PROPOSED GROUNDWATER CLASSIFICATION SCHEME

Ben Green, SRK Consulting (UK) Limited, Cardiff, UK;
Anastasia Boronina, SRK Consulting (UK) Limited, Cardiff, UK;
Richard Connelly, SRK Consulting (UK) Limited, Cardiff, UK;

ABSTRACT

A classification scheme is proposed to provide a level of confidence in groundwater resources for industrial use by reporting by semi quantitative methods. A mine should have as high a level of confidence in its water resource as in its ore reserve. The approach taken in this paper is to combine the methods employed in Russia to characterise hydrogeological regions, with international ore reserve reporting codes such as the JORC Code. Taking hydrogeological criteria, mine water requirements and details of hydraulic testwork, a series of tables and simple empirical equations can be created. A confidence index is developed from these equations which can be used to communicate groundwater issues to the mining company. If necessary, suggestions can then be proposed as to how confidence in the groundwater supply can be improved.

1. INTRODUCTION

Groundwater is an important natural resource and its evaluation needs to be performed under certain standards that are site-specific and dependent on required levels of confidence. These requirements are especially important for the mining industry where mistakes in estimates of water resources might result in large financial losses due to insufficient mine water supply or due to underestimation of dewatering needs.

The necessity to categorise ore resources according to economic considerations and geological confidence was recognised in the mining industry more than 30 years ago. The resulting reporting codes for exploration results, mineral resources and ore reserves are now a routine procedure preceding investment decision. The situation with water resources, and their ability to meet demand, has generally been different: economic aspects and confidence factors, to our knowledge, have been not taken into account in any classification system except that used in the former Soviet Union.

1.1 Russian classifications

In the former Soviet Union, groundwater has been traditionally considered as a part of other natural resources (oil, gas, metals) and has been classified similarly to them.

Groundwater classifications were developed to assess groundwater resources for drinking, domestic, mineral and industrial consumption on a federal scale.

Over the last half of the century, there have been several groundwater classifications (see GKZ (1962), GKZ (1997) for relatively recent classifications, and Bindeman & Yazvin (1970) for a summary of earlier classifications) that differed in their terminology and category ranges, but were similar in the following points:

- designation of an aquifer to a specific category was undertaken for specified water demands;
- categories ranged from the highest to the lowest confidence in the evaluated groundwater resources;
- aquifer categorisation was dependent on site complexity, hydrogeology settings and detail of investigation.

Bindeman & Yazvin (1970) is the most complete work on the Russian groundwater resources evaluations and gives explanations on the GKZ (1962) classification. The authors describe the evaluation procedure and hydrogeological tests requirements for specified types of the aquifers (for example, aquifers in mountain regions, alluvial aquifers near rivers, etc).

The latest Russian groundwater resources classification (GKZ, 1997) divides all evaluated water resources into five categories representing confidence in resource evaluation: A – developed; B – evaluated; C_1 – preliminary evaluated; C_2 – explored; P – possible).

According to this document, designation of water resources to a specific category requires not only a certain level of study detail (quantity of pumping tests etc) but also a specific method for evaluation (hydrodynamic, water balance and/or hydraulic). Selection of an evaluation method depends on site complexity and the type of aquifer.

The State Commission on Evaluation of Natural Resources (GKZ) classification (1997) presents a detailed description of specific conditions by which groundwater resources can be allocated to one of the A, B, C_1, C_2 or P categories.

For example, the resources of the category B have to satisfy the following conditions:

- to be calculated for a known wellfield design, water supply regime and its transient variations, and permitted environmental impacts;

- to describe the confidence of evaluation by referring to drilling logs and pumping test results; types and quantities of pumping tests are dependent on aquifer complexity;
- to present an assessment of inflow components describing where the groundwater originates from;
- to conclude that the water quality remains within allowed standards during the whole period of exploitation;
- to have a sufficient detail of hydrogeological, environmental, sanitary etc. studies in order to obtain necessary factual data for evaluation;
- to have impact assessment on other wellfields and surface water bodies;
- to evaluate other possible environmental impacts and to obtain factual data at a necessary level to design environmental protection measures.

The designation of groundwater resources to a specific category is normally done in Russia by regional hydrogeological organisations and has to be confirmed in the GKZ.

This paper proposes a score based approach to covering similar GKZ designation criteria but using terminology similar to that used in the JORC code

1.2 The JORC Approach to Mineral Resource and Ore Reserve Classification

A code of best practise for the reporting of exploration results, mineral resources and ore reserves was established in 1989 by the Australian Joint Ore Reserves Committee (JORC), to become known as the JORC code (JORC 2004). The objective of the Code was to create a set of standard international definitions for the public reporting of mineral resources and ore reserves. However the JORC code does not extend to the reporting and classification of water resources.

The code requires a Competent Person (CP) on whose work the public report is based. The CP should have a minimum of five years in the relevant field, and ideally be a member of a chartered institution.

In the case of mineral resources, the deposit is "characterised" based on the level of confidence in the geological, mineralogical, and quantitative information available. The following classifications can be awarded:

A **'***Measured Mineral Resource'* is that part of a Mineral Resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a *high level of confidence*. It is based on *detailed* and *reliable* exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes. The locations are spaced closely enough to *confirm* geological and grade continuity.

An '*Indicated Mineral Resource'* is that part of a Mineral Resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a *reasonable level of confidence*. It is based on exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes. The locations are too widely or inappropriately spaced to confirm geological and/or grade continuity but are spaced closely enough for continuity to be *assumed*.

An '*Inferred Mineral Resource'* is that part of a Mineral Resource for which tonnage, grade and mineral content can be estimated with a *low level of confidence*. It is inferred from geological evidence but does not verify geological and/or grade continuity. It is based on information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes which may be of *limited* or *uncertain quality and reliability*.

When compared to the Russian resource classification, there are general equivalents to the JORC Code. These are summarised in Table1.

Table 1: A "Rule of Thumb" conversion of Russian classification to their JORC equivalents (Clayton & Armitage, 2004).

Measured	Indicated	Inferred	Unclassified
A+B			
	C_1		
		C_2	
			P1
			P2+P3

As a guideline, the A and B Russian categories can be considered similar to the *Measured* category as defined in the JORC Code, and the C_1 and C_2 are broadly equivalent to the *indicated* and *inferred* categories. There is not, however, a rigid correlation between the two classifications. For further detail on this the reader is referred to the paper, Clayton R. & Armitage M 2004, Russian resource classification- an SRK view.

It is proposed to use an established Russian way of categorising groundwater resources, communicating them, via a JORC related classification scheme that offers a level of confidence in those reserves.

The objective of the present study is to develop a new semi-quantitative classification for groundwater resources taking into account natural and industrial factors. In analogy to the JORC code, the classification can be used by investors for risk assessment related to mine water supply and dewatering. Alternatively, it can be applied by mining engineers in planning of hydrogeology tests; where the classification helps to assess a scope of a study at a specific mine for a required confidence level of water resources evaluation.

2. SRK GROUNDWATER RESOURCES CLASSIFICATION

It is important to note that the groundwater classification is a matter for skilled judgement by a Competent Person (CP). The CP should be a Chartered Geologist with at least five years of relevant experience in the field of water resources.

We suggest a classification of groundwater resources into four categories that are similar to ore resource classifications: graded from the highest to the lowest confidence levels:

Measured: A 'Measured' Water Resource is that part of a water resource for which the aquifer size and thickness, and volume of water available can be estimated with a *high level of confidence*. It is based on *detailed and reliable* hydrogeological testwork which verifies hydrogeological and/or aquifer continuity. It is based on information gathered through appropriate techniques from boreholes, wells, and mine workings. Hydraulic testwork has been *well organised* with calculations for storage and hydraulic conductivity. Boreholes are spaced closely enough to confirm hydrogeological and aquifer continuity. Numerical aquifer modeling has given *confidence* to the results.

Indicated: An 'Indicated' Water Resource is that part of a water resource for which the aquifer size and thickness, and volume of water available can be estimated with a *reasonable level of confidence*. It is based on limited hydrogeological testwork resulting in assumed, but not verified hydrogeological and/or aquifer continuity. It is based on information gathered through appropriate techniques from boreholes, wells, and mine workings. Hydraulic testwork is too widely or inappropriately spaced to confirm hydrogeological and/or aquifer continuity, but closely enough for continuity to be *assumed*. Hydraulic testwork has been *adequately* organised with some calculations for hydraulic conductivity. Boreholes are spaced too widely or inappropriately to confirm hydrogeological and/or aquifer continuity, but are spaced closely enough for continuity to be assumed. Limited borehole modelling has given *some confidence* to the results

Inferred: An 'Inferred" Water Resource is that part of a water resource for which the aquifer size and thickness, and volume of water available can be estimated with a *low level of confidence*. It is based on limited hydrogeological testwork and assumes aquifer continuity. It is based on limited information gathered from boreholes, wells, and mine workings. Hydraulic testwork has been well organised with calculations for storage and hydraulic conductivity. Boreholes are spaced closely enough to confirm hydrogeological and aquifer continuity. Preliminary numerical aquifer modelling gives *limited confidence* to the results.

Unclassified: In this case, there is insufficient knowledge about the presence of water bearing rocks or the hydrogeology to enable a classification to be made.
We propose to routinely assign evaluated water resources to one of the categories listed above. A semi-quantitative method for categorising is presented below. This is achieved by calculating a confidence index (CI) It is assumed that confidence of water resources and supply evaluation is dependent on three variables: *Relative Water Resources (RWR)*, *Aquifer Knowledge (AK)* and *Aquifer Complexity (AC)*, that in their turn are functions of several parameters.

2.1 Relative Water Resources (*RWR*)

The score is calculated as:

RWR=RWR1 x BF

where:

boundary factor (BF) is ranges from "0.8" for an aquifer with all no-flux boundaries to "1" for an infinite aquifer.

RWR1 – is expressed by scores in Table 2. RWR1 represents the ability of an aquifer to satisfy long-term water demands, that is, *WR/WD*; where *WR* is groundwater resources in the aquifer, and *WD* is water demand.

Table 2: Tabulated scores for *RWR1.*

WR/WD	*RWR1*
<1	1
1-2	2
2-3	3
3-5	4
5-7	5
7-10	6
>10	7

Groundwater resources (*WR*) are calculated by formula [1] for the regional water balance:

$$WR = R*A + S*b*A/t + K*J*B*b \qquad [1]$$

where:

R = aquifer infiltration (m/d);
A = area of concern (m^2);
S = specific yield or storage coefficient (-);
b = thickness (m);
t = time of mine exploitation (days);
K = hydraulic conductivity (m/day);
J = hydraulic gradient (-);
B = cross section length of groundwater flow (m).

Thus, *RWR* varies between 0.8 (very poor ability to satisfy water demands) and 7 (excellent aquifer potential for current water demands).

2.2 Aquifer Knowledge (*AK*)

The function estimates a present level of aquifer knowledge; it is related to quality and quantity of hydrogeology tests (Table 3).

Total score for *Aquifer Knowledge* is calculated as:

AK=TTxDTxQT

$0 \leq AK \leq 100$

Thus, *AK* varies between 0 (No knowledge of aquifer properties) and 100 (excellent knowledge and understanding of aquifer properties)

AK is an additive function, calculated for each of the test types (TT) and accumulated. In the case of different types of hydrology tests conducted, *AK=AK1+AK2* (see Case 1: Kazakhstan Chromite Mine Water Supply below, as an example).

Table 3: Factors and scores for *AK*.

Factor	Score
Type of Tests (TT)	1 – slug tests 2 – pumping tests of short duration (less than 24 hours) 3 – pumping tests of medium duration (24 to 72 hours) with no observation boreholes 4 – pumping tests of long duration (3-7 days) with observation boreholes 5 – Pumping tests 7 days and longer with observation boreholes
Density of Tests (DT)	0 – no tests in the region; pure aquifer knowledge 1- no tests in a target area, good knowledge about the aquifer from a desk study 2 – 1 test in a target area 3 – 2-3 tests in a target area 4 – 4-5 tests in a target area 5 – more than 5 tests in a target area
Quality of Tests (QT)	1 – only apparent hydraulic conductivity values available, no pump test data to verify the interpretation 2 to 4 – confidence in test pumping interpretation results, from lowest to highest

2.3 Aquifer Complexity (*AC*)

This function is a sum of scores gained from different types of aquifer complexity that is presented in Table 4.

Table 4: Factors and scores for *AC*.

Factor	Score
Heterogeneity of Hydraulic Conductivity (HHC)	Ranging from “1” (homogeneous unconsolidated sands) to “5” (crystalline rocks fractured and weathered in different scales)
Variability of Thickness (VT)	1 – constant; 2 – gradually changing; 3 – spatially variable,

The total score for *Aquifer Complexity* is calculated as:

$AC = HHC + VT$

$2 \leq AC \leq 8$

Thus, *AC* varies between 2 (homogenous unweathered aquifer with primary permeability) and 8 (unpredictable in form, fractured, weathered with primary and secondary permeability)

2.4 Designation of groundwater resources to the categories

In order to categorise the groundwater resources, a Confidence Index (*CI*) for values defined in Table 5 is introduced.

Table 5: Tabulated classification of groundwater resources as a function of *CI*.

CI	Category
>6	I - Measured
3-6	II – Indicated
1-3	III - Inferred
<1	IV – Unclassified

As *CI* is a function of *RWR*, *AC* and *AK*, an attempt was made to find a suitable function according to the following methodology:

While *RWR* represents the relative quantity of water available, AK is related to how well we know the aquifer and AC indicates how complex an aquifer is.

CI increases with increasing *RWR and* with increasing *AK*; *CI* decreases with increasing *AC*. *CI* is most sensitive at to *RWR* and at least to *AC*.

Thus, logically *CI* is proportional to *RWR* and is assumed to satisfy the following boundary conditions:

1) If *RWR=1* (poor relative groundwater resources), then even if *AK*=80, *AC*=1, *CI<1* (unclassified).
2) If *RWR*=7 (large groundwater resources or little water demand), for any AC, with very low site specific data (*AK*<10), we will still get 1<*CI*<3 (inferred); In this case, for average study details (*AK*=40), the resources will be indicated.

3) For moderate water resources (*RWR*=4), where the aquifer has average complexity (*AC*=4), one has to have *AK* > 60 (one of the options is 4-5 tests of duration more than 3 days with sufficient interpretation). CI= >6 (measured)
4) If there is no site specific information for the study area (*AK*=0) and water resources are below average (*RWR*<4) then water resources are “unclassified” (*CI*<1).

By calibrating the initially assumed coefficients by the boundary conditions listed above, and based on case studies, the final functional relation for *CI* appeared as the following:

$$CI = \frac{2\,(AK + 40) \times RWR}{AC + 60} \qquad [2]$$

This proposed classification can be incorporated in a spreadsheet that allows fast categorisation of different mine water resources.

3. APPLICATION OF SRK GROUNDWATER RESOURCES CLASSIFICATION

3.1 Case 1: Kazakhstan Chromite Mine Water Supply

The project is located in the northwest of the Republic of Kazakhstan. The climate is continental with hot dry summers (+40ºC) and severe winters (-40ºC). The area is semi-arid with 220-250 mm of precipitation per annum, mainly in the autumn and winter.

Despite low rainfalls and high annual potential evaporation, recharge is relatively high (*R*=150-200 mm per annum) because it occurs over a very flat area in spring due to snowmelt when evaporation is insignificant.

The chromite deposit lies within an ultramafic complex of dunites, peridotites and serpentinites subjected to fracturing and hydrothermal alteration.

The aquifer is highly heterogeneous, water is stored in fractured and alteration zones of different sizes. Estimated water requirements for the mine are relatively low: 30 m^3/h, and it is going to be entirely supplied from the fractured aquifer. Following a hydrogeology desk study, score “5” was assigned for *Relative Water Resources*.

For the groundwater resource evaluation related to the mine water supply, 9 slug tests and one pumping test of 400 minutes duration were conducted at the area less than 10 km^2 (SRK, 2006). From all the tests, drawdown and recovery curves were supplied, the interpretation results are of high confidence (*QT1= QT2= 4*). Finally, *AK = AK1+AK2 = 1 x 5 x 4 + 2 x 4x 4 = 52*.

All scores for the minewater resources are summarised in Table 6 with the *CI* calculated by formula [2] equal to 3.4. This *CI* brings the evaluation of the water resources into the “indicated” category.

Table 6: Scores for the Chromite Mine Water Resources.

Factor	Score
Relative Water Resources *(RWR)*	**5**
Aquifer Knowledge 1 *(AK1)*	
Type of tests 1 *(TT1)*	1
Density of tests 1 *(DT1)*	5
Quality of tests 1 *(QT1)*	4
Aquifer Knowledge 2 *(AK2)*	
Type of tests 1 *(TT2)*	2
Density of tests 1 *(DT2)*	4
Quality of tests 1 *(QT2)*	4
Total for *AK*	**52**
Aquifer Complexity *(AC)*	
Heterogeneity of Hydraulic Conductivity *(HHC)*	4
Variability of Thickness *(VT)*	3
Total for *AC*	**7**
CONFIDENCE INDEX	**3.4**
CONFIDENCE CATEGORY	**INDICATED**

3.2 Case 2: Saudi Arabia Gold Mine Water Supply

The Project is located in Makkah region of Saudi Arabia. The climate is arid with average annual rainfall less than 130 mm that is highly variable from year to year. The average temperatures range from 19ºC in February to 35.7ºC in July. Due to arid climate, recharge from precipitation is very low; in some years there might be no recharge at all. The groundwater resource originates outside the study area in wadi zones.

The geology consists of a complex assemblage of volcanic arc sequences in a continental microplate, that are overlain by successor-basin volcano-sedimentary sequences (Bani Ghayy and Murdama Groups).

Water requirements for the mine operation are 30,000 m^3/month. The calculated RWR gave score of 3.

A hydrogeology study concluded that the most productive aquifer is associated with fracture zones in limestones and sandstones outcropping under desert sands approximately 25 km south to the processing plant. The area of outcrops is around 30 km^2.

To estimate water resources, four pumping tests of more than 72 hours duration were conducted.

The aquifer is highly variable: borehole yields range from less than 0.05 l/s to 24 l/s. The aquifer is limited to one structure and, within this structure, to fractured zones of different sizes and properties. Consequently, the highest score for Aquifer Complexity was assigned (*AC=8*).
The scores are summarised in Table 7 and resulted in *CI=1.9,* that is, a *CI* which corresponds to an “Inferred” Water Resource.

Table 7. Scores for the Gold Mine Water Resources.

Factor	Score
Relative Water Resources (*RWR*)	**3**
Aquifer Knowledge (*AK*)	
Type of tests (*TT*)	4
Density of tests (*DT*)	3
Quality of tests (*QT*)	4
Total for *AK*	**48**
Aquifer Complexity *(AC)*	
Heterogeneity of Hydraulic Conductivity *(HHC)*	5
Variability of Thickness *(VT)*	3
Total for *AC*	**8**
CONFIDENCE INDEX	**1.9**
CONFIDENCE CATEGORY	**INFERRED**

Table 8: Scores for the Titanium Project Water Resources

Factor	Score
Relative Water Resources *(RWR)*	**6**
Aquifer Knowledge *(AK)*	
Type of tests *(TT)*	5
Density of tests *(DT)*	2
Quality of tests *(QT)*	3
Total for *AK*	**30**
Aquifer Complexity *(AC)*	
Heterogeneity of Hydraulic Conductivity *(HHC)*	2
Variability of Thickness *(VT)*	1
Total for *AC*	**3**
CONFIDENCE INDEX	**3.3**
CONFIDENCE CATEGORY	**INDICATED**

3.3 Case 3: Mozambique Titanium Project Water Supply

The project is located in northern coastal Mozambique. It entails the dredge mining of titanium bearing sands, the production of a heavy mineral concentrate in a floating concentrator plant and the separation of final products in a separation plant. Potential water demand for mine operations is quite high: 30,000 m^3/day.

The regional rainfall exceeds 1000 mm per annum, while average potential evapotranspiration is estimated around 2000 mm per annum. Despite the high potential evaporation, rainfall sufficiently contributes to aquifer recharge because of favourable land cover (sands, flat relief) and because of the storm regime of rainfall events.

The aquifer composes of fine, medium and coarse-grained sands of relatively high hydraulic conductivities and quite spatially uniform. Even though the aquifer is thick, of high hydraulic conductivity and with sufficient recharge, there is a boundary of concern: a lake that might be affected by groundwater pumping. After water balance calculations, the score “6” was assigned for *RWR*.

Only one hydrogeology test was conducted in the area larger than 100 km^2 (*DT=2*), comprising of a pumping test of 168 hours duration with 9 observation boreholes. The data are of good quality; but test interpretation was not done properly and the observed drawdown curves were not satisfactory reproduced (*QT=3*).

The *Confidence Index* “3.3” resulting from Table 8 corresponds to” Indicated” Water Resources.

4. LIMITATIONS OF THE GROUNDWATER CLASSIFICATION AND FUTURE DEVELOPMENTS

Evaluated mine water resources are assigned to one of the listed categories in an *a priori* assumption that the results of hydrogeology tests were correctly propagated in water resources estimates. We assume that groundwater modelling, if needed for particular water resource evaluation, is performed with necessary data (recharge and streamflow measurements, piezometry observations, etc.) and sensitivity analysis. Unfortunately, this is not always the case: for example, even though for the Case 3 the aquifer knowledge for the site conditions is sufficient for “Indicated” water supply of 30,000 m^3 per day, the groundwater model is quite poorly calibrated; this fact queries the whole water resource evaluation

The classification does not take into account environmental issues that, in practice, can require additional studies. For example, even if for the Case 1 water supply falls into the category “Indicated” with the present level of aquifer knowledge, more investigations are needed to estimate impact of groundwater pumping on a spring (1.5 km from the mine portal) that is important water supply for the nearby village.
It is suggested that if a potential fatal flaw remains unquantified, then the resource should be “Inferred” at best.

The proposed classification is the first step in quantification of confidence in mine water resources evaluation. The objective of future developments is to make it more quantitative and more objective, based not only on the Competent Person’s judgements but also on numerical groundwater models.

References

Bindeman, N.N. & Yazvin, L.S. (1970) Evaluation of groundwater resources (In Russian: Оценка эксплуатационных запасов тодземных вод). Nedra, 216 p.

Clayton, R. & Armitage, M. (2004) Russian resource Classification- An SRK View. Mining Journal Supplement: Russian Gold- Eastern Promise (September 2004)

GKZ (State Commission on Evaluation of Natural Resources) (1962) Classification of groundwater resources for exploitation (approximate title)

GKZ (State Commission on Evaluation of Natural Resources), 1997. Classification of probable and confirmed groundwater resources. In Russian: "Классификация Эксплуатационных Запасов И Прогнозных Ресурсов Подземных Вод"

JORC (2004) The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC Code, 2004 edition), http://www.jorc.org/main.php

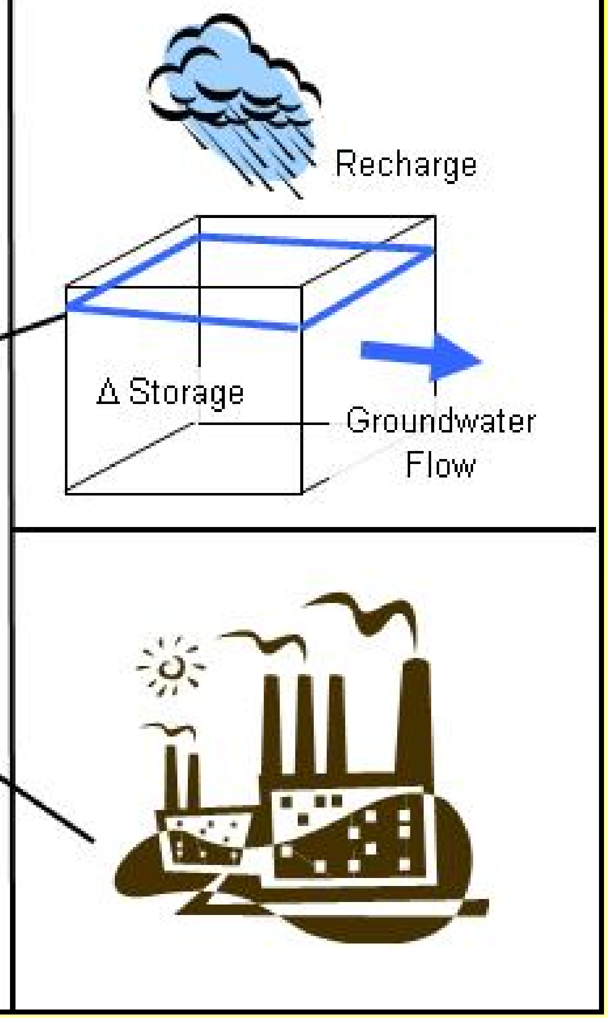
A Groundwater Classification Scheme for Mining Operations

W. Harding

SRK Consulting
Engineers and Scientists

Formula Development 2

$$RWR = \frac{WR}{WD} \times BF$$



2.1. Geology: Topography & Underlying Structure