THE IMPORTANCE OF ACCURATE HYDROGEOLOGICAL CONCEPTUALIZATION - ARE WE CORRECT?

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ABSTRACT
A starting point of any groundwater assessment is the development of a conceptual model of the hydrogeological setting. Accurate conceptualization is important, because it forms the framework upon which all subsequent analyses are made. The sequential nature of the Source Water Protection studies currently being undertaken places an ever-increasing burden on the reliability of previous study components. This paper discusses some of the methodologies that have typically been applied in the early study phases, which (in the author’s opinion) require on-going consideration and re-evaluation.

RÉSUMÉ
Le point de départ de toute évaluation de l'eau souterraine est le développement d'un modèle conceptuel de l'environnement hydrogéologique. Une conceptualisation précise est importante, car elle servira de base sur laquelle les analyses subséquentes seront faites. La nature séquentielle des études de Protection de l'eau à la source actuellement en cours, fait en sorte que la fiabilité des composantes des études précédentes prend une importance sans cesse croissante. Cet article présente un commentaire critique de quelques méthodes utilisées dans les premières phases de l'étude, qui (selon l'auteur) nécessite une attention constante et une réévaluation.

1. INTRODUCTION
Source Water Protection Technical Studies currently being carried out in the Province of Ontario have followed a standardized study format which progresses through a sequence of Guidance Modules. Each module in the series outlines specific technical requirements and has been designed to build upon and incorporate previous studies and investigations, including for example, the 2001/2002 Municipal Groundwater Studies initiatives. A factor critical to the successful completion of the Source Water Protection Report for groundwater supplies is the accurate hydrogeological conceptualization of the study area and the determination of future sustainability based on water budget considerations.

2. THE CONCEPTUALIZATION PROCESS
For the purposes of this paper, conceptualization in hydrogeological evaluations is the process by which an overall understanding of the physical properties of a groundwater flow system is developed. The process is generally regarded as a preliminary step towards the development of a groundwater model, in which a set of assumptions are identified which detail how the real world conditions have been simplified (Bear et al., 1992).

Simplification is a fundamental first step in the process, since it is not feasible to incorporate every detail of the real world into a groundwater model (Anderson and Woessner, 1992). Following the argument that if a simple model will suffice, a more complex model is unnecessary, Dawdy (1969) warns that “this fails in practice unless ‘suffice’ is better defined”. Without simplification, there is a potential for what Leavesley (1994) refers to as “overparameterization of the models” and a danger that “computational and conceptual complexity is substituted for accurate representation of reality” (Grayson et al., 1992).

Therefore, what is desirable at the outset is a concise, qualitative representation of the unique hydrogeological setting being investigated. In typical watershed characterization studies, the conceptualization process focuses on many variables, including the geology and physiography of the study region, the climatic conditions affecting the area, the groundwater hydrogeology and surface water hydrology interactions, and the land use activities which may impact on the quantity and quality of the water resources (Ministry of the Environment, 2006a).

The assimilation of these various sources of data is not a trivial exercise, nor should it be considered complete at the first attempt. As is stated by Bear et al. (1992), the “selection of the appropriate conceptual model for a given problem is not necessarily a conclusive activity at the initial stage of the investigations”, and should be regarded as a “continuous activity”. The same opinions are echoed in the Guidance Modules for the Source Water Protection Assessment Report (Ministry of the Environment, 2006a,b) under the heading of “Continuous Improvement”.

It is within this spirit of continuous improvement that the following observations and opinions are presented for consideration (and hopefully, discussion).
3. DATA SOURCES AND UNCERTAINTIES

3.1 Municipal Groundwater Studies

In 2001, under Ontario’s Operation Clean Water initiative, the Ministry of the Environment embarked on a program to promote groundwater source protection across Ontario. As described in a summary document (Ministry of the Environment, 2001a) the first phase of the program was the assembly of “a solid information base on groundwater conditions at a local and regional scale” and the documentation of potential risks to those resources. The focus of the Municipal Groundwater Studies was the identification of wellhead protection areas and associated potential contaminant sources, based on regional groundwater assessments of aquifer characteristics, regional contaminant source inventories and an evaluation of permitted groundwater withdrawals.

Initially, the groundwater studies developed a conceptual model of the groundwater system for each respective study area. This work was undertaken through a review and analysis of many diverse data sources, including the Ministry of the Environment’s Well Log Database, Permit to Take Water data, Engineers’ Reports for Water Works, consultant’s reports on well field development, published geological mapping and municipal land use information. Data gaps, or areas of sparse information coverage, were to be highlighted as part of the Municipal Groundwater Studies.

One of the goals of the program was to develop “consistent groundwater mapping at a scale of 1:50,000” (Ministry of the Environment, 2001a), for use by later source water protection studies. The Municipal Groundwater Studies, therefore, provide basic hydrogeological information which forms a foundation for the current Source Water Protection Technical Studies. The extent to which they accurately portray the real world directly impacts on the reliability of the watershed studies which ultimately follow.

3.2 Well Log Database

A primary source of hydrogeological information in Ontario is the Ministry of the Environment’s Well Log Database. Under Provincial regulations, water well drillers are required to submit well logs to the Ministry of the Environment upon completion of a well construction. The records contain basic information on the well construction itself, as well as stratigraphic information obtained during drilling, observations of the depths at which water was encountered, static water levels and pumping test information.

Due to the potential for individual soil and rock descriptions to vary from one driller to another, the Ministry of the Environment chose to adopt a standardized "geometric protocol" for the Municipal Groundwater Studies program, which was then applied to the information in the Well Log Database (Ministry of the Environment, 2001b). In addition, certain data validation rules were established to insure that the best quality data was used in any subsequent analysis. Unfortunately, the methodology followed in the data validation stages of the analysis also contributed to the generation of new data gaps and uncertainties.

3.2.1 Location and Elevation Errors

The adoption of standardized data selection and validation rules resulted in the censoring of some of the available water well information. For example, well logs were eliminated from analysis if they lacked precise Universal Transverse Mercator (UTM) co-ordinates or reported elevation values that differed by more than 15 meters from the Provincial Digital Elevation Model (DEM) (Ministry of the Environment, 2001b).

Although at first this would seem to be an appropriate response to filtering potentially poor data from further consideration, it should be recognized that the geospatial data on the water well records were originally generated as a result of regional Ministry of the Environment water well inventory programs. These programs, which pre-dated the availability of hand-held global positioning system (GPS) devices, were labour intensive and were accomplished with seasonal staff visiting each individual well location and marking the well positions on 1:50,000 scale topographic maps.

The information from the maps and the well construction logs were then geo-referenced from the map data by a data entry clerk, and a ground surface elevation value was interpolated by reading contours from the 1:50,000 base map (which had a contour interval of 7.6 m, or 25 feet). The accuracy of the elevation value assigned to the well log, therefore, was dependant on the interpretive skills, and personal dedication, of the data entry clerk.

Today, the requirements of the current water well regulation (O. Reg. 903) stipulate that UTM co-ordinates be filed by the driller upon completion of the well installation, including an absolute estimate of the positioning errors associated with the well location. This, however, is a recent requirement and a majority of the water well records in the Well Log Database are based on much less precise positioning information.

Therefore, given the lower level of accuracy originally incorporated into the database, there is a potential for rejection of valuable hydrostratigraphic information due to a rigid application of these validation rules. In Northeastern Ontario, where the available information is often sparsely distributed to begin with, the censoring of potentially useful data severely limits the abilities of the hydrogeologist to accurately develop a meaningful conceptual model.

3.2.2 Unverified Well Logs

The water well program suffered financial cutbacks beginning in the late 1980’s and, as a consequence, a large number of water well records from the late 1980’s onwards remain unverified (i.e. without UTM co-ordinates). Prior to approximately 2004, the unverified records were displayed in the Well Log Database with fictitious UTM co-ordinates as 999999 mE and 9999999 mN. Since that time, a fictitious UTM co-ordinate representing the geometric centre of the Lot and Concession block has been assigned to these unverified records.

Although the geo-centered well logs are flagged in the electronic form of the database, this information is not clearly displayed in the “paper” versions of the database, which can
be confusing for the un-informed data user. In any event, the elimination of potentially useful water well information from this time period (spanning approximately 20 years duration) must be considered a significant data gap, especially in terms of water level data (since the geology itself hasn’t changed).

The net result of these data validation procedures was that the Municipal Groundwater Studies, and the current Source Water Protection Technical Studies, are based on a sub-set of the available information. Our review of several of the study reports in Northeastern Ontario indicated that the percentage of well records that were used to develop the conceptual models of the aquifers ranged from 54 % to 71 % of the total available records, and of those used, the majority pre-dated the early 1980’s. Specific examples are presented in Table 1.

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Total Available Records</th>
<th>Number of Records Used</th>
<th>% of Total Available Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudbury¹</td>
<td>4,704</td>
<td>3,330</td>
<td>71</td>
</tr>
<tr>
<td>Timmins²</td>
<td>1,348</td>
<td>822</td>
<td>61</td>
</tr>
<tr>
<td>Sault Ste. Marie³</td>
<td>2,500</td>
<td>1,450</td>
<td>58</td>
</tr>
<tr>
<td>North Bay⁴</td>
<td>5,121</td>
<td>2,753</td>
<td>54</td>
</tr>
</tbody>
</table>

¹Golder Associates Limited, 2005
²AMEC Earth & Environmental, 2005
⁴Waterloo Hydrologic Inc., 2006

3.2.3 Water Level Data Uncertainties

For example, water well records for the former Town of Valley East (now part of the City of Greater Sudbury) were plotted as a histogram of the number of records vs. the date drilled (Figure 1). The water well records cluster (timewise) around specific subdivision and town site development phases which happened in the 1960s, the 1970s and again in the 1990s. The majority of the records date from 1960 to 1975, and after 1984, the records remain unverified (i.e. without UTM coordinates being assigned) and were unused in the groundwater assessment.

Figure 1. Histogram of groundwater development trends based on the dates of construction of water wells in the Town of Valley East (now the City of Greater Sudbury). The solid bars in the chart reflect records from a time period when the well verification program was in operation, while the hatched bars indicate currently unverified water well records.

An additional issue involving the age of the well records is the potential rebound of water levels in an aquifer once an alternative municipal water distribution system is brought into an area. For example, in the City of Sault Ste. Marie, although a replacement municipal surface water intake was constructed (in 1986) on the upper St. Marys River, the municipal well field still remains in operation (at a decreased pumping rate) in order to "control artesian conditions" within the aquifer to prevent "basement flooding" (Burnside, 2003).

Based on a personal review of historical file data, the pre-development artesian head in the aquifer in the western part of the City of Sault Ste. Marie was reported to be approximately 5 m to 7 m above grade. Therefore, the calibration of any groundwater model using water well logs dating from a mixture of pre- and post-surface water intake construction periods (in this area) may introduce significant errors into the subsequent analysis.

The mixture of different time lines with different geographical distributions of water level data, therefore, requires careful consideration during the conceptualization process. This consideration of time scales is even more important when...
dealing with a data gap, as identified earlier, spanning approximately 20 years.

3.2.4 Biased Information

The Well Log Database is not an unbiased source of hydrogeological information. Prior to 1984, shallow dug well constructions and owner-constructed water wells were not required to be reported to the Ministry of the Environment (K. Yee, pers com.). Consequently, the exact number of these types of water wells in use, and their geographical distribution, is unknown and under-reported in the Well Log Database.

Statistical inferences relating to the relative proportions of bedrock and overburden well constructions are therefore subject to some debate. Compounding the absence of shallow dug well and owner-constructed well records, in much of Northern Ontario there are only a few local water well contractors with the ability (or expertise) to drill and construct an overburden well installation. The majority of residential water well constructions are bedrock wells, and this leads to a bias in the assessment of the importance of various stratigraphic units on a regional scale. In contrast, the municipal water well constructions in Northern Ontario are all overburden constructions (typically drilled by contractors from Southern Ontario), indicating the vital importance of this under-reported aquifer resource to the municipalities involved.

3.3 Map Scales and Resolution Issues

Another potential source of uncertainty occurs as a result of the loss of detail encountered during the translation of mapped geological and hydrogeological information from one scale to another, or from analogue to digital format. As indicated by Stone (1999), “conceptual models vary with the scale of the study or size of the area selected”, and may involve either hydrogeologic provinces, aquifers or hydrogeological domains within the aquifers themselves.

Tracing the evolution of analogue maps through various compilation scales, Bonham-Carter and Broome (1998) describe the geological data compilation process as involving increasing levels of generalization, skill and “encyclopedic knowledge on the part of the compiler”. Although in the digital age it could be argued that a mapping scale doesn’t exist, the primary data sources used in the present hydrogeological assessments have been based primarily on more artistic and interpretive analogue mapping techniques.

As an example, the Northern Ontario Engineering Geology Terrain Study (NOEGTS) series of surficial geology data base maps (published by the Ministry of Natural Resources) were developed in the late 1970’s from airphoto interpretation of stereo coverage at a scale of between approximately 1:18,000 to 1:38,000 (as well as ground truth verification at selected locations), with the data being summarized on 1:50,000 scale mapping. The maps were subsequently re-drawn at a publication scale of 1:100,000 and, to insure a seamless coverage between adjacent mapped areas, were re-interpreted and filtered to improve presentation.

In Northern Ontario, these maps constitute a primary source of information on the overburden geology. However, in the process of going to analogue publication, the fineness of detail contained in the original 1:18,000 to 1:38,000 scale airphoto interpretations was irrecoverably lost. The fact that these data files are now available digitally does not mean that the data have been re-interpreted, and taking such a dataset that was originally mapped at 1:100,000 and enlarging the scale to (say) 1:20,000 for wellhead protection studies is of questionable merit. Therefore, while such large scale map presentations are reasonable for regional-level analysis, “this level of detail is not appropriate for site-specific interpretation” (Waterloo Hydrologic, Inc., 2006).

3.4 Climatological Data Uncertainties

Since it is rare for a climatological station to be ideally located within the chosen study area, various averaging or interpolation schemes must be undertaken to generate the appropriate climatological data for use in watershed analysis. Common methodologies include Arithmetic Averaging, Isohyetal or Theissen Polygon methods, which produce spatially-averaged values over the entire basin area, or surface fitting methods (Dingman, 2002) which involve interpolation functions (such as Inverse Square or Kriging functions) to describe the spatial variability of the parameter across the basin area.

The intended use of the data, and the time base of the measurements, may affect the averaging or interpolation methods chosen. For example, the Isohyetal method is generally regarded as being more accurate (Viessman et al., 1977), in that it generates a unique set of precipitation contours for each individual rain event. This accuracy is at the penalty of computation time, and other methods, such as the Theissen Polygon method, which fixes the averaging method based on the geometry of the locations of the climatological stations, are more easily entered into spreadsheet and modeling analyses.

If longer term totals are of interest, the method followed may not be as critical. For example, in a three-year study of monthly totals of precipitation for a two-county area in southern New Jersey, Mather (1975) found that there was very little difference between the values obtained from either the Arithmetic Averaging, Isohyetal or Theissen Polygon methods. Therefore, since monthly totals are frequently the time base used in water budget assessments, the use of more computationally-complex assessment techniques may not always be necessary.

Another factor to consider is the degree to which individual point precipitation records, collected at individual weather stations, represent the actual rainfall volumes delivered to a watershed under study. For example, recent advances in weather radar techniques have allowed the calibration and estimation of the actual volumes of rainfall present in a single storm event. Working with Next Generation Radar (NEXRAD) data, Hoblit and Curtis (2000) compared traditional Theissen polygon techniques (using distributed precipitation gauge data) to radar-based methods, and for their study found absolute errors of up to 28 % for storms having a duration of 1 week or less, and up to 11 % for month long durations.
4. THE WATER BUDGET

A key component of the conceptualization process is the determination of the water budget. The water budget, in its simplest form, is an accounting of the water inputs and outputs from a study area, with changes in storage within the aquifers or surface water bodies being used to account for any inequality between inputs and outputs.

If the system being studied is in equilibrium, and if the time base of the study extends through one complete hydrologic year, then it is usually assumed that any changes in storage will ultimately cancel out, giving the simplified water budget as being 'inputs equal outputs'.

The evaluation of the water budget involves the compilation and assessment of several sources of data. The data sources are available from published climate normal data or various on-line sources. In many cases, the location and reliability of the climate data stations requires that the information be adjusted before becoming part of the water budget assessment. A methodology for managing data gaps in the climatological record, which has been adopted by the Ministry of the Environment, is contained in Schroeter et al. (2000).

In terms of the input data used in the water budget assessment, it is important to recognize the difference between 'measured' variables and 'derived' variables. Precipitation, temperature, as well as wind speed, vapour pressure, sunshine hours and dew point temperature, are typically gathered and entered as measured parameters at the climate station. Additional measured parameters include streamflow hydrographs, and groundwater hydrographs, both of which do not generally coincide with the locations of the climate stations, but are at a fixed monitoring point within the study area. Finally, the water uses in the watershed can be assessed, and any transfer of water into or out of the basin can be measured (if a suitable flow meter is present). These measured variables, therefore, are 'hard' data in that they are not dependent on any interpretation error other than the precision of the measurement device (and personnel) used to collect the information.

The derived variables include the estimation of evaporation from the free surface water bodies in the watershed, evapotranspiration from the land surface, runoff and baseflow components of the streamflow records, and recharge. These parameters are either derived from the climatological data, or are generated by analytical methods (usually based on empirically-established formulae). These data are 'soft' data in that there is considerable room for adjustment and interpretation by the user. As indicated by Cherkauer (2004), the biggest concern is "the propagation of error through the calculations" and, in terms of determining recharge from other variables, since each term in the water budget has uncertainties "there is no direct way to verify the accuracy of the resulting recharge".

The uncertainty that is introduced by the use of derived data generates an uncertainty error that (if quantifiable) should be carried through the analysis as an aid in assessing the reliability of the outcome (U.S. Army Corps of Engineers, 1999, Dawdy, 1969). While the groundwater modelling studies typically have reported on errors from a 'predicted vs. actual' perspective (including graphs of model validation runs based on hydraulic head estimates), the documents are generally silent with respect to the errors (or potential errors) associated with the main water budget parameters themselves (precipitation, evapotranspiration and runoff). In short, once calculated, these derived data are often elevated to the status of 'hard' data in follow-on watershed analyses.

4.1 Infiltration Recharge

One water budget component of the Source Water Protection Technical Studies which has been identified as critical to watershed planning is the identification of the net annual recharge to the groundwater flow system. As indicated previously, recharge is a derived variable in that the actual measurement of recharge is very difficult, and is considered "the hardest component to quantify" (Committee on USGS Water Resources Research, 2000). In many modeling situations, the distribution of recharge "is often considered to be a parameter in model calibration" (Jyrkama, 2002), or a value that is adjusted as needed to achieve the desired objective (i.e. making predicted water levels in the model equal actual point elevations in the real world).

As indicated by Sophocleous (2004), difficulties in reliably quantifying ground-water recharge arise from a variety of factors, including

• a limited ability to "identify and quantify the probable recharge mechanisms and important features influencing recharge for a given locality";
• the "nonlinear recharge response with time";
• the "highly variable areal distribution of ground-water recharge";
• the "scarcity of hydrogeological data", and
• the "complexities of the hydrogeologic balance in general".

With regard to the second bullet, Sophocleous (2004) explains that "most recharge processes are nonlinear in relation to time", using the example that a low intensity rainfall may produce no recharge if the evapotranspiration rate is sufficiently high, while the same amount of precipitation over a shorter duration may be sufficient to completely saturate the ground and generate recharge. Therefore, recharge cannot be described by a simple direct relationship to precipitation, since not all precipitation produces recharge.

4.2 Misuse of the Rational Method

Although recharge is recognized as having a non-linear response with respect to precipitation (for the reasons cited above), a methodology to estimate infiltration recharge based upon the Rational Method (Gregory and Arnold, 1932) has been advanced by the Ontario Ministry of the Environment (Ministry of the Environment, 1995 and 2003). This methodology has also been referenced by the Source Water Protection Studies in the Draft Water Budget and Water Quantity Risk Assessment Module (Ministry of the Environment, 2006b). The application of this method stems from an internal draft document circulated within the Ministry of the Environment (Ministry of the Environment, 1995), but
which never was officially accepted or approved for publication, and with valid reason.

The Rational Method is an empirical analysis technique used in urban drainage analysis, and provides an estimate of the peak runoff discharge from a land area. Its function is to assist with the engineering design of hydraulic structures to convey runoff peak flows in surface water systems. It applies strictly to small study areas, and for areas larger than approximately 2.5 km² other assessment techniques (such as more technically-complex hydrograph analyses) "are generally warranted" (Viessman, et al., 1977).

The method is considered linear in that the peak runoff discharge (Q, in m³/day) is linearly related to the rainfall intensity (I, in m/day) and the land surface area (A, in m²) by the formula

\[ Q = C \frac{I}{A} \]  

[1]

where C is an empirical constant (dimensionless), referred to as the runoff coefficient.

The general theory behind the Rational Method is that if a sloping perfectly impervious surface is irrigated at a constant rate for a long enough period of time, a peak discharge will be observed at a discharge point that is exactly equal to the rate of application of water multiplied by the surface area. Since most urban watersheds are not a perfectly impervious surface (and a portion of the applied water will either infiltrate, evapor-transpire or go into storage), the discharge rate will always be less than the rate of irrigation of water onto the area. Therefore, the runoff coefficient is a bulk factor designed to compensate for these various conditions.

Tables of runoff coefficients are published, usually showing a range of values to accommodate various land uses and rainfall intensities (Fetter, 2001, Viessman et al., 1977, Dingman, 2002). The choice of runoff coefficient is a subjective call on the part of the practitioner, because they are often derived from local data and may not be transferable or applicable to other regions (Viessman et al., 1977). Another concern is that the assumption of a constant runoff coefficient ignores the fact that the onset of runoff will vary (even at the same location in a basin) due to differing antecedent moisture conditions in the soils at the time of the precipitation event (Dingman, 2002).

The rainfall intensity (I) in Equation 1 is chosen from characteristic curves of rainfall intensity-duration-frequency (IDF), developed from climatological data for the study area, and is not simply the amount of rainfall (i.e. effective uniform depth) received over the study basin for a particular storm event, divided by the length of time of the storm. Rainfall IDF curves are derived from a review of several years of daily precipitation records, and are established for a particular return frequency using a statistically-based analysis (Gray, 1970, Dupont and Allen, 2000).

The characteristic of the IDF curve that is critical to the Rational Method is the selection of a rainfall duration value that exactly equals the so-called “time of concentration” of the basin being studied. The time of concentration of the basin is equal to the “time required for a particle of water to move from the most hydraulically remote part of the basin to the outlet” (Gray, 1970), and it’s application to the Rational Method recognizes that the peak runoff discharge (Q) will only occur when all parts of the basin are contributing to runoff at the designated outlet. In other words, in order to apply the Rational Method, an assumption is made that the precipitation is constant and uniformly distributed over the entire basin area. For watershed studies, this condition is rarely (if ever) met in the real world.

The time of concentration of a basin is a constant fixed by the internal routing of water towards the outlet point (where the peak runoff discharge is being evaluated). Therefore, under the Rational Method, finding the time of concentration fixes the rainfall intensity as a constant for all subsequent calculations (through the application of the IDF curve), and therefore there is only one unique value for the peak runoff discharge (Q) from the basin being studied.

The Rational Method is not meant to be applied to every individual storm event, and is not a methodology by which runoff can be estimated on an annual basis. It is an empirical method by which drainage systems can be designed, for a given return period.

The simplicity of Equation 1 has led to its misuse in several applications concerning water budget analysis. For example, Fenn et al. (1975) used the Rational Method's runoff coefficients to estimate runoff from a landfill cover, as part of an assessment of leachate generation from solid waste disposal sites. Trommer et al. (1996) applied the Rational Method's runoff coefficients to a study of individual storm events for 15 watersheds in West-Central Florida, and found discrepancies in the estimated peak flows ranging from - 90 % to +1960 %, when compared against actual peak flow data.

The Ministry of the Environment (1995) reference to the Rational Method involves the use of what they term as an “infiltration factor”, which was described as being a constant which could be used to calculate the amount of infiltration over a given study area. In a manner similar to the use of the runoff coefficient, the infiltration factor was to be multiplied by the available water surplus as a way of estimating the amount of groundwater recharge available for a given study area. A table of values of infiltration factors was provided, but was not given any citation or reference in the document. This methodology was later included in the Stormwater Management Planning and Design Manual (Ministry of the Environment, 2003) as well as the Draft Water Budget and Water Quantity Risk Assessment Guidance Module (Ministry of the Environment, 2006b) where it is quoted as the "MOE infiltration method".

In fact, the tables in these publications were taken verbatim from Gray (1970), where it is presented (page 8.5) as "Table VIII.2 Deductions from Unity to Obtain the Runoff Coefficient for Agricultural Areas". From Gray’s text, there was obviously no intent to use the values to calculate infiltration recharge. The table in Gray (1970) is attributed to a much earlier source (Bernard,1935) from which it itself has been copied. The
original author Bernard, in fact, first voiced the method as only "tentative" in a contribution to a paper on the Rational Method by Gregory and Arnold (1932).

There is no indication that the table of values originally suggested by Bernard represents, in any way, a method of determining infiltration from precipitation data. The current practice of applying the runoff coefficients from the Rational Method (or a derivation by subtracting similar coefficients from 'unity') in the estimation of infiltration recharge is, for reasons given, completely unwarranted and incorrect.

4.3. Empirical Estimation Methods

The non-linear response of recharge to precipitation inputs can be described by empirical formulae of the form

\[ R = A \left( P - B \right)^C \]  

where \( R \) is the net annual recharge (in mm), \( P \) is the annual precipitation (in mm), and \( A, B \) and \( C \) are coefficients fitted to the basin characteristics by non-linear regression analysis. This type of equation is attributed to the work of Chaturvedi in India in 1936 (Kumar and Seethapathi, 2002, Lerner, et al., 1990).

The appearance of the constant \( B \) in Equation 2 assigns a lower limit for recharge in order to account for runoff, replenishment of soil moisture deficit, interception losses and evapotranspiration losses (Kumar and Seethapathi, 2002). A similar equation is described by Sophocleous (2004) with the omission of the 'power constant' \( C \) in Equation 2 (in effect, making the relationship linear once again). This type of equation has an advantage in that it is simple to use, but requires calibration to each basin’s unique characteristics.

As an example of how this may apply, annual baseflow vs. annual precipitation values were obtained from an on-going study of the Vermillion River Watershed in Sudbury, Ontario (S. Kaufman, pers com.), and the results are plotted in Figure 2. A total of 33 annual data values (spanning 1970 to 2005) were used in the analysis, baseflow separation being performed manually from the raw discharge monitoring data.

A regression analysis was performed for the Vermillion River Watershed data, assuming the value of the constant \( C \) (Equation 2) was equal to unity, and the following calibration was obtained

\[ R = 0.177 \left( P - 349 \right) \]  

where \( R \) is the annual infiltration recharge (in mm, assumed to be equal to the annual baseflow) and \( P \) is the annual precipitation (in mm). By this analysis, the minimum amount of precipitation that must be exceeded before infiltration recharge can occur was determined to be 349 mm.

In a study of a test area in northern China, Wu and Zang (1994) obtained a high degree of correlation between annual infiltration recharge and annual precipitation. In their analysis, based on an equation similar to Equation 2 with the constant \( C \) equal to unity, they refer to the constant \( B \) as the "threshold rainfall, below which no recharge will be generated". It is this characteristic which makes this methodology more closely approximate real world observations, and further investigation into the application of this technique to Ontario watersheds appears warranted.

5. CONCLUSIONS

A review of the various assumptions and simplifications that have been made during the conceptualization process of several groundwater studies in Northeastern Ontario suggests that caution be applied when carrying the results forward into on-going watershed planning evaluations. Confidence in the results obtained is not simply a calibration exercise, and more discussion needs to be included in the dialogue which will assist the end-user in understanding the limitations of the hydrogeological interpretations provided. In many cases, the end-user of the information will not be a groundwater professional, and they may not have a full appreciation for the uncertainties buried in the analyses.

It is hoped that this discussion will contribute to on-going dialogue so that not only will the best data be utilized in these studies, but that the data will be used with the confidence it deserves.

REFERENCES

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