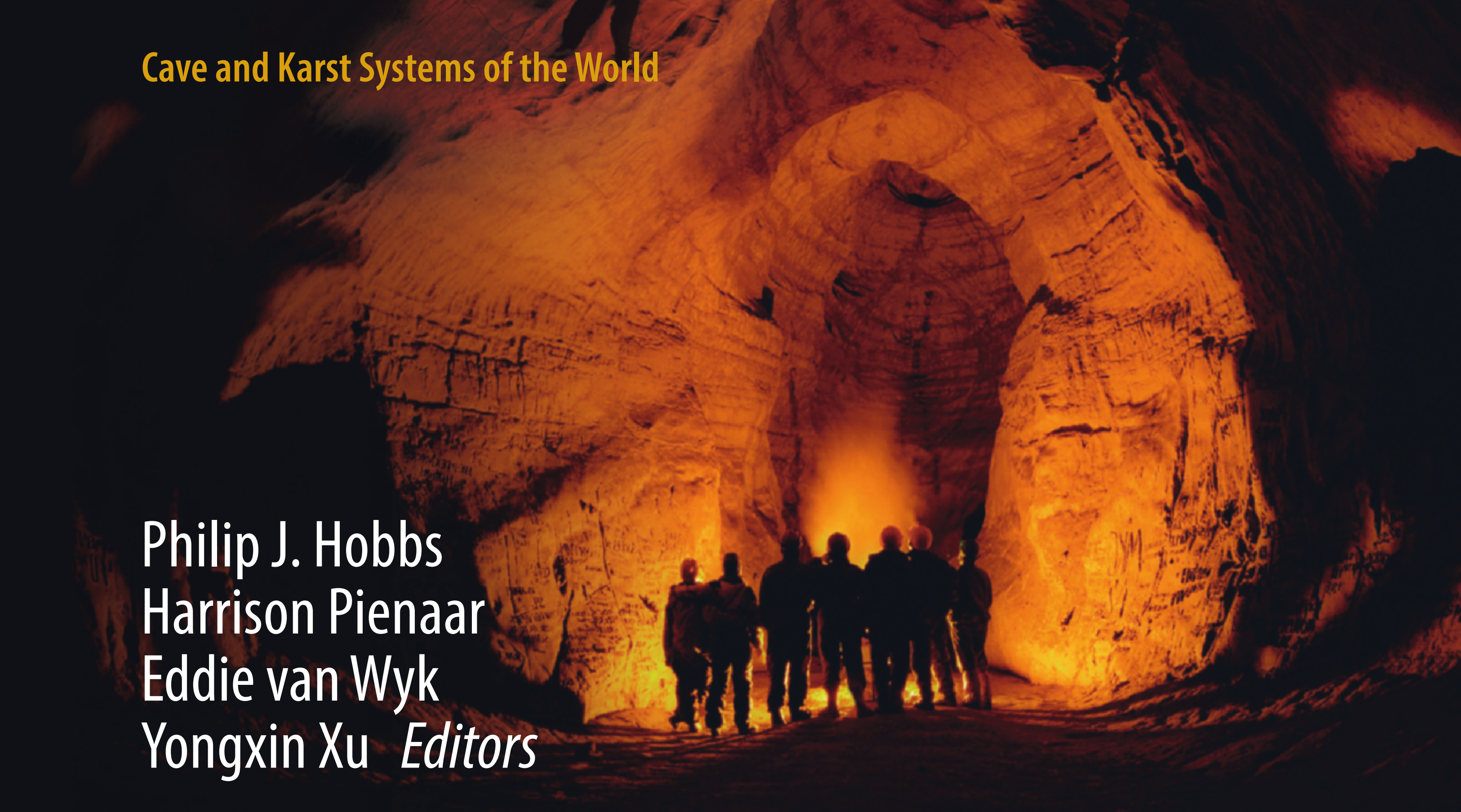
Cave and Karst Systems of the World



Philip J. Hobbs
Harrison Pienaar
Eddie van Wyk
Yongxin Xu *Editors*

Anatomy of a South African Karst Hydrosystem

The Hydrology and Hydrogeology of the Cradle of Humankind World Heritage Site

Springer

Cave and Karst Systems of the World

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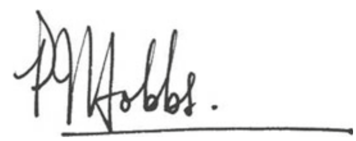
Declaration

I, **Philip J. Hobbs**, declare that this publication is my own work and has not previously been submitted by me for publishing at this or any other institution.



Panoramic view, looking south, of the COH WHS 'core' area in the John Nash Nature Reserve showing the valley carved by the Grootvlei Spruit from left (south-east) to right (north-west) across the landscape; also visible is the early winter smog layer over Johannesburg on the horizon (*Photo* P. Hobbs, date 19/05/2010)

Acknowledgements

It is with gratitude that I acknowledge Prof. Pat Eriksson, former Dean of the Faculty of Natural and Agricultural Sciences, and Prof. Louis van Rooy, Head of the Department of Geology, at the University of Pretoria. It is also fitting that the contributions of the Management Authority of the Cradle of Humankind World Heritage Site (COH WHS), and in particular Mr. Peter (Spike) Mills, Deputy Director Integrated Environment and Conservation Management for the COH WHS and Dinokeng Project, be acknowledged. The Management Authority is thanked for entrusting me with the task of improving the understanding of the water resources environment that contributes to the outstanding universal value of this globally treasured landscape. It is my hope that this publication will serve the Management Authority well in its task of managing and protecting also the water resources component of its UNESCO-entrusted mandate into the future. Peter Mills is thanked for his companionship and support on many excursions into the field.

The contribution of numerous other individuals to the work reflected in this dissertation is acknowledged separately at the end of the text. Many of these are landowners in the study area, and it is my hope that as stakeholders they will benefit from the material and knowledge presented in this dissertation. Others are professional colleagues in the employ of such organisations as the Department of Water and Sanitation (formerly the Department of Water Affairs), the Council for Geosciences and the Council for Scientific and Industrial Research. My thanks go to these individuals for the contribution of their time and effort.

In conclusion, I am thankful for the premeditated and fortuitous factors that a universal intelligence has considered fit to inform my professional career in a scientific discipline that offers so much unsolicited rich return. It is a privilege to contribute towards a better understanding of a complex and largely unseen hydrosystem such as underlies 'The Cradle'.

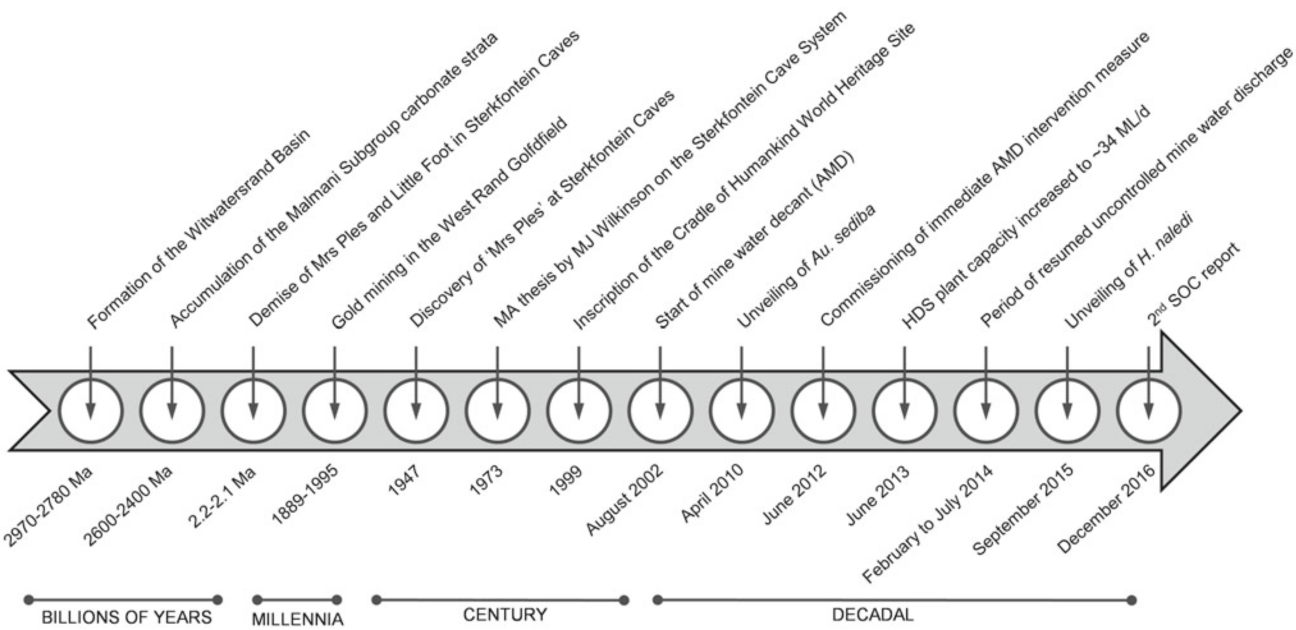
"Entia non sunt multiplicanda praeter necessitatem."
(Entities must not be multiplied beyond necessity.)

John Punch
(Irish theologian 1603-1661)

aka
The law of parsimony (L. Lex parsimoniae)
as formulated by Occam's Razor

View of surface flow and water quality monitoring station A2H049 at the lower end of the Bloubank Spruit at Zwartkop showing hut housing automated stage gauging instrumentation at left, and vertical stage gauge plates in middle and right foreground for visual observation; the blockage by vegetation and debris of the left flank of the weir (right of picture) is not ideal; the northern slope of the 1626 m amsl Zwartkop peak forms the backdrop to this view (*Photo* P. Hobbs, date 05/02/2010)

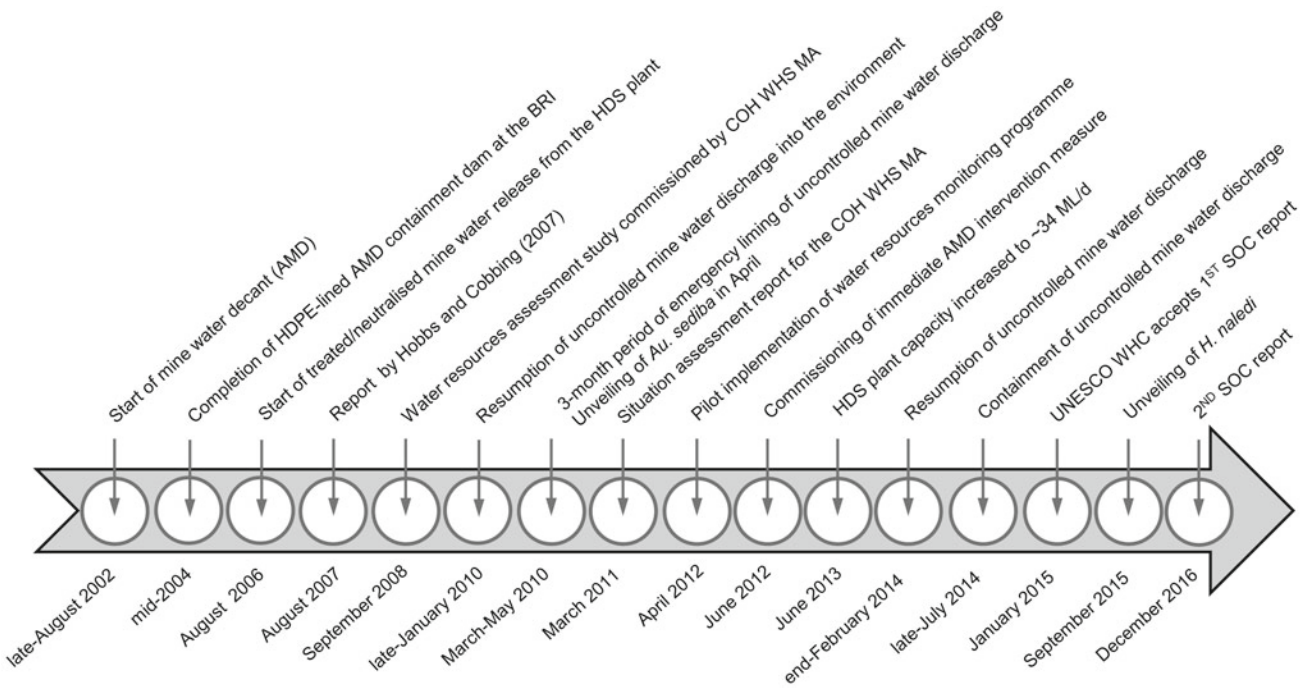
Historical Timeline of Key Events Relevant to this Dissertation



Timeline 1. Historical timeline of key events relevant to the study area. Acid mine drainage and its impact on receiving surface water and groundwater resources is a dynamic phenomenon that is continually evolving in response to both controlled (engineered) and uncontrolled (natural) circumstances. The immediate and short-term intervention measures implemented by the Department of Water and Sanitation (DWS) to control and manage acid mine drainage in the West Rand Goldfield (aka the Western Basin) were commissioned in June 2012. The impact of these measures on the receiving water resources is first manifested in August 2012. This marked the commencement of a new evolving dynamic in the study area, with the termination date for this study of September 2017 representing ~5 years of 'new dynamic' observation

Dolomite pinnacle protruding from a doline formed following flooding by stormwater of a soil borrow-pit alongside Dolomite Road (*Photo* P. Hobbs, date 04/11/2009)

Recent Timeline of Key Events Relevant to this Dissertation



Timeline 2. Recent timeline of key events relevant to the study area. August 2017 marks 15 years since the phenomenon of acid mine drainage first appeared in the Western Basin. The impact of the intervention measures implemented in mid-2010 by the DWS to control and manage AMD in the immediate and short-term started manifesting a positive impact on the downstream surface water resources in August 2012. This represents a key event in the evolving dynamic response of the receiving water resources environment. Under circumstances where much of the hydrological analyses set out in this dissertation use a hydrological and not a calendar year as base temporal unit, this combination of factors signify September 2017 (the most recent complete hydrological year) as an appropriate nominal termination date for the material presented and discussed in this work

Surface expression of the epikarst at the Swartkrans fossil site (*Photo* P. Hobbs, date 18/05/2010)

Extended Summary

Introduction

The fossil hominin sites of Sterkfontein, Swartkrans, Kromdraai and environs (the so-called Cradle of Humankind) were inscribed by UNESCO in 1999 for protection of their cultural heritage in terms of the World Heritage Convention Act (Act No 49, 1999). The Management Authority (MA) of the Cradle of Humankind World Heritage Site (COH WHS) property exercised its mandate to protect also the aquatic environment of the property by commissioning a study aimed at establishing a monitoring system for surface water and groundwater resources in its area of jurisdiction.

The implementation of an appropriate integrated hydrologic and hydrogeologic monitoring programme is crucial to the successful management of the water resources in the COH. An effective routine monitoring programme serves to measure and demonstrate the success or failure of management efforts by the MA to protect the aquatic environment of the property. Such protection is not only required for the preservation of the karst environment and its palaeo-anthropological wealth, but also for the water users who reside in the area and depend on local water resources (primarily groundwater) for their livelihood.

Surface Water Resources

Quantity

The Skeerpoort River system is in a nearly pristine condition. Its perennial nature is sustained mainly by the combined discharge (>300 L/s ≈ 25.9 ML/d ≈ 9.6 Mm^3/a) of three high-yielding karst springs located in the John Nash Nature Reserve. The flow gauging record for the Skeerpoort River indicates a long-term median discharge of ~9.57 Mm^3/a to Hartbeespoort Dam via the Magalies River. This represents ~5% of the net capacity (~190 Mm^3) of the dam.

The flow record for the heavily impacted Bloubank Spruit system indicates a long-term median discharge of ~22.7 Mm^3/a to Hartbeespoort Dam via the Crocodile River. This represents ~12% of the net capacity of the dam. The Bloubank Spruit system experienced above average discharges in its upper reaches via the Tweelopie Spruit and the lower Riet Spruit following the resumption of uncontrolled raw mine water decant in late-January 2010. The combined discharge of raw and treated mine water realised quantified surface water losses of 20 to 32 ML/d to the karst aquifer from the lower Riet Spruit, equating to an infiltration rate of as much as ~90 L/s/km. Together with the discharge from the Percy Stewart Wastewater Treatment Works (WWTW) via the Blougat Spruit, these circumstances resulted in an unprecedented volume of surface water flow in the Bloubank Spruit system through the 2010, 2011 and 2014 winter seasons. The median discharge of ~4.7 Mm^3/a (~13 ML/d) of treated sewage effluent to the Blougat Spruit from the Percy Stewart WWTW equates to ~21% of the long-term median annual discharge of the Bloubank Spruit system.

The Crocodile River flow gauging record at the confluence with its Bloubank Spruit tributary indicates a long-term median discharge of ~9.5 Mm^3/a (~5% of the Hartbeespoort Dam net capacity). As only 15% of this catchment falls within the COH, this discharge is excluded from the aggregate long-term contribution of ~18% (~34.7 Mm^3/a) delivered to Hartbeespoort Dam by the Skeerpoort River and Bloubank Spruit catchments. These catchments together represent ~71% of the study area.

Quality

The Skeerpoort River system delivers a CaMg-HCO_3 water composition of excellent quality. Up until mid-2010, the impact of the poor quality associated with the abnormal combined discharge of treated and raw mine water in the upper reaches of the Bloubank Spruit system was mitigated by the contribution of treated wastewater effluent discharged by the Percy Stewart WWTW and the above average surface water runoff associated with the extremely wet 2010 summer. Since mid-2010, the increase in specific electrical conductivity (SEC) of Bloubank Spruit water from ~50 to >100 mS/m, together with a decrease in pH from 7.2 to 6.9 at the downstream end of the Zwartkrans Basin, reflects the increasing contribution of mine water to the middle reaches of the Bloubank Spruit.

The combination of long-term discharge and water chemistry records for the DWS gauging/sampling stations on the Skeerpoort River (A2H034), the Bloubank Spruit (A2H049) and the Crocodile River (A2H050) allow for an assessment of the total dissolved solids (TDS) loads associated with the respective drainages. This assessment indicates that the Skeerpoort River and (upper) Crocodile River deliver similar TDS loads of 2937 and 3249 t/a respectively, compared to the 10 173 t/a delivered by the Bloubank Spruit system. Again excluding the (upper) Crocodile River load, the values translate into contributions of 22% by the Skeerpoort River and 78% by the Bloubank Spruit system to the total TDS load of 13 110 t/a delivered to Hartbeespoort Dam by the COH drainages. In a regional context, this load constitutes only 13% of that entering the dam, being surpassed by the 51% (51 023 t/a) of the Jukskei River and the 28% (27 579 t/a) of the Hennops River. The balance of 8% (8085 t/a) is shared by the Crocodile River (3%) and the Magalies River (5%).

The quality of surface water resources in the Bloubank Spruit system is further compromised by bacterial contamination and associated elevated nitrate and phosphorus concentrations derived mainly from wastewater effluent. These circumstances also make it difficult to assess the agricultural impacts on the quality of surface water resources, as these are similarly associated with nutrient inputs. As a subset of the total salt load, the nutrient load entering Hartbeespoort Dam is of specific concern given the hypertrophic status of this impoundment. The sampling stations on the Bloubank Spruit system and the (upper) Crocodile River reflect median NO_3-N and PO_4-P loads of 129 and 2.9 t/a, respectively, to the dam in the period 1980 to 2013. A similar appraisal for the Jukskei and Hennops rivers indicates combined median NO_3-N and PO_4-P loads of 1245 and ~104 t/a, respectively, for the same period. In summary, the Crocodile River and Bloubank Spruit systems together contribute <10% to the median long-term NO_3-N load entering Hartbeespoort Dam, being overshadowed by the Jukskei River contribution of ~70% and the Hennops River contribution of ~20%. The PO_4-P load is dominated even more by the Jukskei and Hennops rivers, with the Crocodile River and Bloubank Spruit systems delivering <3% of this nutrient load to the dam annually.

A primary concern for the downstream environment is the impact of mine water, in particular the presence of trace/heavy metals, metalloids and radionuclides, on the quality of water in the Bloubank Spruit system. In the period of maximum likely impact, namely February 2010 to July 2012, median Fe and Mn levels of 0.013 mg Fe/L and 0.003 mg Mn/L in surface water at the lower end of the system on 33 sampling occasions, compare favourably with levels of 163 mg Fe/L and 65 mg Mn/L in composite mine water discharge in the upper reaches of the system on 129 sampling occasions. Mercury levels in surface water typically do not exceed 0.002 mg/L. Arsenic levels similarly seldom exceed the detection limit of 0.002 mg/L. Nickel presents as the most persistent trace metal in upper (headwater) reaches, the median concentration of 0.1 mg Ni/L from 41 sampling occasions exceeding the SANS (2015a) limit of 0.07 mg/L. As with Fe and Mn, Ni levels in the lower reaches of the system do not test the 0.07 mg/L limit.

Uranium levels in surface water nowhere and on no sampling occasion exceeded the analytical detection limit of 0.001 mg/L for this analyte. Radon (^{222}Rn) activity levels representative of the headwater reach in the mine area fall within the minimum detectable activity (MDA) of ~0.5 Bq/L. This compares favourably with the maximum contaminant level (MCL) of 11.1 Bq/L set by the USAs Safe Drinking Water Act (SDWA). Similarly, radium (^{226}Ra) activity levels do not exceed the SDWAs MCL of 0.185 Bq/L for this radionuclide in the extremely sparse set of available data.

The persistence of poor bacteriological quality as reflected in alarmingly high faecal coliform and *E. coli* values associated with surface water in the Bloubank Spruit, continues to represent a significant threat to the 'fitness for use' of this resource. This situation reflects the poor score achieved by the Percy Stewart WWTW in both the 2009 and 2011 DWS 'Green Drop' reports, and in particular the non-compliance in regard to the effluent wastewater quality metric. A thorough evaluation of this threat is thwarted by the non-disclosure of pertinent monitoring data by the local authority.

Groundwater Resources

Quantity

Springs are widely recognised as the most appropriate gauging, sampling and monitoring points in a karst environment. The study has enumerated eleven springs (excluding the seven located in the Krugersdorp Game Reserve) in the subregion. The total number of such features in the subregion is almost certainly greater. Some of the features represent groups of springs (and seeps) located in close proximity to one another. Nine of these drain dolomitic strata, the 'weakest' delivering ~2 L/s and the 'strongest' ~307 L/s. The total yield of these sources amounts to ~827 L/s (~71.5 ML/d ≈ 26.1 Mm^3/a). This equates to ~14% of the net capacity of Hartbeespoort Dam, and reflects the very important contribution of mainly good to excellent springwater to the water resources of the wider region. None of the enumerated springs are subject to regular and routine discharge measurements. Synoptic discharge measurements in this study have served to quantify the yield of many of these features for the first time.

Groundwater quantity is further represented by groundwater level data and information. The study has generated 117 groundwater level measurements from as many sources (18 springs and 99 boreholes). Each of these measurements has been translated into an absolute value representing a groundwater elevation above mean sea level. Together with the locations and elevations of the various springs, this information has led to an improved understanding of groundwater flow and movement especially in regard to the dolomitic strata. As a consequence, redefinition of the physical hydrogeologic environment recognises a degree of compartmentalisation that contributes significantly to a more informed understanding of the karst groundwater environment. A total of ten dolomitic compartments, two of which comprise subcompartments, are identified in the COH. Most of the compartments are drained by springs. Water budget calculations for the seven karst basins drained by springs with yields >20 L/s and factoring in their surface extent, indicates that 17 ± 5% of a mean annual precipitation of 710 mm provides a reasonable approximation of natural autogenic recharge from rainfall for the karst hydrosystem.

The behaviour of groundwater levels associated with the karst aquifer is reflected in the long-term water level records for 15 DWS monitoring boreholes dating back to 1985. In 11 of these instances, the record period extends to the present. An analysis of the data indicates a generally excellent agreement between the mean and median values. This reflects the large measure of constancy in this variable. Further, there is little correlation between the depth to groundwater rest level and the magnitude of water level variation; relatively small variations (<3 m) being associated with both 'deep' (>60 m bs) and comparatively 'shallow' (<30 m bs) water levels. The data set reveals a maximum water level variation value of ~12.2 m, with mean and median values of ~6.2 m and ~5.6 m, respectively. The slightly smaller differences associated with the 5%ile to 95%ile interval are characterised by a maximum value of 9.8 m, and mean and median values of 5.2 and 4.6 m respectively.

The very wet 2010, 2011 and 2014 summers precipitated an exceptional recharge of groundwater resources in the study area. A rise in groundwater rest levels by ~4.9 m on average testifies to these circumstances. Greater water level rises (by up to ~8 m) are attributed to artificial and allogenic recharge associated with the infiltration of surface water contributed from extraneous sources including mining and municipal wastewater effluent. This infiltration has amounted to as much as ~32 ML/d in the case of mine water, and ~7 ML/d in the case of municipal wastewater. The recent (since 2012) groundwater level (water table) elevations in the COH are the highest in the ~30-year record of monitoring.

Quality

Groundwater quality in the COH is defined on the basis of chemical analyses carried out on water samples obtained from 51 sources (7 springs and 44 boreholes). The analytical suite include inorganic, organic and bacteriological variables, heavy/trace metals/metalloids and environmental isotopes as well as pesticide residue analyses employed selectively. In addition, numerous measurements of field variables (pH, EC, ORP/Eh and temperature) have been carried out on an ad hoc basis at a number of springs.

As might be expected, the hydrochemistry reflects a greater or lesser spatial variation depending on the position in the physical hydrogeologic environment. For instance, the subcompartments receiving water of compromised quality in terms of either trace/heavy metals/metalloids and elevated TDS loads associated with mine water, and/or elevated bacterial and nutrient loads associated with municipal wastewater (both representing allogenic recharge), reflect the poorest groundwater quality. Despite its location, however, the Lake water in Sterkfontein Cave continues to reflect an SEC of <70 mS/m as it did in June 2006. Karst basins receiving only autogenic recharge remain largely unaffected in terms of groundwater chemistry/quality.

Conclusions

The understanding of the surface water and groundwater environments in the COH, also in regard to the inter-relationship between these resources, is considerably expanded by this study. This understanding extends as much to the water chemistry aspect as it does to the water quantity aspect. The platform built from historical data, and its integration with a wide range of rigorous and defensible newly-generated and interpreted hydrologic and hydrogeologic data and information, convincingly underpins the situation assessment of the surface water and groundwater environments. This, in turn, has provided the means to objectively gauge the impact of varied and numerous threats on the water resources in the study area, and to develop a coordinated, appropriate and cost-effective water resources monitoring programme. Outcomes of the study that are considered especially significant are summarised as follows.

- The quantification of surface water flow losses, especially those dominated by a mine water character in the lower Riet Spruit valley.
- The quantification of spring discharges.
- The definition of basins/subcompartments and corresponding groundwater resource units (GRUs) associated mainly with the karst formations in the study area.
- The development of semi-quantitative resource water quality objectives (RWQOs) to inform surface and groundwater resource directed measures for the karst portions of the study area.
- The derivation of a fossil site risk assessment that informs the vulnerability of each recognised fossil site and associated cave system in the context of its hydrogeologic setting.

A cause for grave concern is the unprecedented abnormally high flow conditions experienced in the Bloubank Spruit system in the more recent hydrological years, as this discharge is the result of abnormally high mine water decant driven by copious recharge associated with above average rainfall. This has already manifested itself as historical maximum SEC and sulphate values at the lowest end of the Bloubank Spruit system.

Recommendations

The study has identified various concerns that give rise to the following general recommendations.

- The advisability of carrying out a gravimetric survey in the lower Riet Spruit valley extending from the confluence of the Tweelopie Spruit and the Riet Spruit down to the confluence of the Blougat Spruit and the Riet Spruit. The results of such a survey will indicate the measure of karst dissolution present in this important E–W corridor that hosts the N14 national road.
- The advisability of extending the hydrovulnerability assessment to other cave systems in the study area, together with a refinement of the applied assessment methodology.
- The establishment of a monitoring committee comprising a core of key stakeholder groupings, e.g. national, provincial and local government, environment and tourism, agriculture.
- The hosting (by the Management Authority) of a workshop or seminar to communicate the outcomes of the study to as wide an audience of stakeholders and interested and affected parties as are interested.
- The expansion of the mine water treatment capacity in the headwaters of the Tweelopie Spruit to accommodate a decant volume of $\sim$60 ML/d, representing a 2-fold increase in the current treatment capacity.
- The establishment of additional mine water treatment facilities in the headwaters of the Tweelopie Spruit to further ‘polish’ the treated mine water that is generated by the expanded mine water treatment capacity and released into the environment.

Contents

Symbols, Acronyms and Abbreviations

~	Approximately
≡	Equivalent
>	Greater than
>>	Much greater than
≥	Greater than or equal to
≤	Less than or equal to
<	Less than
#	Number
±	Plus-minus
δ	Delta (notation)
Δ	Change in
Σ	The sum of
μg/g	Microgram(s) per gram
%	Per cent (parts per hundred)
‰	Per mil (parts per thousand)
%ile	Percentile
°C	Degree(s) Celsius (centigrade)
°C/m	Degree(s) Celsius per metre
°E	Degree(s) East (longitude)
°S	Degree(s) South (latitude)
^{2}H	Deuterium
^{3}H	Tritium
^{18}O	Oxygen-18
a	Annum
a_h	Hydrological year
A.	Afrikaans
amsl	Above mean sea level
ABA	Acid base accounting
AET	Actual evapotranspiration
A.H.	Agricultural Holdings
aka	Also known as
Al	Aluminium
AMD	Acid mine drainage (or) decant (or) discharge
ARC	Agricultural Research Council
As	Arsenic
ASPT	Average score per taxon
ATSDR	Agency for Toxic Substances and Disease Registry
atm	Atmosphere(s)
Au.	Australopithecus
B	Boron
Ba	Barium

bc	Below collar
BE	Built Environment (a business unit of the CSIR)
bgl	Below ground level
BP	Before present
Bq/g	Becquerel(s) per gram
Bq/L	Becquerel(s) per litre
bs	Below surface
BSR	Bacterial sulphate reduction
bwl	Below water level
C	Carbon
C_X	Concentration (C_U = upstream; C_D = downstream; C_F = furrow; C_S = spring; C_G = groundwater)
C_5	Concentration exceeded 5% of the time (equivalent to 95%ile)
C_{50}	Concentration exceeded 50% of the time (equivalent to 50%ile)
C_{95}	Concentration exceeded 95% of the time (equivalent to 5%ile)
ca.	Circa (about)
Ca	Calcium
Cd	Cadmium
CD	Compact disc
CDSM	Chief Directorate: Surveys and Mapping (in the Department of Land Affairs)
cfu	Colony forming unit(s)
CGS	Council for Geoscience
Cl	Chloride
CMB	Chloride mass balance
CN	Cyanide
Co	Cobalt
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COH WHS	Cradle of Humankind World Heritage Site
CoV	Coefficient of variation
CPOM	Coarse particulate organic matter
Cr	Chromium
CROSA	Cave Research Organisation of South Africa
CSIR	Council for Scientific and Industrial Research
CTR	Corrosion tendency ratio
Cu	Copper
d	Day(s)
dd.ddddd	Degrees latitude (or) longitude expressed to the 5th decimal
dd/mm/yyyy	Date format as day/month/year, e.g. 10/11/2012 ≡ 10 November 2012
DEA	Department of Environmental Affairs (formerly Department of Environmental Affairs and Tourism)
DEAT	Department of Environmental Affairs and Tourism
DED	Department of Economic Development (Gauteng Province)
DL	Detection limit
DLA	Department of Land Affairs
dm	Decimetre
DME	Department of Minerals and Energy
DMR	Department of Mineral Resources (formerly Department of Minerals and Energy)
DMS	Dissolved mineral salts
DO	Dissolved oxygen
DOC	Dissolved organic carbon

DPLG	Department of Development, Planning and Local Government
D:RQS	Directorate: Resource Quality Services (a directorate in the DWS)
DWA	Department of Water Affairs (formerly Department of Water Affairs and Forestry)
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation (formerly the Department of Water Affairs)
EB	Electrical balance (aka ion balance or charge balance)
EC	Electrical conductivity
ECL	Environmental critical level
E. coli	*Escherichia coli* bacteria
EDC	Endocrine disrupting chemical
Eh	Free electron (e^-) activity defined as $-\log_{10}[e^-]$; also assigned the abbreviation pε
e.g.	*Exempli gratia* (for example)
EI&S	Ecological importance and sensitivity
EMF	Environmental management framework
EMS	Environmental management system
EoP	End-of-pipe
EPA	Environmental Protection Agency
Eq	Equation
eq	Equivalent
ERWAT	East Rand Water Care Company
ESE	East-south-east
ET	Evapotranspiration
EurepGAP	Euro-Retailer Produce Working Group Good Agricultural Practice
Fe	Iron
FFG	Functional feeding group
FIB	Faecal indicator bacteria
Fm.	Formation (geological term)
FPOM	Fine particulate organic matter
FSE	Federation for a Sustainable Environment
FSLTS	Feasibility study for a long-term solution (commissioned by the DWS)
G	Billion (10^9)
G1	Gold1 (operating in conjunction with Rand Uranium)
g/t	Gram(s) per ton
Ga	Billion years
GC	Gas chromatograph
GDACE	Gauteng Department of Agriculture, Conservation and the Environment
GDARD	Gauteng Department of Agriculture and Rural Development (formerly GDACE)
Gg/a	Gigagram(s) per annum
GIS	Geographic information system
G.M. Co.	Gold Mining Company
GMU	Groundwater management unit
GNIP	Global network of isotopes in precipitation
Gp.	Group (geological term)
GPS	Global positioning system
GRA	Groundwater resource assessment
GRDM	Groundwater resource directed measures
GRU	Groundwater resource unit
h	Hour(s)

H	Weighting value
H.	Homo
HCO_3	Bicarbonate
ha	Hectare(s)
HDS	High density sludge
HDPE	High density poly-ethylene
H_i	Hazard index
HPC	Heterotrophic plate count (also referred to as total plate count)
i	Hydraulic gradient
I&AP	Interested and affected party
ICOMOS	International Council on Monuments and Sites
ICP	Inductively coupled plasma
IDP	Integrated development plan
i.e.	*Id est* (that is to say)
IGTT	Inter-Governmental Task Team (on AMD)
IGU	International Geophysical Union
IHAS	Integrated Habitat Assessment System
IHIA	Integrated Habitat Integrity Assessment
IMC	Inter-Ministerial Committee (on AMD)
iro	In respect of
iTLABS	iThemba LABS (a National Research Foundation facility)
IUCN	International Union for Conservation of Nature
JFA	Johan Fourie and Associates (Environmental Consultancy)
JNNR	John Nash Nature Reserve
K	Potassium
K_X	Equilibrium constant for mineral X, where X = C = calcite, and X = D = dolomite
Ka	Thousand years
KFD	Koelenhof Farm Dam
kg/d	Kilogram(s) per day
$kg/km^2/a$	Kilogram(s) per square kilometre per annum
kg/m^3	Kilogram(s) per cubic metre
KGR	Krugersdorp Game Reserve
km	Kilometre(s)
km^2	Square kilometre(s)
km/h	Kilometre(s) per second
kt	Kiloton(s)
L.	Latin
LC_x	Concentration causing x% lethality
L/kg/d	Litre(s) per kilogram per day
LMDC	Leadership and Management Development Centre (Nedbank's Olwazini Estate)
LoD	Locus of decant
L/s	Litre(s) per second
LSC	Liquid scintillation counting
L/s/km	Litre(s) per second per kilometre
m	Metre(s)
M	Million (10^6)
m/Ma	Metre(s) per million years
m^2/d	Square metre(s) per day
$m^3/km^2/a$	Cubic metre(s) per square kilometre per annum $\equiv$ mm/Ka
m/s	Metre(s) per second

m^3/s	Cubic metre(s) per second (also referred to as 'cumec(s)')
MA	Management Authority
Ma	Million years
MAD	Mean annual discharge
MAP	Mean annual precipitation
MA_hP	Mean hydrological year precipitation
MAPE	Mean annual potential evaporation
MAR	Mean annual runoff
MAT	Mean annual temperature
max.	Maximum
MCL	Maximum contaminant level
MCLM	Mogale City Local Municipality
MDA	Minimum detectable activity
MDB	Municipal Demarcation Board
MEC	Member of the Executive Council
med.	Median
MG	Mogale Gold (operating in conjunction with Mintails SA)
Mg	Magnesium
mg/kg	Milligram(s) per kilogram
MG/MSA	Mogale Gold/Mintails SA
mg/L	Milligram(s) per litre
mg/s	Milligram(s) per second (1 mg/s $\equiv$ 0.000084 t/d)
min.	Minimum
mL	Millilitre(s)
ML	Megalitre(s) (1 ML $\equiv$ 1 million litres)
ML/d	Megalitre(s) per day
mm/a	Millimetre(s) per annum
mm/Ka	Millimetre(s) per thousand years
mm/yyyy	Month/year (e.g. 01/2010)
Mm^3/a	Million cubic metre(s) per annum
Mm^3/m	Million cubic metre(s) per month
Mn	Manganese
MNR	Motsetse Nature Reserve
Mo	Molybdenum
MP	Management plan
MPN	Most probable number
MRD	Mine residue deposit
mS/m	MilliSiemens per metre
MSM	Monitoring system manual
MSRF	Morphologic suite of rising flow
mV	MilliVolt(s)
n	Count (of sample population)
n.a.	Not analysed
n/a	Not applicable
Na	Sodium
n.d.	Not determined
NAEHMP	National Aquatic Ecosystem Health Monitoring Programme
NE	North-east
NFEPA	National Freshwater Ecosystem Priority Areas
NGO	Non-governmental organisation
NH_3	Ammonia nitrogen
NH_4	Ammonium nitrogen

Ni	Nickel
n.m.	Not measured
nm	Nanometre(s) (1 nm = 1×10^{-9} m)
No	Number
NO_2	Nitrite nitrogen
NO_3	Nitrate nitrogen
NOE	Nedbank Olwazini Estate
NRE	Natural Resources and the Environment (a business unit of the CSIR)
n/s	Not specified
NTU	Nephelometric turbidity unit(s)
O-PO_4	Ortho-phoshate
ORP	Oxidation reduction potential; also simply referred to as 'redox' potential
OUV	Outstanding universal value
p	Page
P	Phosphorus
Pb	Lead
pCi/L	PicoCurie(s) per liter
P_{CO2}	Partial pressure (activity) of CO_2
pε	Free electron (e^-) activity defined as $-\log_{10}[e^-]$; also assigned the abbreviation Eh
pH	Free hydrogen ion activity (α_{H+}) defined as $-\log_{10}\alpha_{H+}$ where $\alpha_{H+} = f$ x $[H^+]$ with f the activity coefficient and $[H^+]$ the hydrogen ion concentration
PO_4	Phosphate
pp	Pages
Pt	Petaton
Pt	Platinum
Ptn	PORTION
Q_X	Flow or discharge (Q_U = upstream; Q_D = downstream; Q_F = furrow; Q_S = spring; Q_G = groundwater)
Q_{25}	Flow or discharge exceeded 75% of the time (equivalent to 25%ile)
Q_{50}	Flow or discharge exceeded 50% of the time (equivalent to 50%ile)
Q_{75}	Flow or discharge exceeded 25% of the time (equivalent to 75%ile)
Q^n	Ranking factor
Q_{min}	Minimum flow or discharge
Q_{max}	Maximum flow or discharge
R.	River
R^f	Reduction factor
RAIS	Risk Assessment Information System
REGM	Randfontein Estates Gold Mine
RET	Riparian evapotranspiration
RHP	River health programme
RI_i	Risk intensity index
RMW	Raw mine water
RSA	Republic of South Africa
RWQOs	Resource water quality objective(s)
RU	Rand Uranium (successor to Harmony Gold)
RU/G1	Rand Uranium/Gold1 (successor first to Harmony Gold and then Uranium1)
RWL	Rest water level
S.	Spruit
SABS	South African Bureau of Standards
SAC	Satellite Applications Centre
SAFF	Submerged aeration fixed film

SAIEEG	South African Institute of Engineering and Environmental Geology
SAKWG	South African Karst Working Group
SANAS	South African National Accreditation System
SANBI	South African National Biodiversity Institute
SANParks	South African National Parks
SANS	South African National Standard
SAR	Sodium adsorption ratio (a calculated chemical variable)
SASS	South African Scoring System
SAWS	South African Weather Service
Sbgp.	Subgroup (a geological term)
SC	Sterkfontein Cave
SD	Standard deviation
SDF	Spatial development framework
SDM	Synoptic discharge measurement
SDWA	Safe Drinking Water Act (administered and overseen by the US EPA)
Se	Selenium
SEC	Specific electrical conductivity (EC @ 25 °C)
SECL	Socio-economic critical level
SEM	Scanning electron microscopy
SHE	Standard hydrogen electrode
Si	Silicon
SI_C	Saturation index of calcite expressed as $\log\{[Ca^{2+}][CO_3{}^{2-}]/K_C\}$
SI_D	Saturation index of dolomite expressed as $\log\{[Ca^{2+}][Mg^{2+}][CO_3{}^{2-}]^2/K_D\}$
SMOW	Standard mean ocean water
SoC	State of conservation
SoE	State of the environment
SO_4	Sulphate
Sp.	Spring
Spgp.	Supergroup (a geological term)
Sr	Strontium
SRB	Sulphate reducing bacteria
SRK	Steffen, Robertson and Kirsten (Consulting Engineers and Scientists)
SS	Suspended solids
S-S	Sibanye-Stillwater (successor to Uranium1)
StatsSA	Statistics South Africa
SW	South-west
t	Ton(s)
T	Transmissivity
t/a	Ton(s) per annum
t/d	Ton(s) per day
t/m	Ton(s) per month
t/ML	Ton(s) per megalitre
T.Alk.	Total alkalinity (as $CaCO_3$)
TC	Total carbon
TCLP	Toxicity characteristic leaching procedure
TCTA	Trans-Caledon Tunnel Authority
TDS	Total dissolved solids/salts
TIC	Total inorganic carbon
TMW	Treated/neutralised mine water
TOC	Total organic carbon
ToC	Table of Contents
TOL	Target operating level

TON	Threshold odour number
ToR	Terms of reference
TR_i	Total risk index
TU	Tritium unit(s) (1 TU = 1 tritium in 10^{18} hydrogen atoms)
Turb.	Turbidity
TWQR	Target water quality range
U	Uranium
UIS	Union Internationale de Spéléologie (International Union of Speleology)
UNESCO	United Nations Educational, Scientific and Cultural Organisation
US(A)	United States (of America)
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
V	Vanadium
V_i	Vulnerability index
VCR	Ventersdorp Contact Reef
vs.	Versus
w	Width
WARMS	Water authorisation and registration management system (a DWS database]
WBTWG	Western Basin Technical Working Group
WCPA	World Commission on Protected Areas
WGC	Water Geosciences Consulting
WGS84	World Geodetic System 1984 (reference ellipsoid for Hartebeesthoek94 Datum)
WHC	World Heritage Centre (could also denote World Heritage Committee)
WHO	World Health Organisation
WMA	Water management area
WNW	West-north-west
WRC	Water Research Commission
WRDM	West Rand District Municipality
WWTW	Wastewater treatment works
XRD	X-ray diffraction
XRF	X-ray fluorescence
y	Year(s)
Zn	Zinc

List of Figures

Overview of Karst

Physical Hydrology

Chemical Hydrology