Unearthing a hidden treasure: 60 years of karst research in the Far West Rand, South Africa

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Karstified dolomitic formations situated in the Far West Rand goldfield of the Witwatersrand Basin constitute a significant groundwater resource in semi-arid South Africa and would be of strategic importance for alleviating the increasing water stress in nearby metropolitan areas. The deep-level gold mines operating below the dolomites have suffered from large volumes of dolomitic groundwater flowing into the mine voids, rendering mining both expensive and hazardous. In order to secure safe and economical mining, the overlying dolomites were dewatered. Here we review research over 60 years, conducted in three of the four major dolomitic compartments affected by dewatering. After more than six decades of research, these aquifers are arguably the most investigated karst systems in South Africa, and possibly worldwide. The data generated are, in many respects, unique, as many measurements can never be repeated, covering stochastic events such as a major water inrush into mine workings and some of the most catastrophic sinkhole developments ever recorded. Given the potential value for improving the understanding of general and local karst hydrogeology, our main goal for this paper is to alert the scientific community to the existence of this resource of mostly unpublished data and research. A no less important aim is to support a systematic collation of these studies which are in danger of being irretrievably lost as mines increasingly close down. Ecological and economic impacts of the flooding of mines in and around Johannesburg emphasise the lack of reliable historical mine data to optimally address the matter. We provide the first comprehensive, yet not exhaustive, overview on the existing studies, briefly discussing scientific content as well as obstacles for utilising the scattered, and often non-peer reviewed, information sources.

Introduction

The goldfield of the Far West Rand is a major deep-level mining area of South Africa, located approximately 50 km south west of Johannesburg (Figure 1). The gold-bearing reefs are covered, amongst others, by thick karstified dolomites, which host some of the largest groundwater resources in South Africa, supporting a range of high-yielding karst springs. Deep-level gold mining in the Far West Rand started in 1934 and soon affected the hydrological and hydrogeological environment.[1] Mining-related impacts included the dewatering of the dolomitic aquifers that caused several karst springs to dry up (Figure 1) and the diversion of streamflow from a river into a nearly 30-km-long pipeline. The impacts of mining have not only initiated numerous water-related studies, but have also created the necessity for ongoing research to develop environmentally acceptable mine closure strategies and sustainable long-term water management options.

Given the large volumes of water involved, and their proximity to water-stressed metropolitan areas affected by increasing water scarcity,[2] we believe that the systematic compilation and evaluation of existing relevant information will be crucial to understanding long-term impacts of historical mining and successfully utilising these valuable water resources in the future.

More than six decades of water-related research in the Far West Rand has generated an enormous amount of knowledge, expertise and data with great potential for developing sustainable post-mine closure strategies in the Far West Rand. The current uncontrolled rise of acidic mine water in the West, Central and East Rand regions poses severe threats to the environment, which will cause significant cost to the taxpayers. This situation illustrates the dire consequences of haphazard and unprepared mine closure, exacerbated by a lack of access to historical data and information. It is therefore imperative to prevent a similar loss of data and expertise in the Far West Rand – the largest of the remaining active goldfields of the Witwatersrand Basin. It is necessary to proactively collate all the available relevant data whilst access to underground structures is still possible and operational mining companies are still in a position to address potential gaps in order to avoid the negative consequences of closure.

Collating the large amount of knowledge proves, however, to be difficult, as much of it is spread across many role players, including the various mining companies/houses, governmental departments, municipalities, consultants and research institutions. Information held by dedicated archives and structured databases is often unavailable, whilst tracing the location of specific reports can be challenging. These difficulties are exacerbated by changes in government personnel as well as in the structure of the mining industry, which often results in existing reports and data no longer being retrievable, as is the knowledge and insight of experts who are no longer working in the field. This phenomenon is termed the 'loss of institutional memory'[1], which leads to repetition of research in the best case and loss of irreplaceable unique information in the worst case.

Another obstacle to utilising the accumulated knowledge results from the fact that much of it was generated without exposure to peer review, or other methods of quality assurance. A large proportion of the literature produced over the last six decades consists of reports drafted by private consultants, government officials and technical mine personnel. Generally driven by matters affecting day-to-day operations, some urgent and case specific, these studies have in common a strong focus on practical applicability rather than scientific rigour. Moreover, many reports are of limited circulation as they are contained in internal, unpublished or confidential documents, severely limiting public access. As a consequence, whilst undoubtedly containing particularly unique data and information, many reports hardly satisfy strict scientific standards in terms of objectivity, quality assurance and referencing. The lack of proper referencing, in particular, frustrates tracing and verifying the sources of information. Dedicated sections explaining the methodology applied for generating the presented data are commonly absent. All this limits the ability of researchers to assess the reliability and quality of the data and information, thus reducing their scientific value. Consequently many reports have to be approached with caution in order to avoid compromising the quality of follow-up studies. Unfortunately this applies to the bulk of available consulting reports which often liberally use information and data from third parties without quoting the original sources.

In addition to raising awareness to these challenges, we aim here, for the first time, to provide a structured overview on the scope and extent of existing literature. To this end, each available study is allocated to one of six topical categories. Geographically, we focus predominantly on literature pertaining to the three currently dewatered groundwater compartments (Venterspost, Bank, Oberholzer) to which the overwhelming majority of studies refers.

As the number of documents concerned with hydrological issues in the Far West Rand runs into the thousands, this overview is not exhaustive. Ideally, this review should be followed by systematically archiving the available sources – preferably in digitised format to allow for collation in a single, centrally managed and searchable electronic database.

Topical categories of research in the Far West Rand

This review covers hydrogeological research in the Far West Rand from the mid-20th century, when industrial-scale deep-level mining, as well as large-scale dewatering of the dolomitic compartments, commenced to the present (2012). Excellent overviews on the course of events related to deep-level mining in the Far West Rand and associated hydrogeological impacts are provided by Swart et al.[3] and Winde[4]. Based on these and other sources, six major research themes were identified, into which the available studies are categorised: (1) general geology of the study area, (2) groundwater-related problems faced by the mines, (3) ground instabilities and sinkholes following the dewatering, (4) hydrogeological characterisation of dolomitic compartments, (5) mining-related water quality issues and (6) closure of mines. These categories are briefly discussed, with a focus on some of the most prominent sources.

General geology of the study area

First published reports of geophysical investigations in the Far West Rand[5,6] date back to the 1930s[7]. De Kock[7] compiled those findings as well as numerous company reports from gold mines, comprehensively addressing the geology of the Far West Rand, describing the major geological formations as well as structural geological features such as the major faults and intrusive and impermeable dykes. Trending roughly north to south, the latter form the eastern and western boundary of the groundwater compartments and thus are essential for understanding the hydrogeology of the Far West Rand.

The work of De Kock[7] provided the basis for later and more detailed studies of the area. Subsequent geological descriptions supplementing his work include those of Brink[8], the South African Committee for Stratigraphy[9], Engelbrecht[10], Robb and Robb[11] and McCarthy[12].

Groundwater-related problems faced by the mines

In many instances, hydrological research was initiated by the ingress of large volumes of groundwater from the overlying karst aquifers into the mine void.

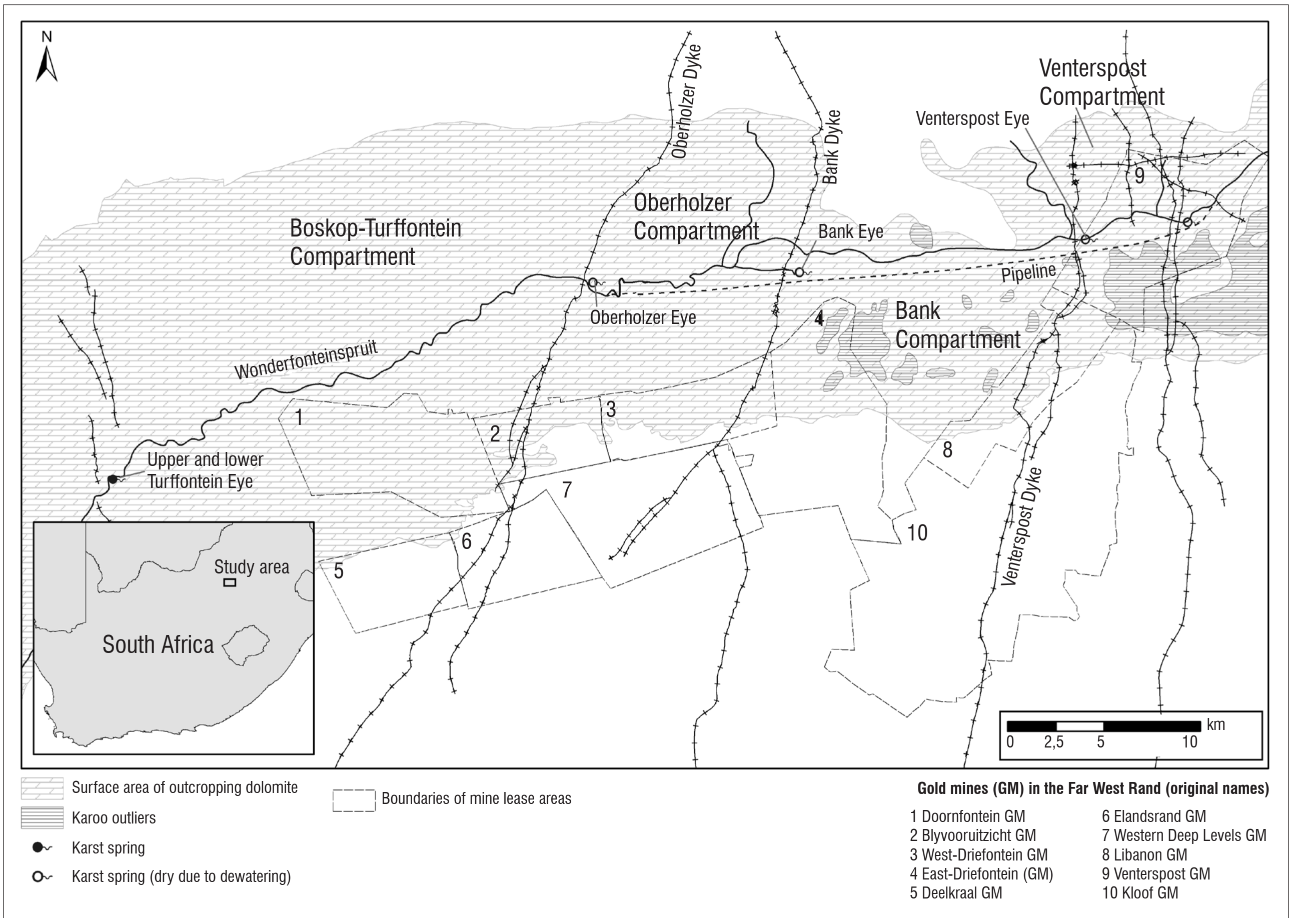

Figure 1: Locality plan and map of the central part of the Far West Rand goldfield showing the surface area of outcropping water-bearing dolomite, the position of dykes and the boundaries of mine lease areas.

In 1957, a tracer test was conducted in the area at Blyvooruitzicht Goldmine in the Oberholzer Compartment (Figure 1) which aimed to determine the rate of recirculation of water pumped from the underground mine void to the surface, followed by ingress into the mine void.[13] From this test, conclusions were drawn on the groundwater flow velocity as well as on the volume of groundwater stored in the dolomite and possible leakage through dykes. The consequences, practicability and economic viability of dewatering the groundwater compartments have been discussed in several unpublished reports.[14-17]

The most significant study on this topic was performed by the Interdepartmental Committee of Dolomitic Mine Water between 1956 and 1960 under the authority of the Minister of Water Affairs. This study thoroughly examined a range of aspects associated with the ever-increasing ingress of groundwater into the growing mine voids. The resultant 'Jordaan Final Report'[18] was a compilation of findings from several detailed studies (e.g. Enslin and Kriel[19]) that, inter alia, also investigated environmental and economic consequences of the dewatering of the two dolomitic compartments under investigation. Many hydrological data (e.g. spring flow volumes) that appear in later studies originate from the 'Jordaan Report', even though the source is not indicated in many instances. Following the recommendations of the report, legal permission to dewater the Oberholzer compartment – as defined by Wolmarans[20] – was granted to the Chamber of Mines by government after the 4-year investigation was concluded. Two of the three mines involved had already started this process well before the permission was granted, as two springs had already ceased to flow. [21]

In 1968, a massive inrush of groundwater occurred at the West-Driefontein mine (Figure 1). The event that eventually led to the dewatering of the Bank Compartment was described in detail by Cartwright[22] and Cousens and Garrett[23]. Valuable facts relating to inrush volumes during and prior to the event are to be found in an unpublished report from the Acting Secretary for Water Affairs.[24]

After official dewatering of the compartments commenced, numerous studies (see following sections) were carried out, aiming to characterise the aquifer system and adjacent geological formations, in order to respond to the various hydrogeological consequences of dewatering and resulting problems encountered during daily operations.

Ground instabilities and sinkholes following dewatering

After dewatering commenced, ground instability – in the form of subsidences and often dramatic sinkholes – rapidly developed. The consequence of lowering the water table demanded scientific attention. Early descriptions of the phenomenon exist[25,26]; later, the processes were described comprehensively by Brink[8]. Bezuidenhout and Enslin[26], Kleywegt and Enslin[27] and Kleywegt and Pike[28] evaluated data from gravimetric surveys carried out in order to delineate high-risk areas for sinkhole formation. In accordance with the serious consequences of sinkholes for the local population and infrastructure, and the associated public and political attention given to the matter, these surveys were unprecedented in terms of their level of detail and spatial scale. The findings of these surveys indicated that the formation of sinkholes depends on specific geological and hydrological conditions relating to the depth and shape of the bedrock surface[26-28], the nature and thickness of the (weathered) overburden[28], the original depth of the groundwater table[26-28] as well as the presence or absence of surface (stream) water[26-28]. Most sinkholes formed in the outcrop area of the chert-rich dolomitic formations (i.e. Monte Christo and Eccles Formations) and were often associated with fault zones, fractures and dyke edges as well as the stream bed of the Wonderfonteinspruit. Beukes[29] found a possible effect of rising water tables (termed 'rewatering') on the rate at which new sinkholes develop. Swart[30], Swart et al.[3] and Winde and Stoch[1] outlined the possible impact of sinkholes on the recharge rate of the dolomitic compartments based on historical heavy rainfall events. Although desirable in order to assess groundwater recharge of compartments under the present conditions, reliable long-term data indicating the impacts of sinkholes on recharge rates do not exist. More recent studies reviewing the history and extent of sinkhole development in the Far West Rand, without necessarily introducing new aspects or concepts, exist from De Bruyn and Bell[31] and Van Niekerk and Van der Walt[32]. A vast quantity of unpublished data (comprising some 2500 documents) on dewatering-related ground movements from 1964 to 2007 has been assembled by the State Coordinating Technical Committee. This work was and is complemented by work at the Geobasecamp of Gold Fields Ltd. in Oberholzer, where many data relating to sinkholes and ground subsidence are captured in a dedicated geographic information system (GIS).

Hydrogeological characterisation of dolomitic compartments

The hydrogeology of the dolomitic compartments, focusing on the structural geology, groundwater storage and recharge as well as the determination of hydraulic parameters, has been assessed by a range of comprehensive and detailed studies. In an early seminal study, Enslin and Kriel[19] delineated surface catchment boundaries of the dolomitic compartments and assessed monthly and annual water balances including artificial sources of recharge and discharge. Subsequent comprehensive hydrological studies exist from Brink[8], Jordaan et al.[18], Enslin[33], Enslin and Kriel[34], Fleisher[35], Vegter[36] and Foster[37].

Martini and Kavalieris[38] described the general genesis and morphology of the Transvaal dolomites, especially the caves. Processes involved in the weathering and karstification of the dolomites in the Far West Rand were described by Morgan and Brink[39] who outlined three vertical zones distinguished by their degree of karstification: a highly weathered nearly porous zone followed by a cavernous zone as well as weakly fractured to solid dolomite. The hydraulic characteristics of vertical fissures in the dolomite were described by Wolmarans and Guise-Brown[40] and Wolmarans[41]. Cross-cutting through all geological formations, these fissures transport groundwater from the dolomite into the mine voids. According to the authors, the hydraulic properties as well as the ability to conduct groundwater down to the mine voids, largely depends on the large-scale folding of the dolomite, whereas fissures in areas of synclinal folding (tension zones) generally generate more ingress water than fissures in areas of anticlinal folding (compression zones). Descriptions of the petrography, thickness and distribution, as well as the hydrology of non-dolomitic rock formations associated with the dolomitic aquifer system, can be found in De Freitas[42].

Various pumping tests have been undertaken for the hydraulic characterisation of the dolomite. Schwartz and Midgley[43] derived values of transmissivity and the storage coefficient of the Bank Compartment by applying the method of Theis[44] to data recorded during the inrush event that flooded West-Driefontein in 1968. Fleisher[35], De Freitas[42] and Bredenkamp et al.[45] describe further pumping tests evaluated by a range of methods. Results indicate a high heterogeneity of the dolomite with transmissivities ranging from a few hundred to several thousand metres squared per day. Geo Hydro Technologies[46] conducted slug tests in the Pretoria Group rocks covering the dolomite at the southern edge of the outcrop area; values of hydraulic conductivity thus obtained were generally lower than those found in the upper dolomite.

In the pumping test analyses quoted above, as well as in those conducted in similar aquifers in South Africa (e.g. van Tonder et al.[47]), it was found that the determination of the storage coefficient is problematic, as values in many cases showed a so-called distance-dependency (referring to the distance between the observation and pumping well). A possible explanation for this observation was provided by Neuman (1994, personal communication quoted in Kirchner and Van Tonder[48]).

The (effective) porosity, which was found to decline with depth, has been assessed by Enslin and Kriel[19], Enslin and Kriel[34], Fleisher[35] and Foster (unpublished data, quoted in Foster[49]). Applied methods include pumping tests as well as borehole and mine shaft log evaluation, spring flow analysis and water balance studies.

On the basis of spring flow hydrographs, groundwater recharge of compartments was described by Fleisher[35] as a two-phase system with an immediate and a delayed component. The long-term average recharge volume of compartments, often quoted as percentage of rainfall, was estimated from natural spring flow volumes[18], the Hill-method[35] and (long-term) pumping rates of mines[50,51]. Bredenkamp[52,53] estimated recharge in two similar dolomitic compartments using chloride profiles and a ^{14}C model, respectively. The possibility of artificially recharging the aquifer via boreholes has been investigated by Enslin et al.[54] who identified possible recharge areas on the basis of data from the gravimetric survey quoted above.

Mining-related water quality issues

Groundwater quality issues relating to the problem of acid mine drainage have been addressed.[55] Pyrite, occurring in mined ore reefs, produces iron hydroxide and sulphuric acid when it comes into contact with water and oxygen. This highly toxic acidic solution may decant on the surface after flooding of abandoned mine voids. As stated by Pulles et al.[56], decanting of mine water is likely to occur to some degree in the Far West Rand after mining ceases. Although the environmental threads linked to acid mine drainage were recently under discussion for other mining areas of South Africa,[57] detailed studies of these aspects are largely lacking in the Far West Rand.

In a study jointly funded by the Water Research Commission and the Far West Rand Dolomitic Water Association, Dill et al.[58] investigated the effects on the quality of groundwater resources of the common practice of using tailings materials for the filling of sinkholes. Dill et al.[58] suggested that uranium levels of up to 300 mg/L are to be expected in leachate from such fillings. These levels indicate that tailings-filled sinkholes are a major risk for polluting groundwater.

Pollution of the environment caused by the water- and airborne transport of uranium originating to large extents from large slimes dams has been addressed by Wade et al.[59], Coetzee et al.[60], Winde[61-63], NECSA[64], Barthel[65] and IWQS[66]. These studies report on elevated concentrations of uranium in ground- and surface water[60,61,63,66,67], riverine sediments[59,60,65], soil[60,65], fish[63,64] and livestock[64]. Current research focuses on the possible associated health risks, including concentrations of uranium and processes and pathways involved in the spreading of uranium. As a major issue in this regard, Winde[67] pointed out the general lack of reliable scientific knowledge on long-term health effects of uranium, which is also reflected by the wide range of uranium limits for drinking water given by different organisations and countries.

Closure of mines

In recent years, as mining in the Far West Rand has passed its zenith, research has shifted towards the challenges of sustainable mine closure and associated hazards. Winde and Stoch[1], Usher and Scott[68] and Winde et al.[69] comprehensively address the environmental impacts of mining with special reference to mine closure strategies. A report of the Department of Water Affairs and Forestry[70] briefly assesses the future (post-mining) water supply potential of the dolomitic compartments. Winde and Stoch[71] were the first to examine the opportunities associated with mine closure by exploring the potential of the area for beneficial post-closure use of mining residuals and infrastructure.

The water quality issues mentioned above, as well as the availability of water, will be influenced by the post-mine closure management of rewatering of the compartments. Different authors have estimated the time it will take for compartments to fill up with infiltrating groundwater once the mines stop pumping. Estimates for the period for the mine void and the dewatered compartment to re-fill range from 15 years[69] to 30 years[51]. Usher and Scott[68] estimated the time it will take for the rewatering of the dolomites (but not the mine void) from groundwater balance studies at a maximum of 30 years and from numerical modelling at 21 years (only Bank Compartment). The time estimated for the rewatering of the Gemsbokfontein West compartment was 7.5 years[72] or between 5.8 and 46 years[73].

The processes of rewatering may be influenced by the formation of a mega-compartment, which could result from hydraulic linking of the previously discrete groundwater compartments of the Far West Rand.[18] This is likely to have serious implications for many features of the hydrological system such as spring flow, the rate of groundwater recharge and the resultant groundwater quality. Although the issue was already mentioned in the Jordaan Report[18] in 1960, the matter has not yet been resolved. The existing uncertainties complicate the assessment of post-mine closure scenarios with regard to aquifer conditions and the associated environmental aspects. As a result, even in investigations into other aspects, an assumption is made about the hydrogeological future by choosing one of the two opposing scenarios[58,74] (i.e. reactivation of spring flow or formation of a mega-compartment in which springs remain dry) or taking both possibilities into account[70].

The mega-compartment concept has recently been subject to opposing views. The concept has been highlighted by Usher and Scott[68] and Scott[75], the latter proposing the possibility of preventing the formation of a mega-compartment by artificially sealing the tunnels that interconnect compartments. Investigations by Gold Fields in collaboration with the Department of Water Affairs showed that this option was not economically feasible (Stoch 2014, oral communication). The mega-compartment concept was rejected by Dill et al.[58] and Swart et al.[51]. Whilst the mega-compartment concept has largely been addressed exclusively on a speculative basis, Swart et al.[51] provided the only existing study employing a scientific methodological approach (based on Darcy's Law) in order to approach the issue on a hydraulic basis. Consequently, Van Niekerk and Van der Walt[32] and Winde and Erasmus[74] propose that the existing research on the topic (i.e. hydraulic consequences of piercing of dykes) is insufficient to reach any firm conclusions.

Conclusions and recommendations

The Far West Rand is a major deep-level gold mining area in South Africa and hosts significant groundwater resources. We have identified some particularities and issues related to the literature relevant to hydrological research in the Far West Rand. Related research over the past six decades has produced a large volume of literature, which is difficult to evaluate systematically owing to a lack of a coherent, central archiving facility and a marked lack of quality-assurance procedures. By subdividing the many complex and overlapping studies into six major topical categories, an overview is provided which reduces the overwhelming complexity of the collection of relevant studies to manageable proportions. The identification of relevant studies for future researchers is hereby simplified. The number of documents obtained (amounting to a total of 765 entities) is listed in each topical category discussed in this review in Figure 2.

Water quality issues related to mining is the single largest category of the six topics covered in this review with a quarter of all documents relating to this aspect (Figure 2). Next largest is the two groundwater-related aspects addressing the hydrogeological properties of dolomite and related water flow. The closure of mines ranks last in terms of the number of relevant documents, as many mines are still active. This study highlights the need to address this aspect in more detail in future. The relatively modest number of documents relating to ground stability reflects the short-term nature of scientific attention.

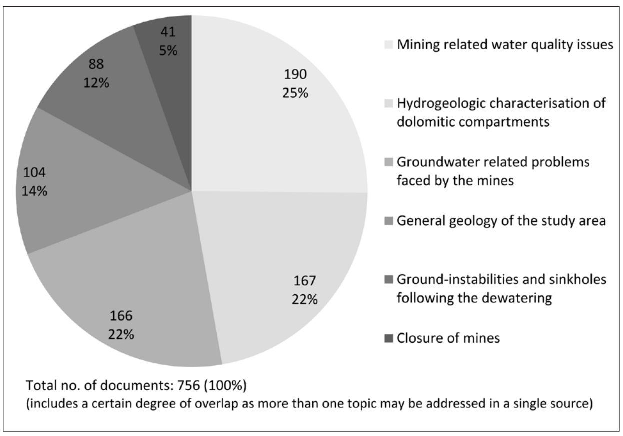

Figure 2: Number (%) of documents per category considered in this review, ranked in descending order.

Once the causes of the sudden appearance of sinkholes and ground subsidence had been understood, the number of dedicated studies on this aspect decreased. However, documents relating to routine observations of ground movement by the State Coordinating Technical Committee alone are currently estimated to number 2500, which would render this aspect by far the best covered.

The fact that much hydrological knowledge is contained in unpublished documents such as internal and confidential reports of companies is a major issue that hampers the effective utilisation of available data. Furthermore, because many documents do not meet scientific standards it is often difficult to evaluate the reliability and quality of the information. However, by putting individual studies into the context of related studies, as well as through intercomparisons, this obstacle can often be overcome, allowing the use of unique and often unreproducible data and studies.

In an effort to ameliorate the problems relating to the literature describing the Far West Rand, an initiative by the Mine Water Research Group of the North-West University (Vaal Triangle Campus) is currently underway. This initiative involves the systematic compilation of all available relevant documents into a single archive approaching some 6000 hard copies. These documents are in the process of being digitised and collated in an electronic catalogue. It is envisaged that all relevant numerical data will ultimately be extracted, georeferenced and transformed into electronic formats for the subsequent incorporation into a central GIS-supported database.

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Dedication

With sadness we learned that Dr Eliezer Joshua (Leslie) Stoch passed away on 24 August 2014. As a long-term resident he was passionate about the study area and much of what is reported in this paper is based on his vast and comprehensive collection of historical documents and was inspired by his contagious enthusiasm for this unique region. We dedicate this paper to him.

Authors' contributions

A.S. drafted the first version of the article and selected the relevant literature. F.W. provided input and background knowledge to all parts of the text and helped with structuring, editing and writing of the final version.

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