# RECHARGE AND DISCHARGE CALCULATIONS TO CHARACTERIZE THE GROUNDWATER HYDROLOGIC BALANCE [1]

by

Robert G. Liddle [2]

Abstract: Several methods are presented to quantify the ground water component of the hydrologic balance; including 1) hydrograph separation techniques, 2) water budget calculations, 3) spoil discharge techniques and 4) underground mine inflow studies. Stream hydrograph analysis was used to calculate natural groundwater recharge and discharge rates. Yearly continuous discharge hydrographs were obtained for 16 watersheds in the Cumberland Plateau area of Tennessee. Baseflow was separated from storm runoff using computerized hydrograph analysis techniques developed by the USGS. The programs RECESS, RORA, and PART were used to develop master recession curves, calculate ground water recharge, and ground water discharge respectively. Station records ranged from 1 year of data to 60 years of data with areas of 0.67 to 402 square miles. Calculated recharge ranged from 7 to 28 inches of precipitation while ground water discharge ranged from 6 to 25 inches. Baseflow ranged from 36 to 69% of total flow. For sites with more than 4 years of data the median recharge was 20 inches/year and the 95 % confidence interval for the median was 16.4 to 23.8 inches of recharge. Water budget calculations were also developed independently by a mining company in southern Tennessee. Results showed about 19 inches of recharge is available on a yearly basis. A third method used spoil water discharge measurements to calculate average recharge rate to the mine. Results showed 21.5 inches of recharge for this relatively flat area strip mine. In a further analysis it was shown that premining soil recharge rates of 19 inches consisted of about 17 inches of interflow and 2 inches of deep aquifer recharge while postmining recharge to the spoils had almost no interflow component. OSM also evaluated underground mine inflow data from northeast Tennessee and southeast Kentucky. This empirical data showed from 0.38 to 1.26 gallons per minute discharge per unit acreage of underground workings. This is the equivalent to 7 to 24 inches of recharge per year. The four methods provide a good comparative way to quantify the groundwater portion of the hydrologic balance.

Additional Key Words: modeling, water budget, mining, coal.

## Introduction

Coal mining operations are required to restore the groundwater recharge rate, ensure protection of groundwater supply, and identify the probable hydrologic consequences of mining to the surface and groundwater systems. The regulatory authority is required to conduct a cumulative hydrologic impact assessment (CHIA) and make a finding on whether material damage to the hydrologic balance will occur.

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2 Rob Liddle is a hydrologist with the US Department of the Interior, Office of Surface Mining, Suite 500, 530 Gay St. SW, Knoxville, TN 37902

The "hydrologic balance" is a regulatory term defined in SMCRA regulations as "the relationship between the quality and quantity of water inflow to, water outflow from, and water storage in a hydrologic unit..." A quantitative prediction of impacts usually requires a quantitative evaluation of the hydrologic balance. In turn this requires a quantified prediction of the groundwater recharge rate and discharge rate. This paper discusses several methods to quantify the ground water component of the hydrologic balance; including 1) hydrograph separation techniques, 2) water balance calculations, 3) spoil discharge techniques and 4) underground mine inflow studies.

## Hydrograph Separation Techniques

One of the options in calculating ground water recharge and discharge is the use of empirical models such as hydrograph analysis. A hydrograph is generated



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from yearly continuous discharge measurements. The baseflow is separated from the storm runoff component graphically and the results can be used to estimate both ground water recharge, discharge and loss through consumption or evapotranspiration. Recent computer models have been developed to do this quickly (Rutledge, 1993).

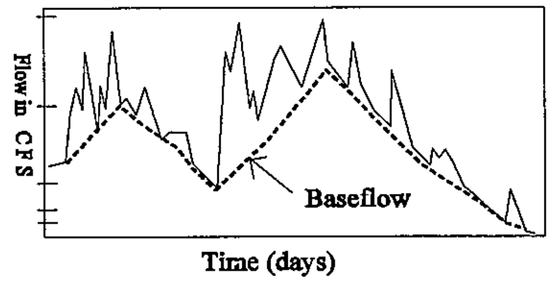
## Methods

Records provided in the U.S. Geological Survey's "Water Resources Data - Tennessee" were reviewed to find surface water gaging locations in the Cumberland Plateau region of Tennessee with at least onc year of continuous daily flow records. Gaging sites needed to be at nick points in the watershed where it can be reasonably assumed that most of the ground water surfaces and recharges the stream prior to the gage site. The watersheds needed to have local ground water flow as opposed to regional trans-valley ground water components. The steep topography of the Cumberland Plateau region makes these conditions easier to find than in other parts of the country. "Stress relief fracturing" is the predominant ground water flow component in these areas (Wyrick, 1981). The review identified 16 watersheds that met this criteria. The USGS in Knoxville supplied the raw data from Watstore in "2 and 3 Card" computer format. The sites that were studied follows:

| USGS # | Sq Mi. | Years | Description |
|---|---|---|---|
| 03407881 | 0.69 | 4 | Anderson Br. - Montgomery |
| 03407875 | 0.67 | 7 | Bills Br near Hembree |
| 03407877 | 2.19 | 5 | Bowling Br. - Smokey Jct. |
| 03409500 | 272.00 | 60 | Clear Fork near Robbins |
| 03407908 | 198.00 | 10 | New River at Cordell |
| 03544500 | 50.20 | 1 | Richland Creek |
| 03408815 | 3.62 | 5 | Crooked Creek near Allardt |
| 03408600 | 1.11 | 5 | Long Br. Near Grimsley |
| 03407882 | 0.92 | 4 | Lowe Br - Montgomery |
| 03571500 | 116.00 | 1 | Little Sequatchie River |
| 03408500 | 382.00 | 56 | New River at New River |
| 03409400 | 98.00 | 2 | White Oak Cr. At Rugby |
| 03571000 | 402.00 | 34 | Sequatchie River - Whitwell |
| 03407875 | 5.08 | 2 | Shack Cr. At Hembree |
| 03407876 | 17.20 | 7 | Smokey Cr. at Hembree |
| 03409000 | 13.50 | 1 | White Oak Cr. At Sunbright |

The procedure of hydrograph separation is discussed in standard hydrology texts (Kresic, 1997; Singh, 1992; Fetter, 1988; Satterlund, 1992). This paper used the recession-curve displacement method developed by the USGS. The baseflow hydrograph is estimated from the total runoff hydrograph, the baseflow recession

Figure 1 - HYDROGRAPH




characteristics, and information about the watershed hydraulics. When baseflow is superimposed on a total flow hydrograph (See Figure 1) the groundwater or surface runoff for any time period may be calculated.

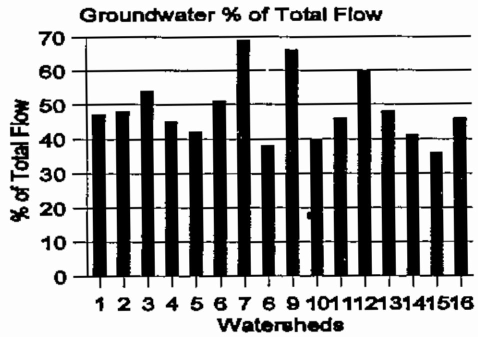
The streamflow records must be compared with yearly temperature and precipitation data to properly interpret the hydrograph and develop the baseflow hydrograph. Many hydrographs representing years of wet, normal, and dry precipitation years need to be evaluated. This process can become tedious when evaluating many years of record. Fortunately computer codes have been developed to allow this analysis to be done quickly. In this project the USGS programs RECESS, RORA, and PART were used to develop master recession curves, calculate recharge, and estimate ground water discharge, respectively (Rutledge, 1993). Documentation with the programs adequately explain the rational and methods used in the code along with limitations of the programs. The model methods have been shown to compare reasonably well with manual hydrograph methods.

Results of the hydrograph separation analysis for the Tennessee coal fields showed average groundwater recharge ranged from 36 to 69% of total flow (See figure 2).

The median base flow percent of total flow was 47% with the 90% confidence limits of 41% and 53%. The smaller watersheds tended to have somewhat higher recharge rates but the result is not statistically significant. Most of the smaller watersheds had few years of record and may be more susceptible to regional ground water flows.

Three watersheds were selected for further evaluation based on their size and years of record. Clear Fork has an area of 272 square miles and 60 years of record. New River has 382 square miles and 56 years of record. Sequatchie River has 402 square miles and 34

Figure 2 - Base Flow Index

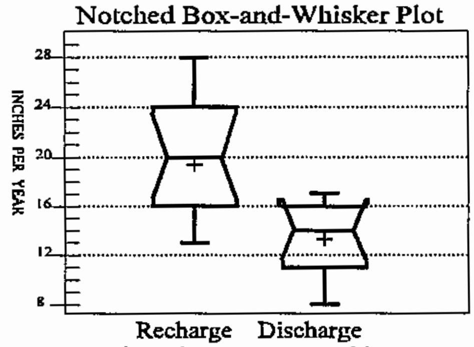



years of record. These watersheds had 13, 14, and 20 inches of recharge per year respectively; with about 56 inches of precipitation per year. Discharge was 11, 11, and 16 inches respectively. The Base Flow index was 45 %, 40 %, and 60 % respectively. These values may be indicative of similar size watersheds in Eastern Tennessee due to similarities in ground water hydraulics (fracture controlled) and precipitation.

The difference between ground water recharge and discharge may be assumed to be loss through consumption or more importantly, groundwater evapotranspiration. The larger watersheds showed losses of about 3 inches of rain per year which is in line with other studies conducted in eastern Appalachia showing 1 to 2 inches of losses (Rutledge, 1993, p.40) from shallow groundwater. The total evapotranspiration from soils and surface systems is not evaluated by this technique.

For the Cumberland Plateau as a whole, data were summarized using only those watersheds with 4 or more years of record. The median recharge was 20 inches/year with a 90% confidence interval of 16.4 to 23.8 inches. The median groundwater discharge was 14 in/yr with a 90% confidence interval of 11.8 to 16.2 inches. The following figure shows the interquartile ranges, medians, means and extremes (Statgraphics):

Notched Box-and-Whisker Plot




Sites w/ 4 or more years of data.

Water Budget

A monthly water balance can be calculated for the watershed of interest using information on precipitation, infiltration rates, soil moisture holding capacity, evaporation and transpiration. One such water budget was calculated independently by personel of Skyline Coal Company, a subsidiary of Cypress/Amax (Skyline, 1996) using the Thornthwaite method. A copy of the water balance calculations is contained as an attachment to this paper. Rainfall was 63.9 inches, evapotranspiration was 24.9 inches, direct runoff was 19.9 inches or 31% of total precipitation. The water budget showed a yearly recharge rate of 19.1 inches per year (base flow index of 49%) for the Cumberland Plateau area near the Sequatchie River. This compares favorably with the hydrograph separation techniques previously discussed that showed about 20 inches per year recharge for the Sequatchie River.

Spoil/Aquifer Discharge Techniques

If a reclaimed surface mine receives most of its recharge from surface infiltration, then by measuring the discharge from the spoils a recharge rate can be calculated (assuming all assumptions are valid). This situation often occurs at larger surface mines near the drainage divide where recharge from adjacent areas is minimal and recharge from underlying aquifers does not occur. Upgradient streams, in-spoil ponds, or adjacent aquifers may bias calculations. One may have to wait several years until the spoil water table stabilizes to do this analysis. In theory, however, one can measure the flow from all spoil springs from a mine, convert it to cubic feet per year and divide by the area of the spoil in square feet. This gives a result in feet (or inches) of yearly precipitation.

This method can also be used to qualitatively determine whether recharge to spoils is occurring from adjacent areas. If the amount of recharge is well above the regional norm then it is possible recharge from adjacent or underlying aquifers is occurring in significant amounts. OSM installed a parshall flume at a reclaimed 576 acre surface strip mine and measured flows for several years. This site had developed acid mine drainage despite spoil handling, lime additions, and an anoxic drain. The average spoil discharge from the site was 642 gpm. Assuming a recharge area of 576 acres, this amounts to 1.79 feet or 21.5 inches of recharge per year. This recharge amount is typical of other values obtained by OSM for the region. Therefore dewatering of adjacent abandoned mines is thought to be minor and the site itself is causing the acid mine drainage.

One can also determine premining groundwater recharge rates using similar methods. And in particular, aquifer recharge rates can be separated from soil interflow rates. Instead of measuring spoil discharge, wells placed in the undisturbed aquifer can measure hydraulic gradients and conductivity of the water bearing unit below the ground surface. By measuring the fluctuations in water levels, a seasonal flow rate of that aquifer can be calculated using Darcy's Law.

One should evaluate a portion of the unsaturated aquifer that meets the following requirements: the watershed should be undisturbed, no ground water is being pumped in the area, stress relief fracturing is minor, the headwaters of the ground water basin are near, and no artificial or underlying recharge is occurring. If these conditions are met, a deep aquifer recharge rate is estimated by determining the annual flow rate for the aquifer in an area that has defined recharge boundaries. The groundwater flow rate (per year) divided by the areal extent of recharge to the aquifer gives you feet of rainfall per year. This deep aquifer recharge rate subtracted from the total available soil recharge gives the annual discharge rate from interflow at the soil/bedrock interface.

OSM calculated the recharge rate for the unconfined Newton Sandstone aquifer in southern Tennessee. Pump tests from 7 area wells were to determine hydraulic conductivity. Hydraulic conductivities were 0.77 to 1.21 ft/day. The hydraulic gradient was measured from three wells, and the area of recharge (about 500 acres) was estimated from the potentiometric contour map of the area that was developed from about a dozen nearby wells. Data was supplied by Skyline Coal Company. The results showed the aquifer was being recharged at a rate of 0.7 to 4 inches per year. The amount of water available for recharge (passing through the soil horizon) was previously calculated as 19 inches per year using both a water balance and hydrograph separation techniques. This means of the 19 inches of recharge, about 17 inches leaves the watershed through interflow and about 2 inches is available for deeper percolation. This site is in an area with little stress relief fracturing and should not be considered indicative of all areas. However, I interpret the results to show what most practicing hydrologists already know, that is, premining bedrock recharge rates are small compared to post mining spoil aquifer recharge rates. In flatter spoil areas, interflow at the spoil/soil interface may be low, resulting in large amounts of the total precipitation on an area migrating through the spoils. However, in steep mine areas interflow at the soil/spoil interface has been shown to be significant (Carrucio, 1993 ).

Mine Inflow Rates

Underground mine discharge rates can also be studied to quantify a range of underground mine recharge rates one can expect in a given geologic environment. Either mine pumping records or postmining portal discharge records can be used to measure the seasonal discharge rate. The recharge area to the mines may be estimated by taking the underground mine workings map (usually available from MSHA) and adding an angle of draw and calculating the affected area. Again, one must be on guard for other recharge sources, undetected discharge locations, fracturing considerations, full vs. partial extraction, etc. Because of these many factors, this technique may not give reliable estimates of groundwater recharge rates but may aid in the predicting portal discharges from future mining in similar coal seams and geologic environment.

OSM used this technique to evaluate the rate at which underground mining could dewater or "pirate" water from one watershed into another. The area studies was in the Tackett Creek and Clear Fork watersheds on the Tennessee and Kentucky border. This is an area of very high topographic relief with significant stress relief fracturing as evidenced by contour strip operations and underground mine face-ups. Flow meters or buckets were used to measure portal discharges from 5 nearby underground mines. The average discharge rate for the summer months was divided by the estimated affected area of the underground workings. The discharge rates (Table 1) were converted into gallons per minute per acre of underground workings and also into inches of recharge per year for comparison with previous recharge studies.

Table 1- Underground Discharges

| Site | Area | Flow | recharge | recharge |
|---|---|---|---|---|
| | acre | gpm | gpm/ac | in/yr |
| GW1 | 91 | 35 | 0.38 | 7.32 |
| GW2 | 79 | 100 | 1.26 | 24.38 |
| Block | | | 0.5 | 9.67 |
| Mat1 | 3645 | 720 | 0.19 | 3.8 |
| Mat2 | 10316 | 720 | 0.07 | 1.34 |
| Kent | 47 | 15 | 0.32 | 6.14 |

The variability in the results is attributed to the affects of stress relief fracturing, full vs. partial extraction, etc. Some mines were mining near the subcrop whereas other mines were deeper and under more cover. An attempt was made to evaluate the data through regression by pairing discharge rates with linear feet of coal crop undermined, depth of cover, and barrier pillar distance. However, there are not enough data to do a reliable regression analysis. Hopefully with more data the variation in mine inflow rates can be better understood.

However, the present results do show a useful procedure and have provided OSM and the mining companies a method of predicting a range of mine inflows for their future operations.

## Summary


Recent computer codes enable a quick analysis of hydrographs for estimating ground water recharge and discharge. Readily available USGS daily discharge records in computer format can be used in these models. The results of this study showed a median recharge rate of 20 inches/year for the Cumberland Plateau. The 90% confidence interval of the median was 16.4 to 23.8 inches/year.

Simplified water budget calculations can be made using approximate methods such as that of Thornthwaite to estimate water available for recharge. Results of calculations for the southern Tennessee coal fields by Skyline Coal Company showed about 19 inches of the yearly rainfall is available for recharge.

Spoil discharge measurements and calculation of premining aquifer recharge rates can help distinguish between infiltration that leaves the watershed as interflow along the soil/bedrock interface and water that actually percolated into underlying shallow bedrock aquifers. Preliminary calculations showed that premining infiltration rates of about 19 inches per year consisted as 17 inches of interflow and only about 2 inches of aquifer recharge for a flat site with little stress relief fracturing. Whereas after mining the spoil aquifer recharge rate was almost 19 inches with little interflow at the spoil/soil interface. I suspect rates for steep mines or for areas with stress relief fracturing wouldt be different from these results.

Underground mine inflow measurements were used to estimate recharge to the mine workings of 3.8 to 24.38 inches per year. This was used to estimate mine discharge rates of 0.07 to 1.26 gallons per minute per acre of mined out workings. Data showed variability resulting from various depths of cover, barrier pillars, partial vs. full extraction, and influence of stress relief fracturing.

Combined, these four methods can be used to evaluate both regional and local groundwater recharge and

discharge rates. Care must be exercised in applying results from one site to another given the variability in geology. However, they can contribute to the understanding of the hydrologic balance for an area and in quantifying the impacts from mining.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