USE OF MODFLOW DRAIN PACKAGE FOR SIMULATING INTER-BASIN TRANSFER OF GROUNDWATER IN ABANDONED COAL MINES[1]

Mark D. Kozar[2] and Kurt J. McCoy

Abstract. Simulation of groundwater flow in abandoned mines is difficult, especially where flux to and from mines is unknown or poorly quantified, and inter-basin transfer of groundwater occurs. A study was conducted in southernmost West Virginia to better understand inter-basin transfer of groundwater in above-drainage abandoned coal mines. The Elkhorn area was specifically selected, as all mines are located above the elevation of tributary receiving streams, to allow accurate measurements of discharge from mine portals and tributaries for groundwater model calibration.

Abandoned mine workings were simulated initially as a layer of high hydraulic conductivity bounded by lower permeability rock in adjacent strata, and secondly as rows of higher hydraulic conductivity embedded within a lower hydraulic conductivity coal aquifer matrix. Regardless of the hydraulic conductivity assigned to mine workings, neither approach to simulate mine workings could accurately estimate inter-basin transfer of groundwater from the adjacent Bluestone River Watershed.

To resolve the problem, a third approach was developed. The MODFLOW DRAIN package was used to simulate seepage into and through mine workings discharging water under unconfined conditions to Elkhorn Creek, North Fork, and tributaries of the Bluestone River. Drain nodes were embedded in a matrix of uniform hydraulic conductivity cells that represented the coal mine aquifer. Drain heads were empirically defined from well observations, and elevations were based on structure contours for the Pocahontas No. 3 mine workings. Use of the DRAIN package to simulate mine workings as an internal boundary condition resolved the inter-basin transfer problem, and effectively simulated a shift from a topographic-dominated to a dip-dominated flow system, by dewatering overlying unmined strata and shifting the groundwater drainage divide up dip within the Pocahontas No. 3 coal seam approximately five kilometers into the adjacent Bluestone River Watershed. The simulation of mine entries and discharge using the MODFLOW DRAIN package produced estimated flows of 0.46 and 0.26 m^3/s for the Elkhorn Creek and North Fork watersheds respectively, which matched measured flows for the respective watersheds of 0.47 and 0.26 m^3/s.

Additional Key Words: Groundwater flow, numerical model

---

[1] Paper presented at the 2012 National Meeting of the American Society of Mining and Reclamation, Tupelo, MS ***Sustainable Reclamation*** June 8 - 15, 2012. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] Mark D. Kozar is a Hydrologist with the U.S. Geological Survey, Washington Water Science Center, Tacoma, WA 98402, [2]Kurt J. McCoy is a Hydrologist with the U.S. Geological Survey, Virginia Water Science Center, Richmond VA, 23228.

Proceedings America Society of Mining and Reclamation, 2012 pp 304-320

DOI: 10.21000/JASMR12010304

http://dx.doi.org/10.21000/JASMR12010304

Introduction

Underground mining has the potential to alter the hydrology in the Appalachian Plateaus on a relatively large scale (Callaghan et. al., 1998) by modifying boundary conditions and aquifer hydraulic properties. Hydrologic interconnection between highly permeable above-drainage underground mines promotes a shift from a classic topographically-dominated groundwater flow regime (Ferguson, 1967; Wyrick and Borchers, 1981; Harlow and LeCain, 1993; Sheets and Kozar, 2000) to one that is dip-dominated, with groundwater capture areas that greatly exceed the boundaries of individual mines (Lopez and Stoertz, 2001).

A case study of an abandoned underground coal mine in the Pocahontas No. 3 coal seam in southern West Virginia is presented to highlight the transition from topographically-dominated to dip-dominated groundwater flow in a mined basin of the Appalachian Plateaus. The Pocahontas No. 3 coal seam has been extensively mined by underground methods in West Virginia since the 1880s. An extensive network of abandoned mine voids in the Pocahontas No. 3 have since filled with good-quality potable water that is accessed via springs, mine outfalls, and wells for public supplies. Groundwater in abandoned Pocahontas No. 3 mines near Elkhorn, West Virginia flows by gravity to the west along a gentle dip slope to discharge points at the seam outcrop. Above-drainage mines in the Pocahontas No. 3 seam that potentially contribute to flow at Elkhorn extend up dip to the Appalachian Plateau front approximately five kilometers to the east (Fig. 1).

This paper summarizes three modeling approaches using MODFLOW to investigate the influence of mining on groundwater basin configuration and boundary conditions in above-drainage portions of the Pocahontas No. 3 coal seam. The project was completed in cooperation with the West Virginia Department of Environmental Protection, West Virginia Department of Health and Human Resources, and the West Virginia Geological and Economic Survey. Previous researchers have used MODFLOW in mined settings (Toran and Bradbury, 1988; Goode et. al., 2011; Zaidel et. al., 2010) although MODFLOW limitations need to be considered prior to modeling in partially saturated or geologically complex mined environments (Booth, 2002; Adams and Younger, 2001). Extensive field data from the Elkhorn study are used to support assumptions in the development and calibration of the groundwater flow models.

Purpose and Scope

The purpose of this paper is to present findings of a 3-year hydrogeologic investigation of abandoned coal mine workings in the Pocahontas No. 3 coal seam in the Elkhorn area, West Virginia. Development of groundwater flow models for abandoned underground coal mines present unique challenges, and this paper will focus on methods used to simulate groundwater flow in above-drainage abandoned mine workings in a largely un-deformed structural setting. Emphasis will be placed on the data collected for the project and why they were collected, refinement of the conceptual understanding of groundwater flow in the study area, and the use of the MODFLOW DRAIN package to simulate inter-basin transfer of groundwater within abandoned mine workings.

Approach

A multi-phase approach was taken to better understand the prolific abandoned coal-mine aquifers which supply the majority of water used for public supply in the study area. The Elkhorn area, West Virginia was selected as the area of study for several reasons after an extensive statewide search for suitable sites. First, the abandoned coal mines in the Pocahontas No. 3 coal-mine aquifer in the study area are all above local drainage. Assuming minimal leakage through the base of the mine workings, outflows from the mines could be directly measured. Second, the absence of mined seams overlying or underlying the Pocahontas No. 3 coal seam reduces the hydrogeologic complexity of the area to a manageable level.

Numerous field data were collected to define a conceptual model of groundwater flow in a typical mined basin of the Appalachian Plateaus. Mine boundaries within the study area were digitized by the West Virginia Geological and Economic Survey (WVGES). Seven monitoring wells were installed in an east-west transect along the dip of the Pocahontas No. 3 coal seam adjacent to Elkhorn Creek. Borehole geophysical logs were collected to ascertain the nature and extent of fractures and bedding plane separations within the Pocahontas No. 3 mine aquifer and overlying and underlying strata. A streamflow gauge and precipitation monitoring station was installed on Johns Knob Branch, a tributary to Elkhorn Creek, fed primarily by large outfalls from the Pocahontas No. 3 mine aquifer, to quantify the amount of water discharging from the mine during various hydrologic conditions. Monthly water-level measurements were made in each of the seven monitoring wells; two wells were equipped with monitoring instrumentation to provide an hourly record of water levels within and below the Pocahontas No. 3 mine aquifer. Aquifer tests were conducted on two wells to better understand hydrologic properties in strata below the Pocahontas No. 3 coal seam.

A steady-state numerical model of groundwater flow was developed using MODFLOW-2000 (Harbaugh et. al., 2000) to test the conceptual understanding of topographic-dominated versus dip-dominated groundwater flow. The model was calibrated with water levels measured in the seven wells completed for the project and 96 base flow discharge measurements made at mine outfalls and along the main stem and tributaries to North Fork and Elkhorn Creek. Parameter estimation using PEST (Doherty 2010a, 2010b) was conducted to further refine the models and to assess parameter sensitivity. Results of the modeling provide significant insight into the methods used to simulate inter-basin transfer of groundwater within abandoned mine workings.

Description of the Study Area

The study area (Fig. 1) is located in the southernmost part of West Virginia's low-sulfur coalfield. It is comprised of a portion of the Elkhorn Creek watershed on the south and west, the North Fork watershed to the north, and by a portion of the Bluestone River watershed to the east. The total study area encompasses 152.3 square kilometers (km^2), but the 95.8 km^2 area comprised of the Elkhorn Creek and North Fork tributaries was the primary emphasis of the study. The study area includes the 56.5 km^2 area of the Bluestone River watershed, as the No. 3 Pocahontas coal seam in the watershed is structurally up dip of the North Fork and Elkhorn Creek watersheds and was thought a priori to be a potential source of inter-basin transfer of groundwater (Fig. 1). This region of the Appalachian Plateaus is highly dissected with topographic relief exceeding 300 meters (m).

Geologic Setting

The primary rocks cropping out in the study area are the layered sandstones, shales, and coal seams of the Pocahontas and New River Formations (Fig. 2). Regional dip is to the northwest at approximately 14.2 m/km (< 2°). There are at least ten named coal seams in the Pocahontas Formation, with four of minable thickness in the study area: the Pocahontas Nos. 2, 3, 4 and 6. By far the Pocahontas No. 3 was the most valuable coal seam, being heavily mined within the study area beginning in the early 1900's. The Pocahontas No. 3 seam generally ranges in thickness from 1.2 – 2.1 m, and has been completely mined out underground in the study area, and its outcrop area widely contour surface mined. The lowest minable coal seam, the Pocahontas No. 2, has not been mined within the study area. The Pocahontas No. 4 seam, while not mined in the immediate study area, is heavily mined approximately 4.8 km west of the town of Northfork. The Pocahontas No. 6 has been mined by surface techniques within the footprint of the study area.

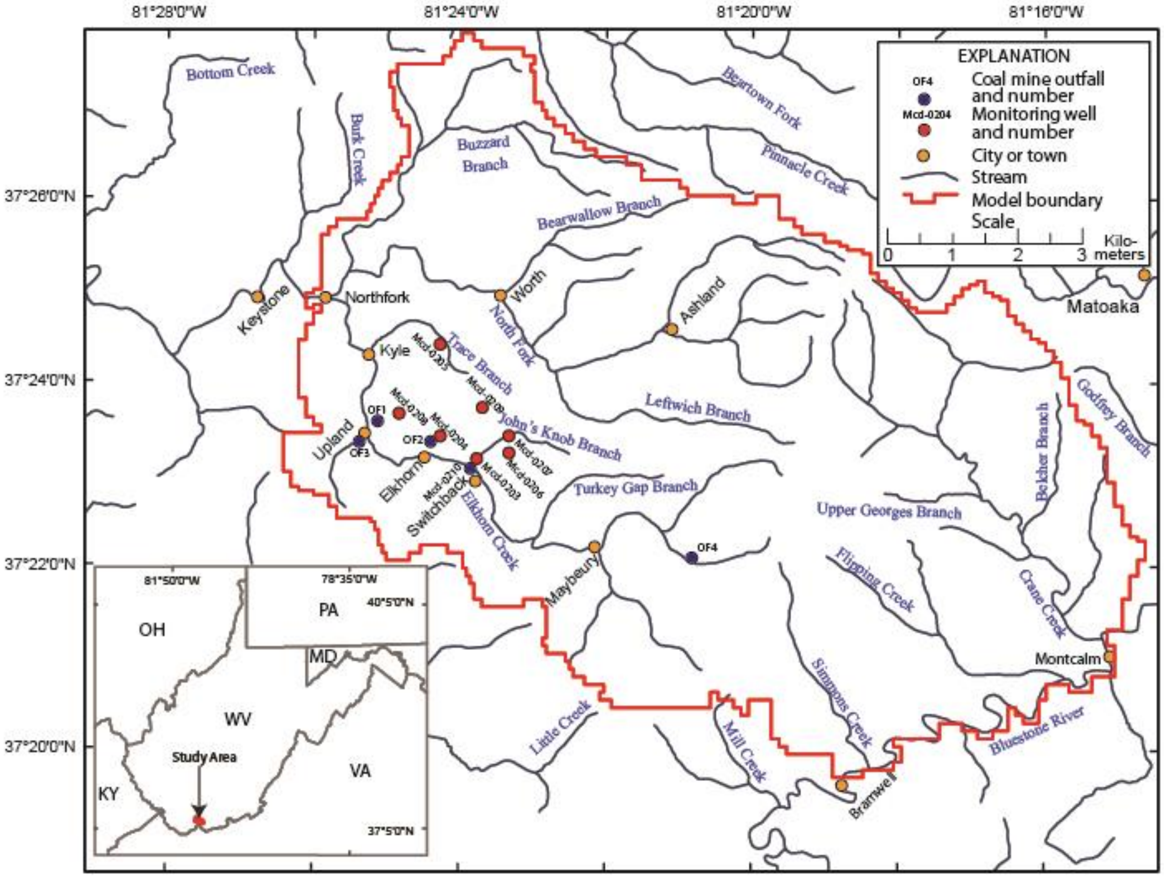

Figure 1. Location of the study in the Elkhorn area, McDowell County, West Virginia.

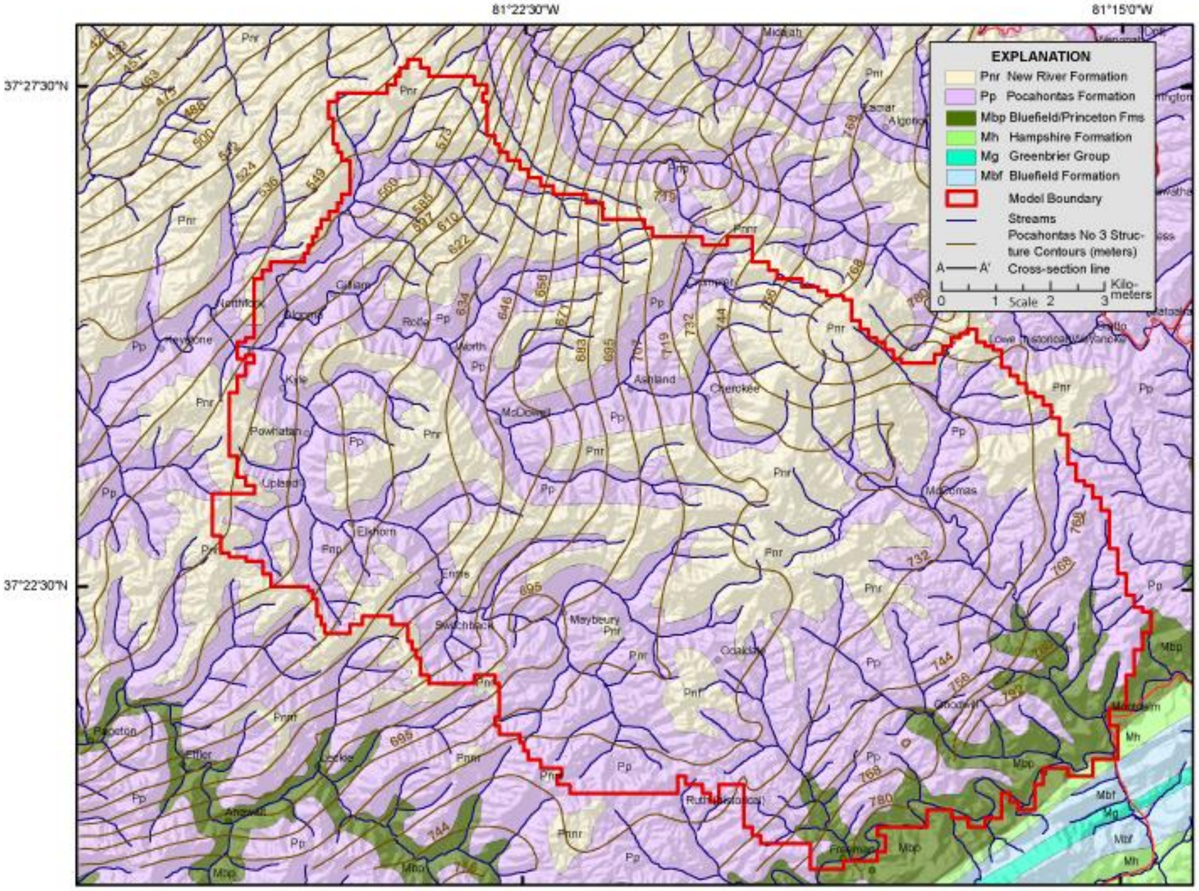

Figure 2. Geologic map of the study area showing geologic formations, structural contours for the base of the Pocahontas No. 3 coal seam, and the boundary for the groundwater-flow model developed for the Elkhorn area, West Virginia.

Conceptual Model of Groundwater Flow

Wyrick and Borchers (1981) expanded upon Ferguson's (1967) original stress-relief model to describe groundwater flow in the Appalachian Plateaus as occurring primarily in bedding-plane separations beneath valley floors and in nearly vertical and horizontal stress-relief fractures along valley walls. Near-surface groundwater flow in valley and hillside settings occurs in a network of fractures formed by the unloading of compressional stresses. Harlow and LeCain (1993) found downward gradients driving flow in a stair-step pattern, alternating among vertical joints, faults, and fractures, and horizontal bedding-plane separations. Groundwater age dating supports the concept that recharge occurs primarily in topographically high areas (ridges) and flows laterally and downward toward valley floors (Fig. 3) through shallow fractures in the bedrock

(McCoy and Kozar, 2006; Sheets and Kozar, 2000). A revised conceptual model of groundwater flow in unmined strata in the Appalachian Plateaus is presented in Fig. 3.

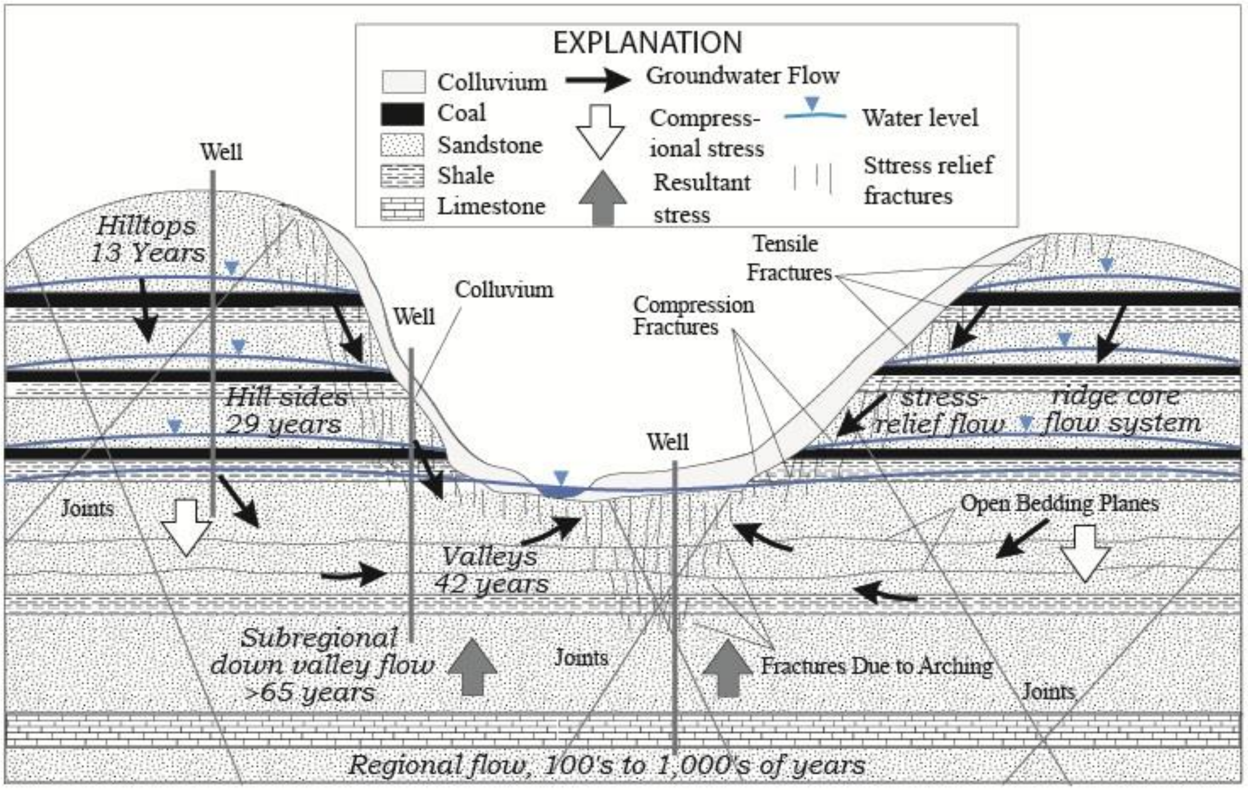

Figure 3. Revised conceptual model of groundwater flow in an unmined Appalachian Plateaus fractured-bedrock aquifer, including apparent age of groundwater [modified from Ferguson, 1967, Wyrick and Borchers, 1981, and Sheets and Kozar, 2000].

There are limited studies of groundwater flow in abandoned mine workings of the southern West Virginia coalfields, most of which have focused on public supplies in below-drainage workings (Ferrell, 1992; WVDEP, 2007). Previous conceptual models developed elsewhere for above-drainage mine aquifers consist of partially or fully flooded mines that freely drain to discharge points or portals along the outcrop (Donovan and Fletcher, 1999). Investigations of above-drainage mines routinely take advantage of discharge points to assess mine hydrology (Burbey and others, 2000), resulting in some uncertainty about hydrologic conditions within the abandoned workings. Seven wells drilled during the present study show that large portions of the strata overlying the Pocahontas No. 3 mine aquifer were relatively devoid of water, and the minimal water encountered was found in coal seams. The results from drilling suggest nearly complete dewatering of coal, sandstone, and shale strata above abandoned mine workings. Observed mine water levels during the course of this study are consistent with phreatic flow along the dip of the Pocahontas No. 3 coal seam within abandoned mine workings. A revised conceptual model of groundwater flow in mined strata is presented in Fig. 4.

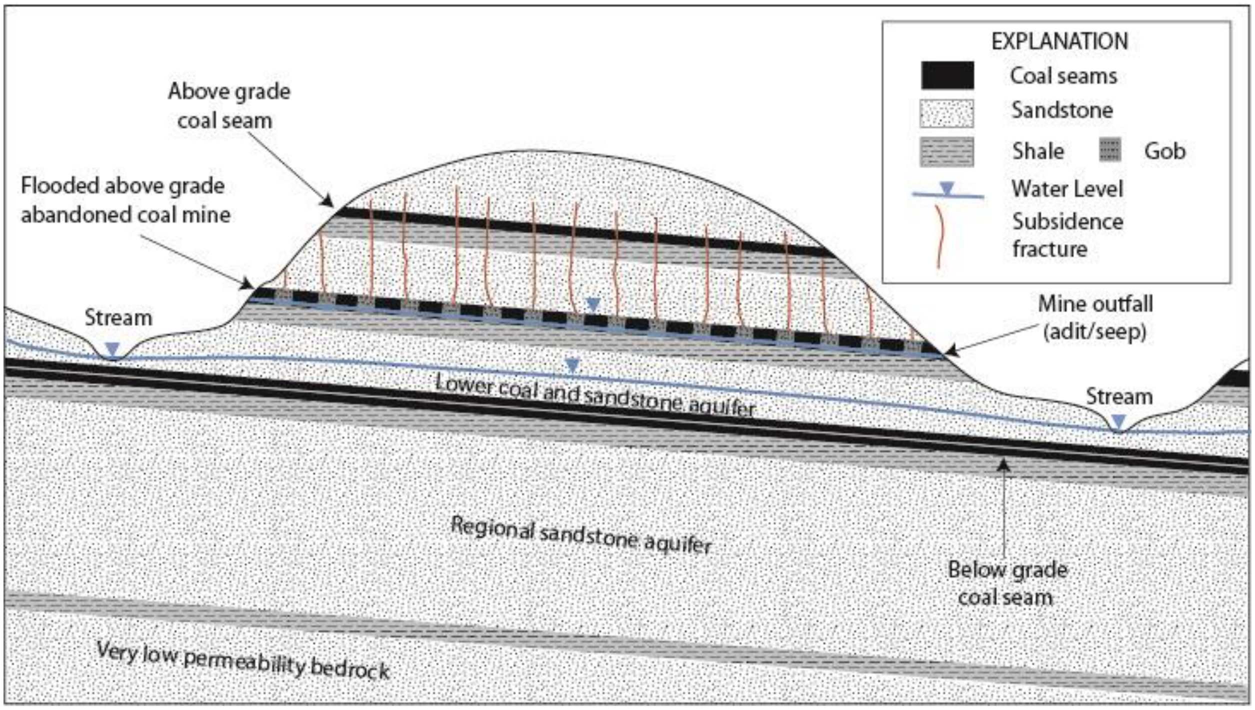

Figure 4. Revised conceptual model of groundwater flow in above drainage abandoned underground coal mines, showing breaching of overburden strata due to subsidence fracturing resulting from extraction of coal in the Pocahontas No. 3 coal seam, Elkhorn area, West Virginia.

Borehole video logging of abandoned mine workings in the Pocahontas No. 3 coal seam revealed significant accumulation of angular material within mine voids resulting from subsidence of overlying strata and/or collapse or spalling of coal pillars. Near complete dewatering of overlying strata apparently resulted in a change from topographically-dominated to dip-dominated groundwater flow in the mine aquifer. In above-drainage mined areas, geologic structure, especially the dip of coal seams and occurrence of synclinal troughs or anticlinal arches, become major controls on the configuration of groundwater basins. Local variations result in structurally high and low areas along the floor of the mine, potentially allowing local pools of groundwater to accumulate in the topographic lows between intervening structural highs. Mine outfalls typically occur at abandoned portals and can be large where portals coincide with synclinal troughs. Many legacy mine outfalls in the Elkhorn dating to the 1920’s and 1930’s are on the down dip side of hill slopes, which allows free flow drainage of water from abandoned mine workings in the Pocahontas No. 3 coal seam. Such down dip portals are no longer allowed under requirements of the Surface Mining Control and Reclamation Act of 1977.

Two streams, Johns Knob Branch and Buzzard Branch, have anomalously large discharge when compared to their respective surface-water drainage areas. The anomalously large discharge of these two streams is due to inter-basin capture of groundwater from adjacent watersheds (Fig. 5). Johns Knob Branch, a primary emphasis of the study, emanates from mine outfalls that coincide with a west-southwest oriented synclinal trough in the Pocahontas No. 3 coal seam, whose axis is coincident with mine outfalls discharging to Johns Knob Branch. Median base flow per square kilometer for gaged streams in the southern coalfields of West Virginia is approximately 0.007 $m^3/s/km^2$, but Johns Knob Branch has a base flow per unit surface-water drainage area of 0.072 $m^3/s/km^2$. Thus the stream is capturing groundwater over a much broader area than can be explained by the 2.10 km^2 surface-water drainage area. Given measured base flow for Johns Knob Branch of 0.152 m^3/s, and the median base flow per unit surface-water drainage area of streams in the southern coalfields of 0.007 $m^3/s/km^2$, a minimum groundwater drainage basin area of approximately 21.7 km^2 is necessary to produce the mean streamflow recorded at the Johns Knob Branch gauging station. Thus, the groundwater recharge source area is approximately 10 times larger than the corresponding surface-water drainage area for Johns Knob Branch, and is due to inter-basin capture and transfer of groundwater from up-dip extent of the Pocahontas No. 3 coal mine aquifer within the Bluestone River watershed.

Previous Simulations of Groundwater Flow for Abandoned Mines

Quantitative groundwater models have been designed to estimate inflow to abandoned workings (Banks, 2001; Winters and Capo, 2004), route groundwater through interconnected mine voids (Adams and Younger, 2001), and assess residence times (Winters and Capo, 2004). Modeling of the complex hydrostratigraphy and mine-to-mine interaction in mine aquifer systems is difficult, but results can be used for regional-scale water budgets (Adams and Younger, 2001).

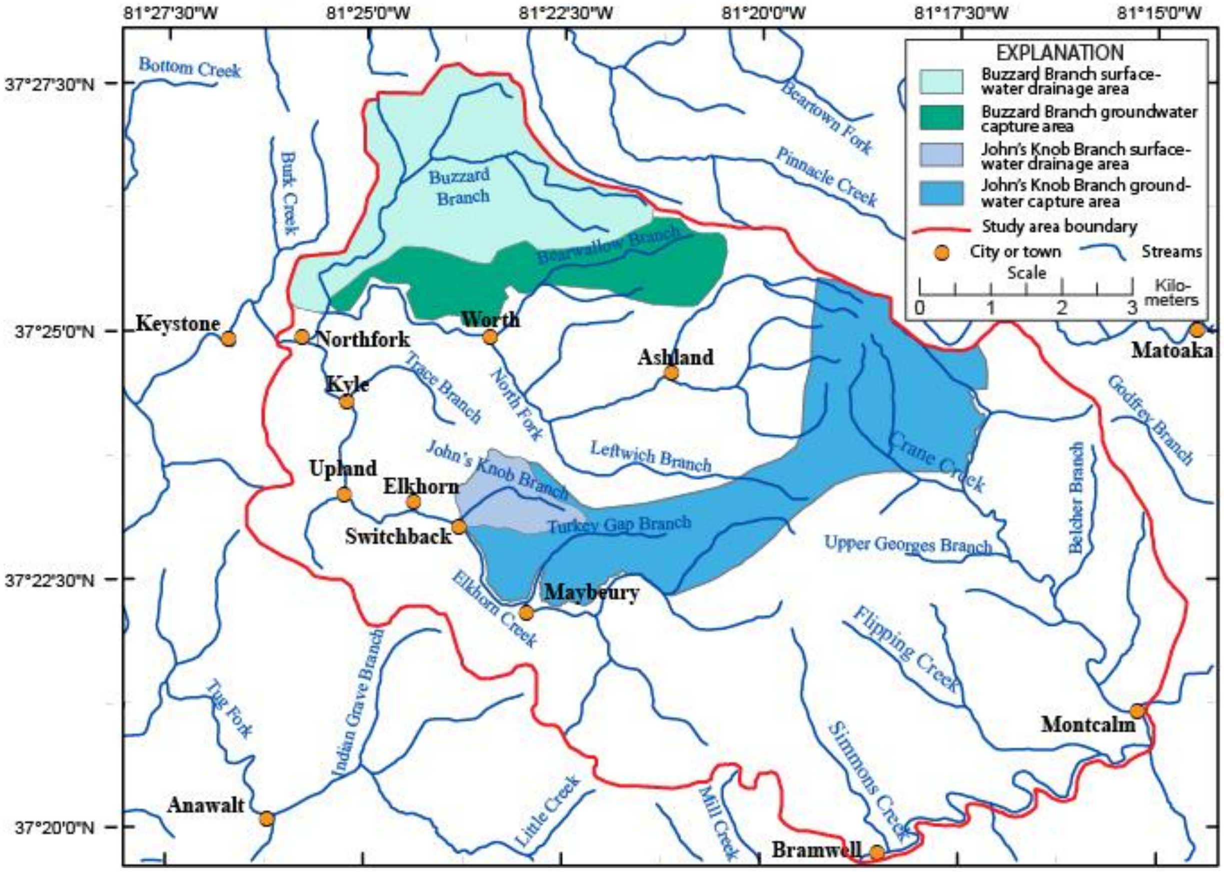

Figure 5. Surface-water drainage areas and estimated groundwater capture areas required to produce measured flows for Johns Knob Branch and Buzzard Branch, in the Elkhorn area, West Virginia. [Bedrock and coal seams dip from east to west].

Use of MODFLOW to model groundwater flow has been considered inappropriate in some mined settings due to high fluid velocities, turbulent flow, and variably saturated media (Booth, 2002). Adams and Younger (2001) note problems with spatial and temporal discretization that make convergence of MODFLOW models in mined areas difficult. Zaidel et. al., (2010), however, found accurate prediction of seepage rates can be achieved with careful attention to grid spacing. Their assessment suggests limitations with the use of MODFLOW in simulations of seepage to underground mine workings can be overcome by considering cell sizes in context of the geometry of actual mine openings. Others have used the DRAIN package (Toran and Bradbury, 1988) and multi-colliery units (Goode et. al.,, 2011) in MODFLOW simulations of mine aquifers.

Approach for Simulating Groundwater Flow in Above Drainage Mines

A 4-layer groundwater flow model (Fig. 6) was developed to represent the hydrogeologic setting using the U.S. Geological Survey modular three-dimensional finite-difference groundwater-flow model MODFLOW-2000 (Harbaugh and others, 2000). Layer 4 represents deeper rock below local tributary streams, layer 3 represents the rock in the valley bottoms including areas of intense stress relief fracturing, layer 2 represents the abandoned Pocahontas No. 3 mine workings, and the upper layer (layer 1) represents rock overlying the abandoned Pocahontas No. 3 mine workings. Since the Pocahontas No. 3 coal seam crops out at an elevation above the local tributary streams, the Hydrogeologic Unit Flow (HUF) package was used to establish the layering for the model.

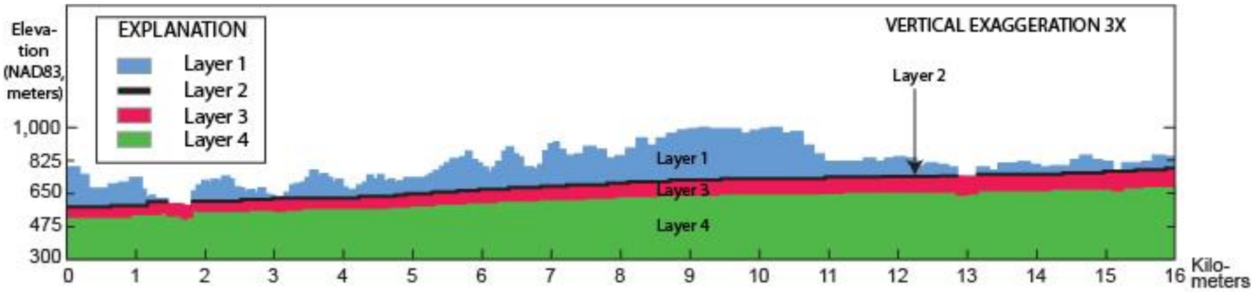

Figure 6. Cross section showing layers of the numerical groundwater-flow model developed for the Elkhorn Area, West Virginia.

Three different modeling approaches were attempted to simulate groundwater flow in the abandoned mine workings of the Pocahontas No. 3 coal seam. The abandoned mine workings in layer 2 were initially simulated A) as a layer of high hydraulic conductivity within the model, and alternatively, B) as a series of high hydraulic conductivity cells embedded in a lower hydraulic conductivity coal matrix, representing room and pillar mine entries. These methods of indirectly simulating mine workings with sharp contrasts in aquifer properties were unable to accurately simulate the inter-basin transfer of groundwater from the Bluestone River watershed to the adjacent North Fork and Elkhorn Creek watersheds (Fig. 5 and Table 1). Conceptualization of the workings as highly permeable layers alone was ineffective in shifting the drainage divide far enough to the east to simulate all of the inter-basin transfer of groundwater which flows laterally down dip within abandoned mine workings from as far as 5 km to the east within the Bluestone River watershed (Fig. 7).

Table 1. Groundwater flow model results representing mine voids by three different methods; as A) a layer of high hydraulic conductivity within the model, B) as a series of high hydraulic conductivity cells embedded in a lower hydraulic conductivity matrix, and C) using the MODFLOW DRAIN package to simulate mine voids.

	Measured base flow (m^3/s)	Simulated base flow method A (m^3/s)	Simulated base flow method B (m^3/s)	Simulated base flow method C (m^3/s)
North Fork	0.26	0.32	0.32	0.26
Elkhorn Creek	0.47	0.33	0.34	0.46
Johns Knob Branch	0.09	0.01	0.02	0.10
Buzzard Branch	0.09	0.07	0.08	0.07

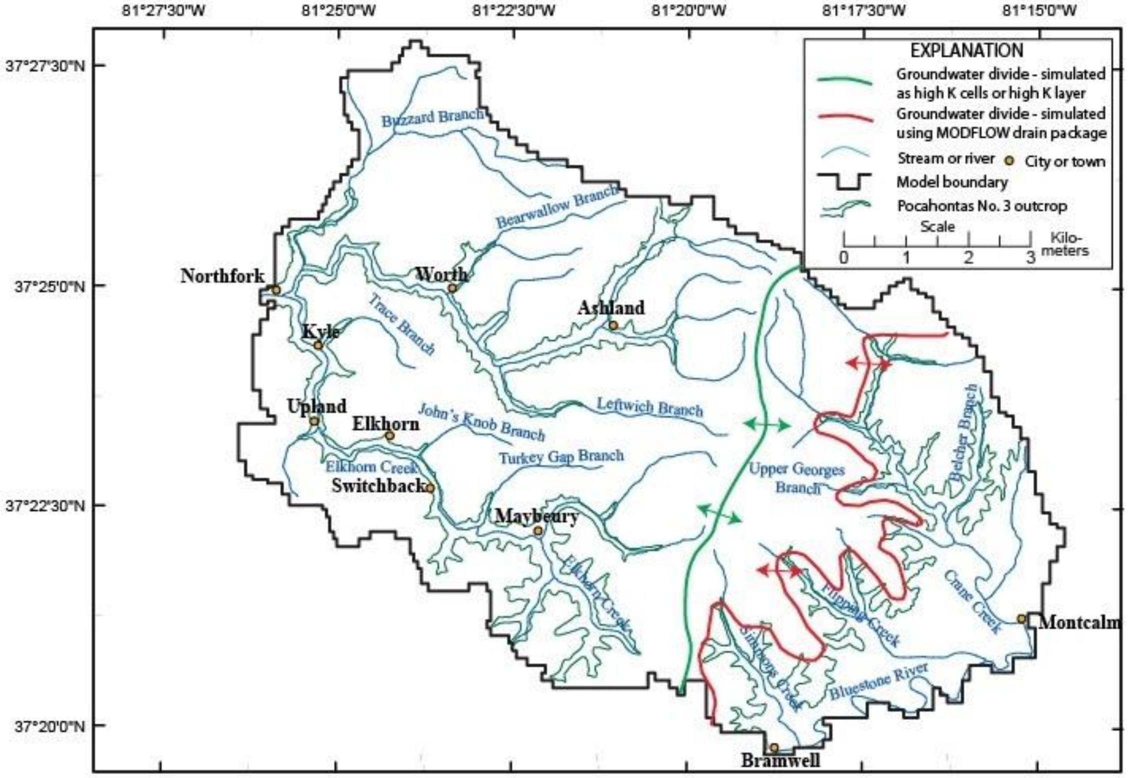

Figure 7. Relative position of groundwater divides simulated as A) a layer of high hydraulic conductivity (high K layer) within the model, B) as a series of high hydraulic conductivity cells (high K cells) embedded in a lower hydraulic conductivity matrix, simulating room and pillar mine entries, or C) using the MODFLOW DRAIN package to simulate the mine entries within the abandoned Pocahontas No. 3 coal mine workings.

To resolve the inter-basin transfer of groundwater problem, a third approach had to be developed to produce model results that were consistent with water level and base flow observations and to move the groundwater drainage divide far enough to the east to capture additional groundwater along the base of the Pocahontas No. 3 coal seam from structurally up-dip areas 5 km east in the Bluestone River watershed. The problem was resolved by C) using the MODFLOW DRAIN package to simulate the mine entries of the abandoned Pocahontas No. 3 coal mine workings. Mine entries were simulated as drain nodes with empirically defined specified heads based on elevations from a structural contour map of the base of the Pocahontas No. 3 coal seam, and conductance determined through model parameter estimation using PEST (Doherty, 2010a, 2010b). Since accurate mine maps showing mine entries, portals, and elevations were unavailable, a structural contour map of the base of the Pocahontas No. 3 coal seam served as the basis for drain elevations in layer 2 of the model. Known mine outfalls and mine portals were shown on the 1925 U.S. Geological Survey Bramwell, W.VA-VA 1:62,500 topographic quadrangle were simulated as outfalls for the abandoned mine aquifer within the model.

Results of the Simulations

Computed water budgets for the North Fork, Elkhorn Creek, Johns Knob Branch, and Buzzard Branch based on the simulations of the abandoned mine workings for approaches A and B, clearly indicate that the first two approaches were unable to accurately simulate base flow augmented by inter-basin transfer of groundwater within the abandoned Pocahontas No. 3 mine workings from up-dip areas within the Bluestone River watershed to the down dip North Fork and Elkhorn Creek watersheds (Table 1). Base flows resulting from approach C, the use of the MODFLOW DRAIN package to simulate the abandoned mine workings, however, compared well to measured flows in the respective watersheds, and reflected a change from topographic-dominated to dip-dominated flow. The use of the MODFLOW DRAIN package also altered the groundwater drainage divide moving it up dip to the east approximately five kilometers within the adjacent Bluestone River watershed. Model simulations prior to use of the DRAIN package for simulating mine workings produced estimated flows of 0.32 to 0.34 m^3/s in each of the similar sized Elkhorn Creek and North Fork Watersheds. The simulation of mine entries and discharge using the MODFLOW DRAIN package produced estimated flows of 0.46 and 0.26 m^3/s for the Elkhorn Creek and North Fork watersheds, which matched well with measured flows for the respective watersheds of 0.47 and 0.26 m^3/s.

Summary

This report summarizes water budgets from three modeling approaches using MODFLOW 2000 to investigate the influence of underground coal mining on groundwater flow processes and basin boundaries in above-drainage portions of the Pocahontas No. 3 coal seam in McDowell County, West Virginia. The study area was specifically selected, as all mines simulated are located above the elevation of tributary streams, and there is little interaction with overlying and no interaction with underlying mine workings. This approach allowed accurate measurements of discharge to be made from mine portals and tributary streams to provide data for groundwater model calibration, and reduced the overall complexity of the simulations to a manageable level. A conceptual model developed for the study area suggested that inter-basin transfer of groundwater in above-drainage mines is possible, as conditions permit a shift from topographic- to dip-dominated flow.

Three different methods were tested to simulate inter-basin transfer in the Pocahontas No. 3 abandoned mine workings. Initially the abandoned mine workings were simulated A) as a layer of high hydraulic conductivity within the model, and alternatively B) as a series of high hydraulic conductivity cells embedded in a lower hydraulic conductivity matrix, simulating room and pillar mine entries. These methods of simulating mine workings were ineffective in simulating inter-basin transfer of groundwater, which results from a shift from topographic-dominated to dip-dominated flow. A third approach C) was necessary to represent mine entries as an internal boundary condition within the matrix of a coal aquifer. Mine entries were assigned as drain nodes with empirically defined specified heads based on elevations from a structural contour map of the base of the Pocahontas No. 3 coal seam, and conductance determined through model parameter estimation using PEST.

Use of the DRAIN package improved model accuracy and validated the conceptual model of dip-dominated flow through abandoned mine workings; increasing the groundwater capture area by shifting the groundwater divide to a location approximately five kilometers up dip within the Pocahontas No. 3 coal seam in the adjacent Bluestone River Watershed, coincident with the up dip extent and outcrop area of the Pocahontas No. 3 coal seam. The two model simulations prior to use of the MODFLOW DRAIN package for simulating abandoned mine workings produced estimated flows of 0.32 to 0.34 m^3/s in each of the similar sized Elkhorn Creek and North Fork

watersheds, but failed to estimate dip-dominated inter-basin transfer of groundwater from the adjacent Bluestone River watershed. The simulation of mine entries and discharge using the MODFLOW DRAIN package produced estimated flows of 0.46 and 0.26 m^3/s for the Elkhorn Creek and North Fork watersheds, which matched measured flows for the respective watersheds of 0.47 and 0.26 m^3/s, and effectively simulated inter-basin transfer from the adjacent Bluestone River watershed.

Literature Cited

Adams, R., and P.L. Younger, 2001. A strategy for modeling ground-water rebound in abandoned mine systems: Ground Water, v. 39, p. 249-261. *http://dx.doi.org/10.1111/j.1745-6584.2001.tb02306.x*.

Banks, D. 2001. A variable-volume, head dependent mine water filling model: Ground Water, v. 39, no. 3, p. 362-365. *http://dx.doi.org/10.1111/j.1745-6584.2001.tb02319.x*.

Booth, C.J. 2002. The effects of longwall coal mining on overlying aquifers: Geological Society, London, Special Publications 2002, v. 198, p. 17-45. *http://dx.doi.org/10.1144/GSL.SP.2002.198.01.02*.

Burbey, T.J., T. Younos, and E.T. Anderson. 2000. Hydrologic analysis of discharge sustainability from an abandoned underground coal mine: Journal of the American Water Resources Association, v. 36, n. 5, p. 1161-1172. *http://dx.doi.org/10.1111/j.1752-1688.2000.tb05718.x*.

Callaghan, T., G.M. Fleeger, S. Barnes, and A. Dalberto. 1998. Chapter 2, Groundwater flow on the Appalachian Plateaus of Pennsylvania: 39 p In Coal mine drainage prediction and pollution prevention in Pennsylvania, Brady, K., Smith, M., and Schueck, J., [eds.], Pennsylvania Department of Environmental Protection, Harrisburg, PA.

Doherty, J. 2010a. PEST, Model-independent parameter estimation—User manual (5th ed., with slight additions): Brisbane, Australia, Watermark Numerical Computing.

Doherty, J. 2010b. Addendum to the PEST manual: Brisbane, Australia, Watermark Numerical Computing.

Donovan, J.J., and J. Fletcher. 1999. Hydrogeological and geochemical response to mine flooding in the Pittsburgh coal basin, southern Monongahela River basin: Project WV-132 Report to the U.S. Environmental Protection Agency, 47p.

Ferrell, G.M. 1992. Hydrologic characteristics of abandoned coal mines used as sources of Public water supply in McDowell County, West Virginia: U.S. Geological Survey Water-Resources Investigations Report 92-4073, 37 p.

Ferguson, H.F. 1967. Valley stress relief in the Allegheny Plateau: Association of Engineering Geologists Bulletin, v. 4, p. 63-68.

Goode, D.J., C.A. Cravotta, III, R.J. Hornberger, M.A. Hewitt, R.E. Hughes, D.J. Koury, and L.W. Eicholtz. 2011. Water budgets and groundwater volumes for abandoned underground mines in the Western Middle Anthracite Coalfield, Schuylkill, Columbia, and Northumberland Counties, Pennsylvania - Preliminary estimates with identification of data needs: U.S. Geological Survey Scientific Investigations Report 2010-5261, 54 p.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p., accessed May, 2009, at *http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-92.pdf*.

Harlow, G.E., Jr. and G.D. LeCain. 1993. Hydraulic characteristics of, and ground-water flow in, coal bearing rocks of southwestern Virginia: U.S. Geological Survey Water-Supply Paper 2388, 36 p.

Lopez, Dina L., and M. Stoertz. 2001. Chemical and physical controls on waters discharged from abandoned underground coal mines, Geochemistry: Exploration, Environment, Analysis, v. 1, p. 51-60. *http://dx.doi.org/10.1144/geochem.1.1.51*.

McCoy, K.J., and M.D. Kozar. 2006. Relation of chlorofluorocarbon age dates to water quality in aquifers of West Virginia: U.S. Geological Survey Scientific Investigations Report 2006-5221, 36 p.

Sheets, C.J., and M.D. Kozar. 2000. Ground-water quality in the Appalachian Plateaus, Kanawha River Basin, West Virginia: U.S. Geological Survey Water-Resources Investigations Report 99-4269, 25 p.

Toran, L., and K.R. Bradbury. 1988. Ground-water flow model of drawdown and recovery near an underground mine. Ground Water, v. 6, no. 6, p 724-733. *http://dx.doi.org/10.1111/j.1745-6584.1988.tb00423.x*.

Winters, W.R., and R.C. Capo. 2004. Ground water flow parameterization of an Appalachian coal mine complex: Ground Water, v. 42, no. 5, p. 700-710. *http://dx.doi.org/10.1111/j.1745-6584.2004.tb02724.x*.

WVDEP (West Virginia Department of Environmental Protection). 2007. SCR-15, An Evaluation of the Underground Injection of Coal Slurry in West Virginia, Phase I: Environmental Investigation, 80 p.

Wyrick, G.G., and J.W. Borchers. 1981. Hydrologic effects of stress relief fracturing in an Appalachian valley: U.S. Geological Survey Water-Supply Paper 2177, 51 p.

Zaidel, J., B. Markham, and D. Bleiker. 2010. Simulating seepage into mine shafts and tunnels with MODFLOW. Ground Water, v. 48, no., 3, p. 390-400.
https://doi.org/10.1111/j.1745-6584.2009.00659.x