Development, analysis, and application of RORA and PART for estimating groundwater recharge and discharge in humid settings – A resource for frequently asked questions about the programs.

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Introduction

The RORA and PART computer programs were developed for the AP-RASA study, which was a Regional Aquifer Systems Analysis (RASA) conducted by the U.S. Geological Survey (USGS). This RASA covered the Appalachian and Piedmont "AP," which consists of three physiographic provinces: The Valley and Ridge, Blue Ridge, and Piedmont (Figure 1). The northern boundary of the study was the southern extent of continental glaciation; a separate RASA dealt with the glaciated northeast. Early in the planning phases of AP-RASA it was determined that streamflow data might be used to estimate aquifer characteristics and for this reason the programs were developed during the study. The programs estimate groundwater recharge and discharge on the basis of daily streamflow data. Although the programs were developed for AP-RASA, they have transfer value to many humid settings. This may include a significant portion of the 26-state area east of the Mississippi River shown in Figure 1.

This document serves as a supplement to reports by Rutledge (1993, 1998, and 2000) that describe the theory and use of the RORA and PART methods, and additional publications in the journal *Groundwater*. The document was prepared in response to frequently asked questions about the methods and their application to real field settings. Also included is a discussion of the PULSE program (Rutledge, 1997), which is an alternative to the fully automated methods and provides greater insight about those methods. This document describes aspects of RORA and PART that have come to light since the time they were originally documented, such as the time scale at which results can be reported, an improved understanding of the effects of groundwater evapotranspiration, and suggestions about the utility and limitations of groundwater-level data for method evaluation. Also included are points that are relevant to the significant amount of technical discussion of the methods—especially RORA—that has occurred in the literature; and comments about comparisons between program results and the results of independent methods. Materials presented below have been previously published in the literature; one of the objectives of the document is to make readers aware of those publications.

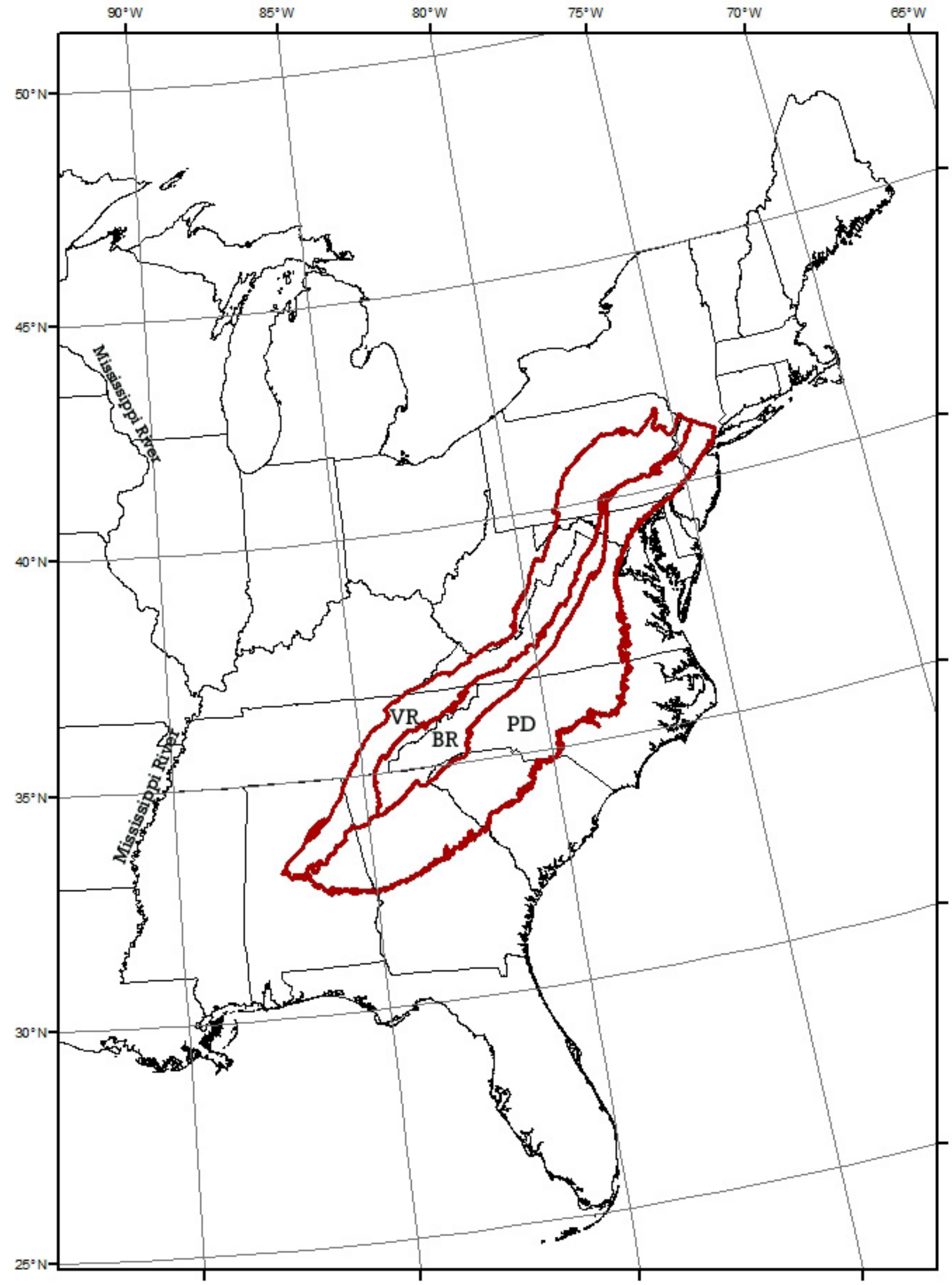

Figure 1. The AP-RASA study area, which consists of the Valley and Ridge (VR), Blue Ridge (BR), and Piedmont (PD) physiographic provinces (Rutledge and Mesko, 1996).

Sections that follow:

Description of the Methods

The Rorabaugh method for estimating groundwater recharge is based on a mathematical model (Rorabaugh 1964) that calculates groundwater discharge to a stream after a recharge event. The method has been employed manually in USGS studies (Wilder and Simmons 1978; Bevans 1986; Gerhart and Lazorchick 1988; Hoos 1990). Also known as the recession-curve displacement method, it is implemented by the RORA program (Rutledge 1998; 2007). The method is based on the estimation of the total potential groundwater discharge of the aquifer at a critical time after the storm peak. Two estimates of the total potential groundwater discharge are obtained for each streamflow peak – one extrapolated from the period of recession that precedes the peak and the other from the period that follows the peak. The recharge is determined from the difference. For more discussion of the computer algorithm the reader is referred to Rutledge (2007).

Base-flow record estimation, or "hydrograph separation," has been applied historically using a variety of manual procedures (Barnes 1939; Snyder 1939; Olmsted and Hely 1962; Chow 1964). The PART program was adapted from specific methods called streamflow partitioning (Knisel and Sheridan 1983; Shirmohammadi and others 1984). The method consists of the estimation of a daily record of groundwater discharge as part of the total stream-discharge record. The algorithm scans the record for days that fit a requirement of antecedent recession, designates groundwater discharge to be equal to streamflow on these days, and then linearly interpolates the daily record of groundwater discharge for days that do not fit the requirement of antecedent recession. For more explanation of the computer algorithm the reader is referred to Rutledge (1998). Other computerized hydrograph separation methods include HYSEP (Sloto and Crouse 1996).

In some hydrologic settings, the long-term groundwater discharge might be roughly equal to groundwater recharge, as long as other components of the groundwater budget are relatively small, such as groundwater evapotranspiration. Similarity between results of RORA and PART is evident for basins in the AP-RASA study (Figure 2). Some of the quantities in Figure 2 are large relative to typical quantities in the East because AP-RASA included the Smokey Mountain region where annual precipitation is notably large.

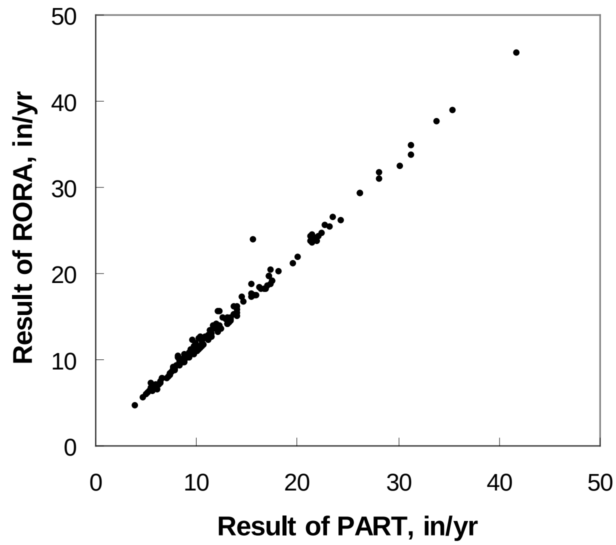

Figure 2. Relation between recharge estimates from the RORA program and discharge estimates from the PART program, on the basis of a large time scale. Each point represents one of 157 streamflow stations in the AP-RASA study and gives the mean for the time period 1961-1990. (Rutledge and Mesko, 1996, figure 17)

When the programs were available for the first time (Rutledge 1993), the author advised that results tend to be most reliable when the mean groundwater recharge or discharge is reported for a large time period such as a year or more. This did not present a problem for the earliest application of the methods (Rutledge and Mesko 1996), as results were reported for decades. A few comments about findings in later reports are relevant to the use of these two programs at a smaller time scale. First, in a fairly detailed analysis of a hydrograph it was shown that RORA calculations on the basis of each peak may exhibit problems but that these problems may cancel if a larger time scale is reported (Rutledge 2000, page 29). In the same publication it was shown that results of RORA compare with the manual Rorabaugh method if quarter-year quantities are compared. In yet another analysis, the distribution of monthly estimates generated by RORA was similar to the monthly distribution of groundwater-level rises (Rutledge 2007). The author notes that the earliest recommendations about time scale were fairly conservative and that quarter-year or seasonal results are reliable; monthly results can be used in some cases.

Program results for a small basin in Pennsylvania are shown in Figure 3 (from Rutledge 2007). There are differences between monthly estimates calculated by RORA and PART because RORA calculates recharge (R) yet PART calculates discharge (D). In some cases, recharge estimates made with the RORA program are “spiky” in comparison to the results of classical hydrograph-separation methods such as PART. This might be perceived as a problem, but R in natural flow systems may actually be spiky relative to D. This tendency might increase as smaller time scales are considered, such as the week or day. Depending on the needs of any given hydrologic study, either one of these two variables might be considered to be more important than the other. The author is making the distinction between R and D because many hydrograph-separation methods are estimating D.

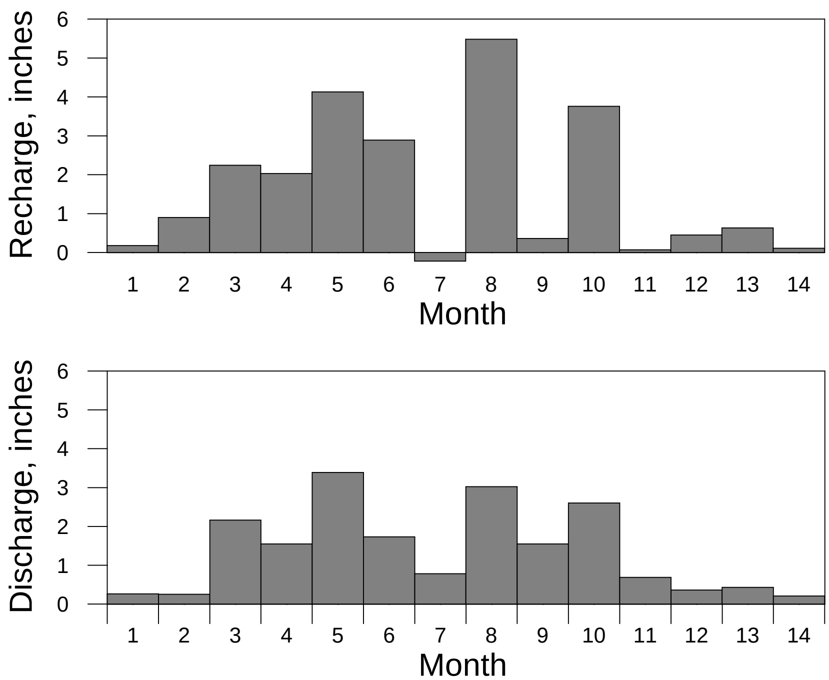

Figure 3. Monthly estimates generated by the RORA program (recharge, top graph) and by the PART program (discharge, lower graph) for a streamflow station in Pennsylvania (from Rutledge 2007). (Month 1 is August 1977 and month 14 is September 1978.)

The RORA program detects peaks in streamflow then makes calculations of recharge for each peak. A potential misconception about the program is that the magnitude of the streamflow peak determines the magnitude of recharge. Nonetheless, the calculation of recharge is strictly determined by the displacement of the recession curve. Most large storm events result in large recharge but some do not: those that do not result in large recharge tend to be evident in the summer. The program detects a recharge event wherever it detects a peak in flow, but many will have very little quantitative significance as recharge.

As noted previously, the Rorabaugh Method was applied using manual methods in a number of USGS hydrologic studies prior to the existence of the RORA program. The results of the manual methods might be compared with results of RORA. Conclusions may depend on a number of factors including hydrologic conditions and the specific techniques utilized in the manual method. For example Rutledge and Daniel (1994) described somewhat favorable comparisons yet Mayer and Jones (1996) indicate greater departures.

In addition to AP-RASA, the programs have been used in several large-scale studies. These include statewide application of RORA in Minnesota (Delin and others 2007; Lorenz and Delin 2007), New Hampshire (Flynn and Tasker 2004), West Virginia (Kozar and Mathes 2001), Ohio (Dumouchelle and Schiefer 2002), and Pennsylvania (Risser and others 2005). The last two citations included PART. Additional applications of PART include the state of Virginia (Nelms and others 1997), the lower peninsula of Michigan (Holtschlag 1997), and the Great Lakes Basin (Neff and others 2005). All of these studies included many streamflow gaging stations. The programs have been applied in smaller-scale studies described in a later section and many additional references not cited in this document.

Station Selection

The advantages of computerization are the avoidance of subjectivity and the capacity to analyze large datasets. A disadvantage is the potential for errors of various kinds that can be inevitable when any procedure is computerized. For the RORA and PART programs, some of these problems can be avoided if there is careful consideration of the compatibility between the method and the datasets that are to be used. In this context, a dataset corresponds to the characteristics of the record obtained at a streamflow-gaging station but just as important it corresponds to the characteristics of the basin that contributes flow to that station. The methods are intended for analysis of the groundwater system of a basin for which a streamflow-gaging station at the downstream end is the only point of outflow. Regulation and diversion of flow should be negligible. Preferably, all or nearly all groundwater in the basin should discharge to the stream. It is generally recommended that stations draining more than 500 square miles should be avoided, but this is arbitrary and the upper limit for drainage area may vary depending on climate and hydrologic setting. More discussion of station selection is given by Rutledge (1998) and a number of regional or statewide studies such as Rutledge and Mesko (1996), Flynn and Tasker (2004), Risser and others (2005), Lorenz and Delin (2007), Delin and others (2007), and Barlow and others (2014).

In the study for which RORA and PART were developed, the long-term estimates calculated by the two programs were similar (Figure 2). It might be tempting to believe that if the results of the two programs are profoundly different in some other hydrologic setting then one or both of the programs is not appropriate for use in that setting. This would be a generalization and exceptions might exist. Another criterion for station selection is the shape of the streamflow hydrograph, as indicated by Rutledge (2000, page 10-11). In that example, the use of RORA was questionable because the drainage area is very large (7,880 mi^2) and includes a part of a major wetland. It is also noteworthy that Halford and Mayer (2000) found that the bank storage effect is significant in this basin.

Significance of the PULSE Program

Since its initial publication, questions have arisen about the applicability of the RORA method under certain conditions. These questions include its applicability at small time scales, which might be expected because the method was developed for the purpose of long-term estimates of recharge. Another issue is that the mathematical model that underlies RORA does not explicitly allow for groundwater evapotranspiration or leakage to and from the water-table aquifer. It is also noteworthy that RORA does not calculate a hydrograph of daily groundwater discharge.

In order to address the deficiencies noted above, an alternative method was developed (Rutledge 1997). The PULSE program calculates daily groundwater discharge in a basin as a function of user-designated recharge events. PULSE can be considered a forward method that applies the original mathematical flow model developed by Rorabaugh (1964), unlike the RORA inverse method. Scientists who work with the fully automated methods might be interested in a particular application of PULSE, in which it is not used as an alternative to RORA but is instead used to evaluate results calculated by RORA. This is done by generating a synthetic record of daily groundwater discharge (using PULSE) then treating that synthetic record as input to the RORA program. If conditions are ideal, then the recharge calculated by RORA will be equal to the input recharge to PULSE. Tests of this kind also can be employed to assess the effects of various conditions that are not ideal, as described by Rutledge (2000). Topics include methods for deriving the recession index, variation of the time of recharge, and a method for reducing errors caused by direct surface runoff.

As indicated by Healy (2010, 87-90), an intriguing topic is the effect of groundwater evapotranspiration (GWET) on recharge estimates made by RORA. When RORA was first documented the effect was not known, but mathematical tests described by Rutledge (2000) allowed improved understanding. These tests consisted of the use of PULSE to generate synthetic records of groundwater discharge based on hypothetical recharge and GWET, followed by the use of RORA to analyze the synthetic record. Results indicate RORA calculates *effective recharge*, which is recharge minus GWET. The PULSE program calculates the effect of GWET using a formulation derived directly from Daniel (1976). Results should be considered with some degree of skepticism because, as noted by Daniel, the model applies GWET uniformly along the cross section from hydrologic divide to the stream, yet in nature it may be restricted to the part of the section that is near the stream. Daniel (1976) includes further discussion of model limitations. More discussion of recharge, groundwater evapotranspiration, and effective recharge is provided by Healy (2010), indicating the need for further analysis of these variables.

The PULSE program incorporates groundwater recharge (model input) with groundwater discharge (model output). As noted by Rutledge (2014), it may provide a convenient means by which the groundwater scientist can assess results of the automated methods such as RORA, PART, and HYSEP, as these methods have a certain black-box nature. The program also may aide in the determination of whether or not the automated methods are appropriate for use.

The Use of Groundwater-Level Records in Conjunction with the Programs

Because the RORA and PART programs function using streamflow, a topic of considerable interest among groundwater scientists in the Eastern United States is the independent verification of their functionality and results using groundwater-level data. It appears that the most promising technique is the water-table fluctuation (WTF) method described by Healy and Cook (2002). The method is based on the idea that if the specific yield (S_y) is known, and if the water level rise (H_o) due to a recharge event is measured, then recharge is equal to S_yH_o. As noted by Healy and Cook (2002), this may be the most widely used method for estimating recharge. They describe the technique in considerable detail, emphasizing uncertainly in the value of S_y and other limitations. They describe earlier applications of the method, for example that by Rassmussen and Andreasen (1959). An important aspect of the method is the need to designate or extrapolate the groundwater level that would have occurred in the absence of the recharge event, and various techniques are compared by Delin and others (2007). Heppner and others (2007) compare results of the WTF method with lysimeter techniques. Comparisons between the WTF method and RORA are described in the next section of this document.

The WTF method requires S_y. In a variation on the technique, Rutledge (2007) used groundwater-level rises to evaluate the relative temporal distribution of recharge, treating S_y as an unknown. This publication compared monthly groundwater-level rises with monthly estimates generated by RORA.

Another use of groundwater levels—which might be significant to PART—is a rating-curve technique for estimating the hydrograph of groundwater discharge. The procedure is to take point-in-time measurements of groundwater levels and base flow when there is no surface runoff, assemble a relation between the two variables, then use that relation along with the full groundwater-level record to generate a hydrograph of groundwater discharge. The method is illustrated by Rasmussen and Andreasen (1959, figure 6 and plate 7). The rating curve also might be used to estimate the variability of groundwater discharge. This may require the establishment of a proportional relation between the two variables, in which water level is expressed relative to the outflow boundary. Regardless of the use of a rating curve, caution is warranted as the relation between water level and groundwater discharge may not be unique (Kraijenhoff van de Leur 1958; Barlow and Moench 1998; Rutledge 2000; Moench and Barlow 2000).

The recession index might be a source of difficulties with the application of the Rorabaugh Method, whether it is implemented by RORA or other methods. This variable must be measured prior to executing the recharge model, so any difficulty doing so may introduce uncertainties in the estimate of recharge. Halford and Mayer (2000) used groundwater-level information to demonstrate the recession index can be much larger than the values obtained from streamflow records. In considering the topic, the reader might also consider a method developed by Rorabaugh (1960) for estimating the hydraulic diffusivity of an aquifer from groundwater-level recession data. As noted by Rutledge (2006), water levels must be expressed relative to the level of the outflow boundary and the level will vary along its length if the boundary is a flowing stream. The author encourages the program user to review these publications if groundwater levels are used to evaluate the recession index.

Concerns about the recession index were expressed by groundwater scientists in the East prior to Halford and Mayer (2000). One of the advantages of automation is the ease with which variables can be tested. Based on the author's experiments in the 1990s a range of different values for the index will cause changes in the recharge calculation that might be considered small relative to the uncertainty of recharge estimation (Rutledge 1998, pages 29-30).

Comparisons of the Programs with Other Methods for Recharge and Base-Flow Estimation

It is generally accepted that multiple methods should be employed for arriving at estimates of recharge (Scanlon and others 2002; Nimmo and others 2005; Healy 2010). This is not always possible because of constraints on time, equipment, funding, and historical data. Also, any given publication that describes recharge may do so as part of an expansive hydrologic study covering many other topics. Thanks in part to the USGS Groundwater Resources Program, a number of studies have focused on recharge in recent years, and this program placed considerable emphasis on humid settings. The purpose of this section is to describe some of the studies that have included use of RORA, PART, or both, and that also include one or more independent methods for estimating recharge or discharge. *Independent* methods are those that use datasets other than streamflow and are based on physical concepts and theory that differ from the streamflow methods. The author emphasizes that the following is a very brief summary of a complex topic and that scientists who are interested in the comparison of recharge methods should peruse the publications cited below.

In a state-wide study in Minnesota, Delin and others (2007) used three local-scale methods for estimating recharge (unsaturated-zone water balance, water-table fluctuations, and age dating of groundwater). They also used a basin-scale method (RORA). The estimates generated by the RORA program were regionalized using a regional regression recharge (RRR) model (Lorenz and Delin 2006) that incorporated soil and climate data. The RRR model provides an estimate of annual recharge for any point in the State, with the exception of peatlands. As noted by Delin and others (2007), the estimates from the RRR model were (1) about 41 percent less on average than the unsaturated-zone water-balance estimates, (2) ranged from 44 percent greater to 12 percent less than estimates based on the three water-table fluctuation methods, and (3) were about 4 percent less than the age-dating method. In general, recharge rates estimated by the RRR model compared favorably to the local and basin-scale recharge estimates. The authors also noted that the recharge estimates using the RRR model could be a good source of input for regional groundwater-flow models.

A study of various sites in the Coastal Plain of North Carolina (Coes and others 2007) included four recharge methods: (1) water-table fluctuations at seven sites, (2) groundwater-age dating at three sites, (3) an unsaturated-zone method using Darcy's law at two sites, and (4) the RORA program at five streamflow stations. They found results generated by RORA were substantially lower than rates estimated using methods 1 and 3 and concluded that groundwater recharge and discharge were not synchronous and (or) a substantial amount of water may have been lost from the aquifer to evapotranspiration and (or) leakage to underlying aquifers. For this reason, they considered the result of RORA to be "net recharge." (Methods 1 and 2 were considered to be total recharge and method 3 was considered to be potential recharge.) In considering all four recharge methods, the authors noted that they differ from one another in the range of space and time scales that they represent, and in the type of recharge that they estimate (Coes and others 2007).

Risser and others (2009) compared numerous methods for estimating groundwater recharge (and discharge) in a small basin in central Pennsylvania. The study included four independent methods for recharge estimation: (1) unsaturated-zone drainage from lysimeters, (2) daily water balance, (3) water-table fluctuation, and (4) Rorabaugh equations by use of computer programs RORA and PULSE. They also studied results of base-flow methods PART and HYSEP. Results based on streamflow data correlated highly with r^2 values of at least 0.96. Recharge methods 1, 2, and 3 were not as closely correlated as the streamflow methods, although there was a high correlation between method 1 and 2. Of the recharge methods, results from RORA differed significantly from most of the other methods, and method 1 differed from the fewest of the other methods. They compared annual estimates and found that the largest estimates were usually generated from RORA or method 1. In evaluating all of the methods, Risser and others (2009) noted that results are difficult to compare directly because most methods determine some surrogate of actual recharge (potential recharge, net recharge, or base flow) that represent different segments of the watershed and are determined from different types of datasets, each with their own errors.

Sanford and others (2012) estimated surface runoff and base flow for a large number of stations in the state of Virginia using chemical hydrograph separation. The separations, based on specific conductance, revealed that the average base flow was 72 percent of streamflow, as compared to the results of PART that indicated that 61 percent of streamflow consists of base flow. The authors note that, historically, when comparisons are made between the chemical techniques and "graphical" techniques, the latter will tend to underestimate the size of the base-flow component for individual runoff events.

The publications cited above indicate there has been a considerable range of findings when the results of RORA and PART have been compared with a variety of independent methods. This may be of particular significance to groundwater scientists in the Eastern United States.

Comments about Topographic Relief

Publications describing various forms of hydrograph separation have noted that surface runoff can present problems that limit the utility of the methods (Halford and Mayer 2000, Kish and others 2010). In areas of low relief, these problems may require special allowances in the way the methods are implemented (Stewart and others 2007). In the AP-RASA study area (Figure 1), relief is moderate in some areas and substantial in others. For this reason, the time of surface runoff was considered to be fairly short. Rutledge (1998 pages 31-32) describes a technique for minimizing errors due to surface runoff in low-relief basins but, as noted, there are limitations on applying that technique. The programs were developed for the AP-RASA area and have had considerable utility in large portions of the Eastern United States (Figure 1); however, there may be some areas where the programs are not appropriate, such as low-relief areas of the Florida peninsula. The PULSE program might be considered as an alternative to RORA in those areas because the user can calibrate according to local knowledge of the time of surface runoff.

High relief might present problems that affect the Rorabaugh Model. The issues have been addressed to a limited extent. For example, Rutledge (2003) showed that the model can be used under conditions of downvalley flow given certain cautionary statements about the recession index. A study of a basin in central Pennsylvania indicated a short lag time between precipitation and recharge even though the unsaturated zone is fairly thick (Rutledge 2014). The author suggests further research to evaluate the effects of topographic relief, and perhaps the AP-RASA study might help to provide a foundation for analysis. A question that might be considered is whether a given problem is restricted to methods based on Rorabaugh (1964). If it is, then perhaps it would affect results of RORA but not PART. Figure 2 indicates a fairly stable relation between results of the two programs and represents a wide range of topographic relief.

History of Software Releases

These programs have been implemented using various techniques as a result of increased program demand, variation in data sources, and changes in computer platforms. The following paragraphs describe developments over the period 1993 to 2007:

1993 – The programs were documented for the first time (Rutledge 1993). The FORTRAN source codes were provided on a disk that was distributed with the report. The report described how to compile and load the programs on a Data General AViiON Workstation. At the time, the use of Personal Computers (PCs) was not widespread among USGS scientists, and the USGS did not serve streamflow data on the World Wide Web. The documentation included instructions for retrieving data from a USGS database (ADAPS), which required special access. The format of the data was a “2 and 3 card” file, which was a carryover from card-reader technology. An auxiliary program TRANS would convert data into a Z-file (Rutledge 1993) that could be read by RORA or PART. As noted in the documentation report, the programs were developed for AP-RASA.

1998 – A new documentation was published (Rutledge 1998). The programs included new features that were not available in 1993. For example, results were provided at various time scales, such as the year, quarter-year, and month. The programs included various warning messages to prevent errors. The programs were placed on an FTP site, but most features of program use were the same as in 1993.

2000-2007 – A number of additional enhancements took place during this time period. The programs were adapted for PC use and the Windows operating system, as this platform had become prevalent in the USGS. The programs also were adapted for reading data directly in the format that was available on public web sites maintained by the USGS. This format provided the date and a daily streamflow on each line in the file. (The TRANS program was not required for the new versions.) A new auxiliary program SCREEN could be executed prior to RORA or PART to provide the user with information about the extent of the streamflow record. Informal user manuals were written for RORA and PART. The programs were placed on the following web sites, along with the user guides, auxiliary programs, and various files that were essential: http://water.usgs.gov/ogw/rora/ and http://water.usgs.gov/ogw/part/ .

2014 – The programs were assembled along with other programs into a groundwater toolbox (Barlow and others, 2014). The GW Toolbox is a customized interface built on the non-proprietary, open-source MapWindow geographic information system software. This provides graphing, mapping, and analysis capabilities in a Microsoft Windows computing environment. The GW Toolbox allows for the retrieval of data from the USGS National Water Information System, downloading geographic information coverages including meteorological data from the National Oceanic and Atmospheric Administration National Climatic Data Center, and analysis of data with several preprocessing and postprocessing utilities.

Variation in computer implementation can create difficulties for program users. However, any computer application that has value to hydrologic studies may require updates to keep the application current. It is noteworthy that there have been no significant changes in the actual computer algorithms of RORA or PART.

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