrate over the whole distance of 15m (from the stream to the groundwater monitoring-pipe) during daytime (10h), a transmission constant (kf-value) of $4.2x10^{-4}$m/s would result. Compared to transmission constants given for floodplain sediments (10^{-6}…10^{-8}m/s, Matthes, 1990), this is two orders of magnitude higher. Based on the latter the stream water only could infiltrate several centimetres into the bank sediments. Thus it is unlikely that stream water really reaches the groundwater pipe to cause the water table there to rise.

It rather seems that the infiltrated stream water is “stored” in the bank sediment (“bank-storage”) and dams up the groundwater, which flows towards the stream. Thereby a hydraulic link is formed, which as kind of a seesaw-effect transmits the level changes in the stream to the groundwater pipe in the floodplain. This is backed by time series of electric conductivity (EC) in the groundwater, which show no significant drop while the water level rises, which would be the case if stream water (with low EC) seeps in. When the water level in the stream drops again, the bank-storage flows back into the channel and allow the “dammed up” groundwater to exfiltrate into the stream.

In general, it seems that strong positive hydraulic gradients temporarily can stop contaminated groundwater from exfiltration but in fact do not allow stream water to penetrate deep into the floodplain. Since stream level fluctuations are magnified and the groundwater table therefore always rises higher than stream, ultimately exfiltration (baseflow) dominates even during such periods of pronounced stream-flow fluctuations. Because of the low hydraulic conductivity of floodplain/bank-sediments, the occurrence of a certain hydraulic gradient over time is more important than its actual value.

4.3. Implications of hydraulic interactions for uranium transport and contamination

4.3.1. Stream contamination

Since groundwater is the major source of diffuse pollution of the Koekemoer Spruit, the diurnal turn-around of water flow between stream and alluvial aquifer implies a daily cycle of contamination. Due to an artificially flow-regime, contaminated groundwater can only seep into the stream during night-time when the stream-flow is low. In fact, the hydraulic gradient and thus the inflow of contaminated groundwater reaches a maximum at exactly the point in time where stream-flow and thus dilution of dissolved contaminants is the lowest of the day. This results in peaks of concentrations of dissolved uranium and other heavy metals in the streamwater.

Apart from possible effects on benthic and other aquatic organisms, those pulses also may have hydro-chemical implications, like e.g. concentration-related changes of the speciation of dissolved metals. Due to changes from solute into solid phases, the latter process strongly determines the mobility (rate of downstream transport) of the metals and the extent of the associated sediment contamination. In this regard also duirnal cycles of stream chemistry (discussed in part III) must be considered.

In addition to this, sulphate crusts on bank sediments 10-15cm above the water table were observed. They form during the day by the evaporation of capillary ascending stream water from the bank sediments. The precipitated sulphates often contain extremely high concentrations of uranium and other heavy metals (as it was shown in part I). Since the water table in the Spruit fluctuates between 10–40 cm/d, these crusts are frequently re-soluted, polluting the stream with uranium and other heavy metals.

4.3.2. Floodplain contamination

The daily rhythm of waterborne stream-pollution at the Koekemoer Spruit also have implications for the current monitoring programme of the DWAF, which relies entirely on water samples taken during daytime only. Without changing the sampling protocol in this particular case, the actual stream water pollution is unlikely to be detected. Since many other active goldmines are also operating in dolomitic areas (Carletonville area, East Rand), with similar pumping schemes for dewatering the underground mine workings, artificial flow-regimes like in the Koekemoer Spruit are likely to be found in streams of such areas as well. Thus, current set-ups of (expensive) monitoring programs should be re-considered and modified according to the local circumstances.

4.3.3. Monitoring

Beside the possible consequences for stream contamination, the fluctuating groundwater levels are also likely to affect the transportation of dissolved uranium through the floodplain sediments. Along with the rising and falling groundwater table, also the redox-potential of the floodplain sediments periodically changes between reducing conditions (when submerged) and oxidising conditions (when dry). By redox-initiated co-precipitation of insoluble iron hydroxides (which later turn into oxides) and manganese oxides, dissolved uranium is frequently extracted from the groundwater and immobilised in the sediments. In addition to adsorption, this process contributes to the contamination of floodplain sediments. It particularly affects that range of the (unsaturated) sediment-column, which periodically is exposed to atmospheric oxygen. It often leads to the formation of red layers of sediments covered with hematite (Fe_2O_3), in which extremely high concentrations of uranium are found.

5. Conclusions

Gold mining activities in the study area do not only directly affect the water quality of the Koekemoer Spruit, but also modify hydraulic conditions. Mining related modifications include the alteration of the natural flow-regime in the Koekemoer Spruit to a completely artificial one. Furthermore, the main alluvial aquifer of the stream is affected by seepage from slimes dams, which migrates towards the Koekemoer Spruit, causing elevated groundwater levels in the associated floodplain.

Using real time *in-situ* measurements, close hydraulic links between the stream and the groundwater could be established. Although the steep hydraulic gradient between slimes dams and stream determines the general direction of water flow (resulting in dominating exfiltration/baseflow), also the inverse process takes place. In dry weather periods the direction of water flow between stream and groundwater reverses on a daily basis. This is caused by pronounced diurnal fluctuations of the stream-flow, which causes magnified fluctuations of up to 90cm per day in the associated groundwater table. These hydraulic fluctuations determine the extent of water-borne stream pollution and are likely to affect the aquatic biota by diurnal pulses of dissolved uranium and other heavy metals.

In addition to impacts on the stream, the artificial flow regime also affects the contamination of floodplain sediments. The periodical rising and falling of the associated groundwater table frequently lead to redox-initiated co-precipitation of uranium along with Fe/Mn-hydrous oxides, which preferably accumulate in the upper layers of the floodplain sediments.

The situation at the Koekemoer Spruit is not an isolated occurrence. Many goldmines are active in dolomitic areas, and it is expected that similar surface water – ground water interactions and resultant diffuse contamination will be found at most of these mines. This situation necessitates the revision of water quality monitoring protocols.

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