IAH 2010
Krakow

BIULETYN PAŃSTWOWEGO INSTYTUTU GEOLOGICZNEGO 441: 33–42, 2010 R.

SURFACE WATER–GROUNDWATER INTERACTION IN THE FRACTURED SANDSTONE AQUIFER IMPACTED BY MINING-INDUCED SUBSIDENCE: 1. HYDROLOGY AND HYDROGEOLOGY

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Abstract. Mining-induced subsidence under surface waterways enhances surface water–groundwater interaction due to the enlargement of existing fractures, development of new fractures and the separation of bedding planes. Fracturing of streambeds and rockbars causes surface flow to divert to subsurface routes. The surface water–groundwater interaction in an undermined stream in the Southern Coalfield of New South Wales, Australia, has been assessed by analysing hydrological data including flow measurements upstream and downstream of the longwall panels. The data suggests leakage of surface water to the subsurface through fractured streambeds and rockbars. Mining-induced fracturing across the catchment is likely to have caused increased rainfall infiltration, reduced runoff, and reduced baseflow discharge, resulting in streamflow reduction and possibly loss, particularly during low flow conditions affecting the catchment's water balance. During medium and high flow conditions, the streamflow loss is relatively small in comparison to the total volume of flow in the stream, as the capacity of the subsurface system limits the volume of water that can enter subsurface routes. Streamflow reduction in mining-impacted catchments is likely to be an effect of the spatial distribution and density of fracture networks, changes in porosity and permeability of the subsurface rock mass, changes in groundwater storage capacity, modification to baseflow discharge and alteration of the hydraulic gradient near streams.

Key words: longwall mining, surface water–groundwater interaction, streamflow reduction, fractured aquifer, Australia.

INTRODUCTION

The importance of water resource protection and the maintenance of stream function has increased following the observed surface water–groundwater connectivity in areas where mining-induced subsidence has led to declines in baseflow discharge to streams.

Impacts to surface hydrology include the loss of surface flow, the development of ponding, enhanced surface water–groundwater interaction, increased erosion, and deterioration of surface water quality (Peng *et al.*, 1996; Booth, Bertsch, 1999; Sidle *et al.*, 2000; Booth, 2002; Lucas *et al.*, 2009). There have been various studies undertaken above active longwall mines, providing some insight into mining-induced subsidence on the temporary or permanent loss of streamflow and the increase in surface water–groundwater interaction. Relatively little is known about flow losses as a result of longwall mining. Some of the published papers which cover this aspect of impacts of mining on surface water flow were investigated in the Appalachian Coalfield, USA (Tieman *et al.*, 1987, 1992; Dixon, Rauch, 1988, 1990; Carver, Rauch, 1994), Utah Coalfield, USA (Slaughter *et al.*, 1995), East Midlands, England (Shepley *et al.*, 2008) and Southern Coalfield, New South Wales, Australia (Jankowski, 2007, 2009; Jankowski *et al.*, 2008).

The stream-aquifer system can be classified based on the predominant local groundwater flow component for:

– underflow-component with groundwater flow longitudinal to a stream;
– baseflow-component with groundwater flow lateral to or from a stream;
– or a combination of both.

The above three groundwater flow types are postulated in the Waratah Rivulet catchment, Southern Coalfield, New South Wales (NSW), Australia, impacted by longwall mining, through the development of new fractures, enlargement

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of existing fractures, separation of bedding planes and the modification of stream topography (Jankowski, 2007, 2009). The conceptual lateral and longitudinal flow model of surface water–groundwater interaction in a mining-impacted area was described by Jankowski (2007). The inflow of surface water into the subsurface mainly occurs along vertically outcropping fractures, joints, and veins that provide dominant pathways for surface water to infiltrate an aquifer. Depending on the opening, length, and position of fractures, the surface water–groundwater interaction can be permanent or temporary. Streamflow may be permanent or temporary based on the following scenarios:

Permanent flow occurs when the:

- stream is connected-gaining and there are baseflow contributions from an aquifer in the local groundwater flow system;
- size and distribution of the surface fracture network is small, limiting surface water infiltration;
- capacity of the subsurface system to store water is lower than the streamflow infiltration rate.

Temporary flow occurs when the:

- baseflow contribution is small and unreliable;
- size and distribution of the surface fracture network is large, allowing increased surface water infiltration;
- capacity of the subsurface system to store water is higher than the streamflow infiltration rate.

The location of surface water inflow depends on the interconnectivity of vertical fractures and horizontal bedding planes. Some fractures and bedding planes are well connected and others are not, which can result in complex flow patterns, with flow in part of the stream and a lack of flow in another part, particularly during low flow conditions. Several recharge-discharge zones can be present along a streambed, causing surface water to recharge the subsurface and reappear downstream as surface flow. Cracks in rockbars further complicate the system. Vertical flow can extend to substantial depths depending on the fracture network and whether there is low permeability material present, such as claystone or shale. Horizontal inflow of surface water depends on the extension of bedding planes and their opening. Some large opened bedding planes can be used as preferential pathways for groundwater flow (Jankowski, 2007).

Because the interaction between surface water and groundwater depends on factors such as topography, streambed morphology, the surface water level and groundwater level (hydraulic gradient), several different surface water–groundwater connections can develop during pre-mining, mining, and post-mining periods (*op. cit.*). As there are no detailed studies on how subsidence modifies surface flow, it is necessary to develop a conceptual model based on hydrogeological flow principles in fractured aquifer systems. Many scenarios can by drawn from this approach; simple surface water–groundwater interactions and complex/multiple interactions with several recharge-discharge zones and mixing points (*op. cit.*). Mining induced-subsidence can cause the fracturing of streambeds and rockbars, with the enlargement of existing fractures, the development of new fractures, separation of bedding planes and changes in channel geometry (Sidle *et al.*, 2000; Kay *et al.*, 2006). A reduction in streamflow may not only be the result of fracturing streambeds and rockbars in the main stream overlying an active longwall mine; mining-induced fracturing can extend across the catchment and its tributaries, generally bounded by the limit of subsidence and/or angle of draw. Increased fracturing allows rainfall to infiltrate and recharge fractured aquifers, reducing runoff available for recharging streams. Although rainfall recharge to the shallow aquifers can increase, groundwater levels can also decline due to the mining-induced fracturing of the rock mass, causing the dewatering of shallow aquifers and reducing baseflow discharge. Fracturing of the banks of streams and tributaries can also reduce streamflow during high flow conditions. Streamflow reduction is also an effect of the spatial distribution and density of fracture networks, changes in porosity and permeability of the subsurface rock mass, changes in groundwater storage capacity, modification to baseflow discharge and alteration of the hydraulic gradient near the streams.

Prior to mining the streams in this area were usually connected-gaining, with groundwater level above the lowest streambed elevation. However, shallow piezometers located near the stream close to the edges of already mined longwall panels indicate that shallow groundwater close to the stream is affected by subsidence, causing the majority of groundwater levels to be below the streambed, causing the stream to be disconnected-losing with the diversion of surface water into subsurface voids. It is expected that lateral flow dominates natural rainfall recharge of the aquifer, whereas longitudinal flow is expected to dominate subsurface flow. Fractures, joints and bedding planes still provide pathways for subsurface flow; however the openings are smaller than they would be above the active mining panel. There is usually surface flow in the stream at this location; however surface flow also recharges the subsurface system with a relatively fast infiltration rate, indicating a high hydraulic conductivity of the aquifer. In an area where the compressional phase of subsidence is present fractures are partially re-closed and there is limited vertical and horizontal extension of fractures and bedding planes, the groundwater level has partially recovered and groundwater discharges through vertical fractures under pressure often in streambeds (Jankowski *et al.*, 2008).

This paper discusses flow reductions and losses in a small drinking water supply catchment impacted by longwall mining and the possible hydrological and hydrogeological processes that resulted in the streamflow reduction.

STREAMFLOW REDUCTION / LOSS

The Waratah Rivulet catchment in the Southern Coalfield, NSW, Australia, which is the focus of this paper, has been subjected to mining-induced subsidence, with extensive fracturing of streambeds and rockbars. Before mining, the predominantly incised streams flowing over sandstones were connected-gaining with the hydraulic gradient towards the stream. Although no baseline data was collected prior to the commencement of mining, nearly two years of monitoring data has provided sufficient hydrological information to undertake an initial assessment of flow conditions in the catchment. There are three gauging stations located on the main stream (Jankowski, 2010), monitoring flow upstream of the mining area (on the boundary between recent longwall mining and previous board and pillar mining), within the mining area (on the boundary between longwall mined and non-mined areas and inside the area outlined by the angle of draw, above the rib zone, which defines the limit of subsidence to 20 mm) and downstream of the currently mined area.

Figure 1 shows the streamflow data from the main stream between April 2007 and February 2010. Analysis of the data indicates that the upstream gauging station (G1), which is located on the upstream edge of the mining affected area, is expected to represent close to natural flow conditions. Figure 1 shows that this gauge has lower flow during dry periods compared to the other gauging stations. This difference in volume is expected, considering the drainage area increases from 1,124 ha at G1, 1,627 ha at G2, and 2,090 ha at G3. Therefore, there is expected to be increased volume contribution to G2 and G3 from additional runoff, tributary creeks and baseflow discharge. During periods of prolonged dry weather, the reduction in surface flow becomes evident, presumably because there is limited capacity in subsurface system for surface water to enter the shallow aquifer.

When G2 flow data is subtracted from G3 flow data, the volume of water at the downstream location is in many occasions lower than the volume of water at the upstream location (Fig. 2). The sharp losses shown in Figure 2 typically occur just before large rainfall events and may represent a lag in travel time. Therefore, these high losses are not used in any of the following calculations and interpretation.

A streamflow reduction can occur between G2 and G3 of up to 2 Ml/day during low flows, when there is expected to be a dominance of baseflow discharge. The average loss during low flows is around 0.7 Ml/day. The total streamflow loss over the 624 days of measured flow from April 2007 to February 2009 was around 345 Ml. A number of representative low flow days have been selected from the record and the daily flows from the three gauging stations are shown in Figure 3 and normalised per unit of area for each drainage basin in Figure 4. These figures indicate that the flow

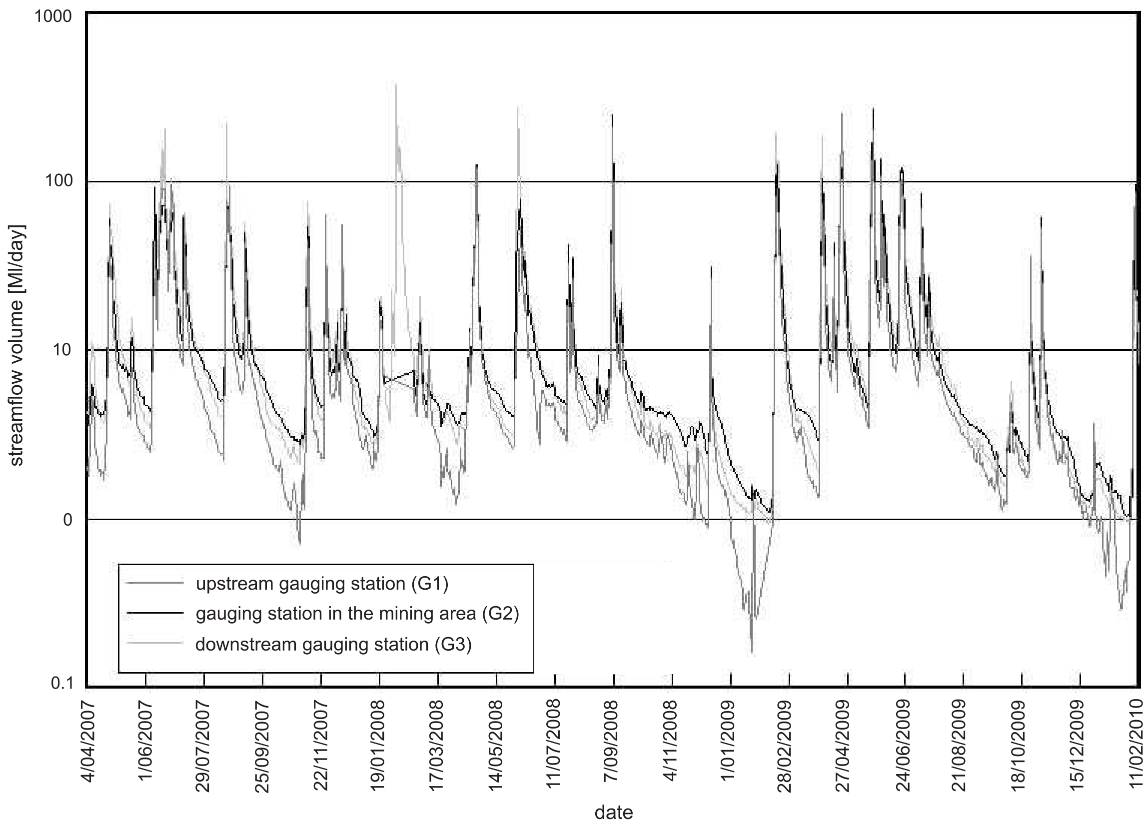

Fig. 1. Comparison of streamflow upstream (G1) in the mining area (G2) and downstream of the mining area (G3)

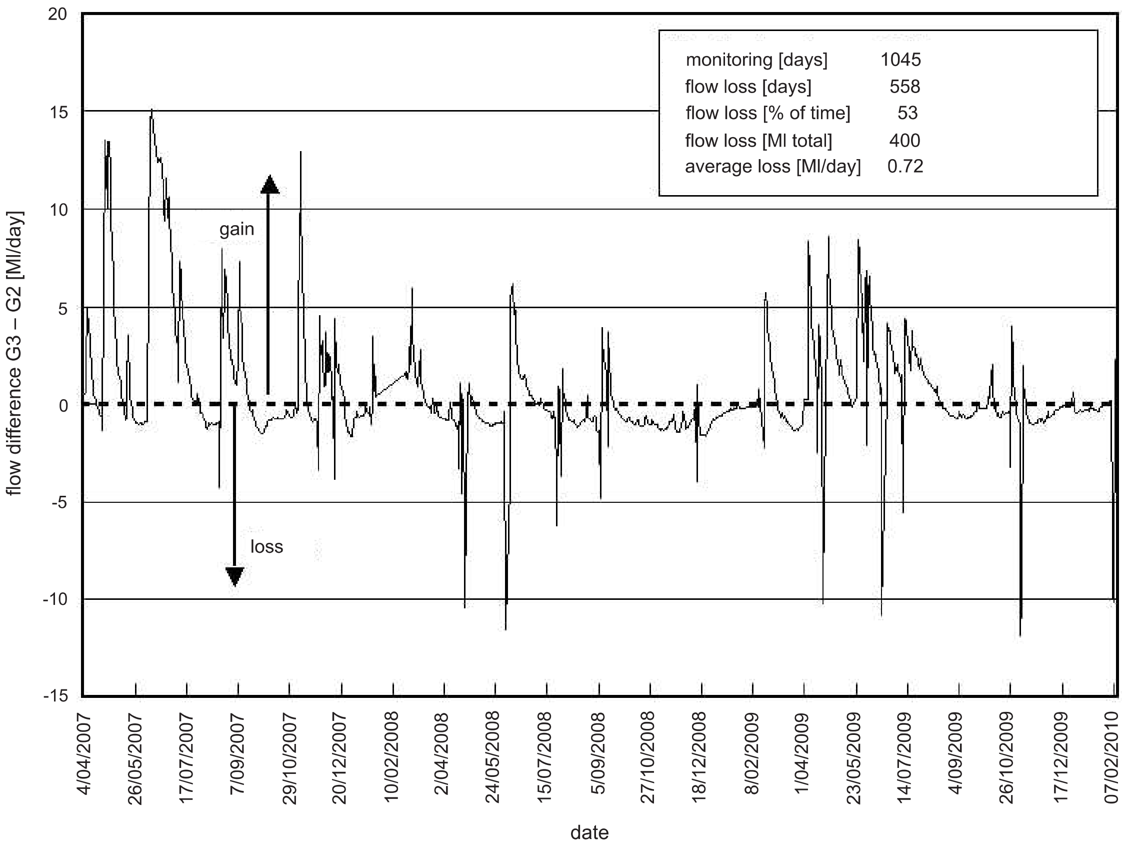

Fig. 2. Flow difference between downstream (G3) and mining area (G2) gauging stations

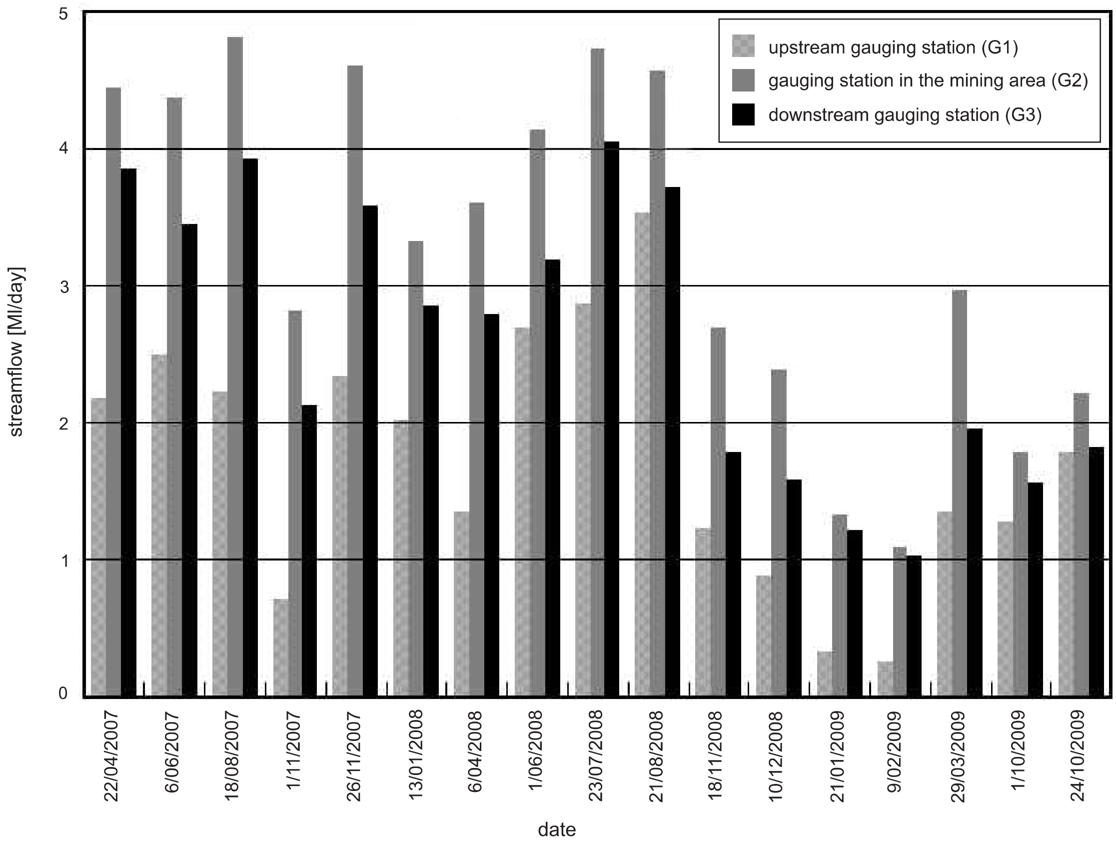

Fig. 3. Representative streamflows during low flows (baseflow discharges) at each gauging station

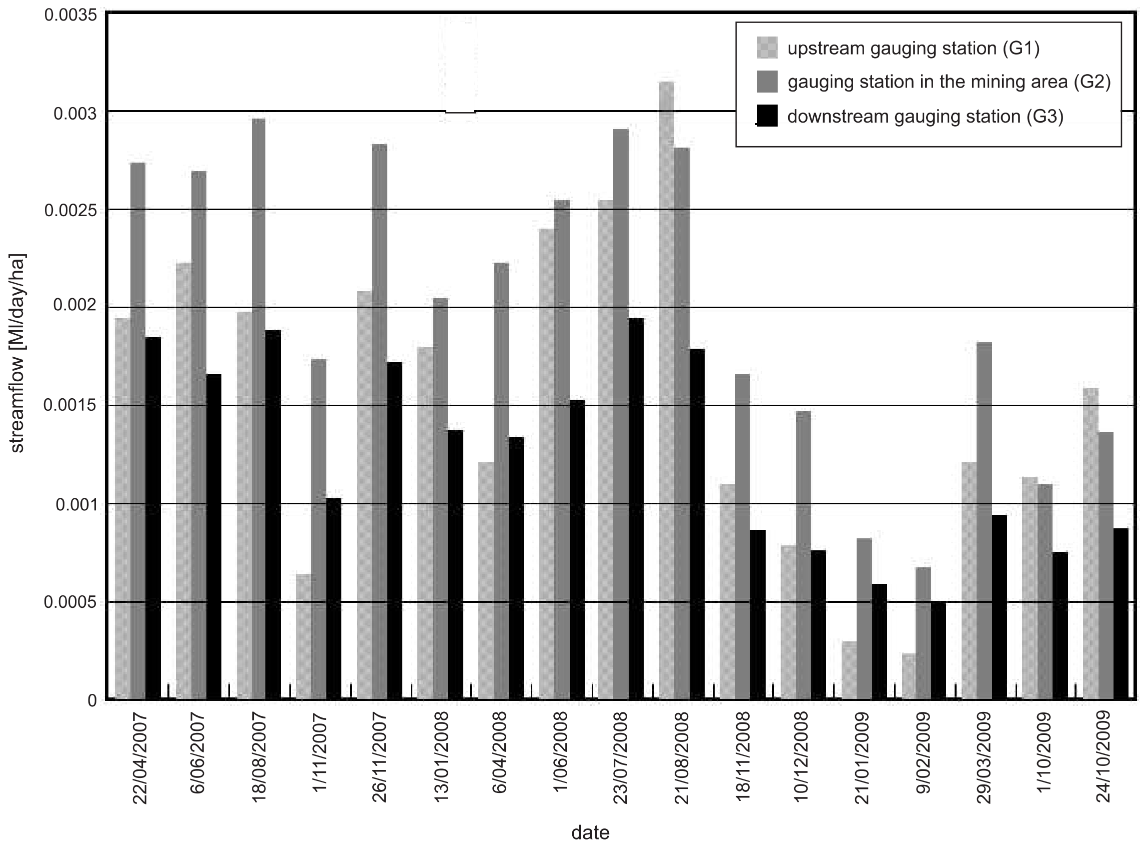

Fig. 4. Normalised streamflows during low flows (baseflow discharges) at each gauging station

on these days is greater at G2 than G3. As these low flows are expected to be dominated by baseflow discharge, baseflow discharge was calculated for each drainage basin bound by the gauging station, by subtracting flow upstream from flow downstream and dividing by the drainage basin area. For G1, baseflow was calculated by dividing the flow at G1 by the drainage basin area bound by G1. As shown in Figure 5, G1 and G2 have positive baseflow discharge and baseflow increases downstream, except on 21 August 2008, which may be due to rock movements associated with subsidence and the rapid recharge of the shallow aquifer. However G3 is showing negative baseflow during all representative low flows presented in Figure 5, indicating that baseflow may not have discharged between G2 and G3 or streamflow loss is higher than streamflow gain through baseflow discharge.

A method for analysing losses is to calculate the ratio of daily flow volume at the downstream gauge to that at the upstream gauge, and then plot this ratio against the actual flow volume at the upstream gauge (Costelloe *et al.*, 2003). Figure 6 illustrates that most losses occur during low flow conditions, with more than 95% of losses occurring when flow was below 8 Ml/day. However it should be noted that during the monitoring period low flows prevailed, with loss also occurring during moderate and high flows.

A plot of streamflow at G2 versus streamflow at G3 on a log-log scale is at Figure 7, showing gain and loss of flow at G3. According to Figure 7, there are only a few events during low flow conditions where there is a streamflow gain at G3.

Most streamflow losses occur during very low flows dominated by baseflow discharges (<5 Ml/day), low flows (5–10 Ml/day) and low to moderate flows (10–20 Ml/day):

– during very low flows (<5 Ml/day), when baseflow would normally dominate, the daily flow at G3 was on average –22.5% lower (ranging between 26.7% and –75.5%) than that at G2;
– during low flows (5–10 Ml/day), the daily flow at G3 was on average –0.2% lower (ranging between 38.2% and –67.3%) than the flow at G2;
– during low to moderate flows (10–20 Ml/day), the daily flow at G3 was on average 16% (ranging between 49% and –32%) of the flow at G2;
– during moderate flows (20–100 Ml/day), the daily flow at G3 was on average 12% (ranging between 40% to –53%) of the flow at G2.

The streamflow loss between gauging stations G2 and G3 occurred in 558 days (53%) during monitoring period of 1045 days with a total loss of 400 Ml and an average loss of 0.72 Ml/day. The above analysis of flow data indicates that streamflow losses occurred during very low, low and low to moderate flows, decreasing with increasing flow rate. The largest reduction in flow from the upper to lower part of the stream occurred during very low flows, when baseflow discharge is expected to dominate. Therefore, it may be

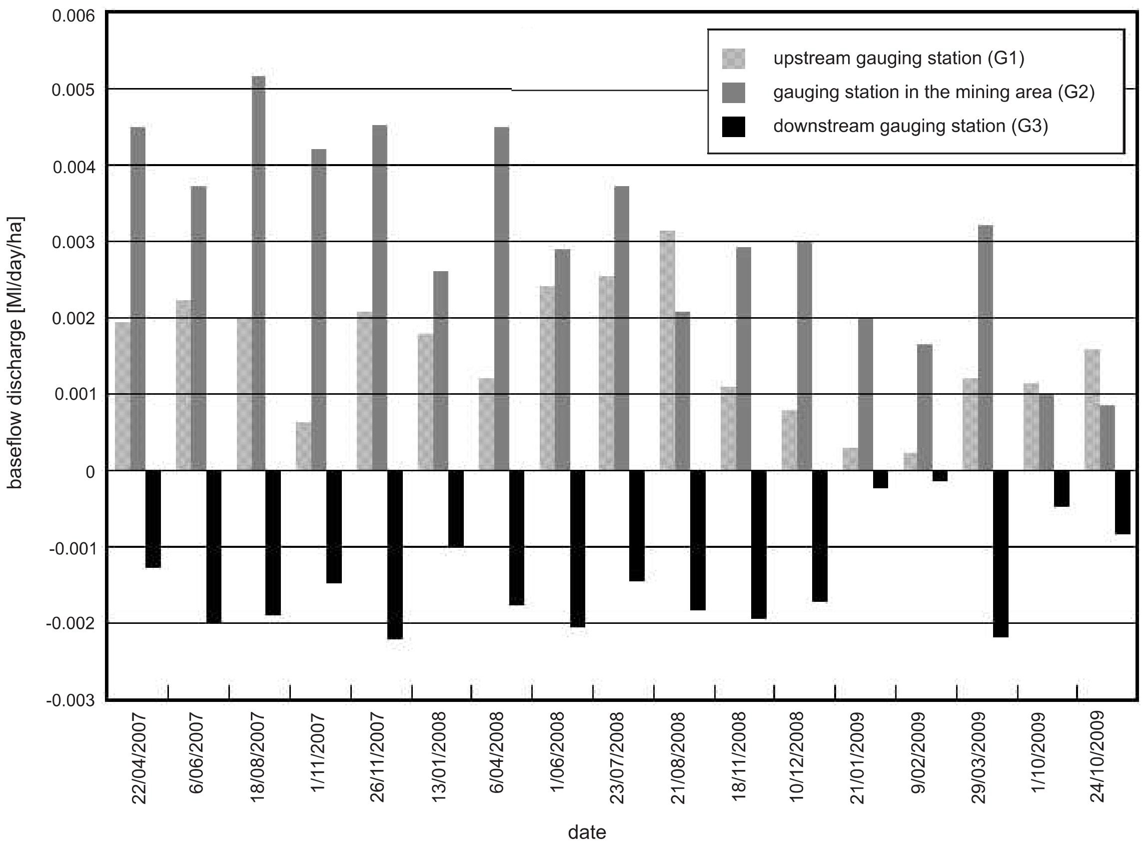

Fig. 5. Normalised baseflow discharges at each gauging station

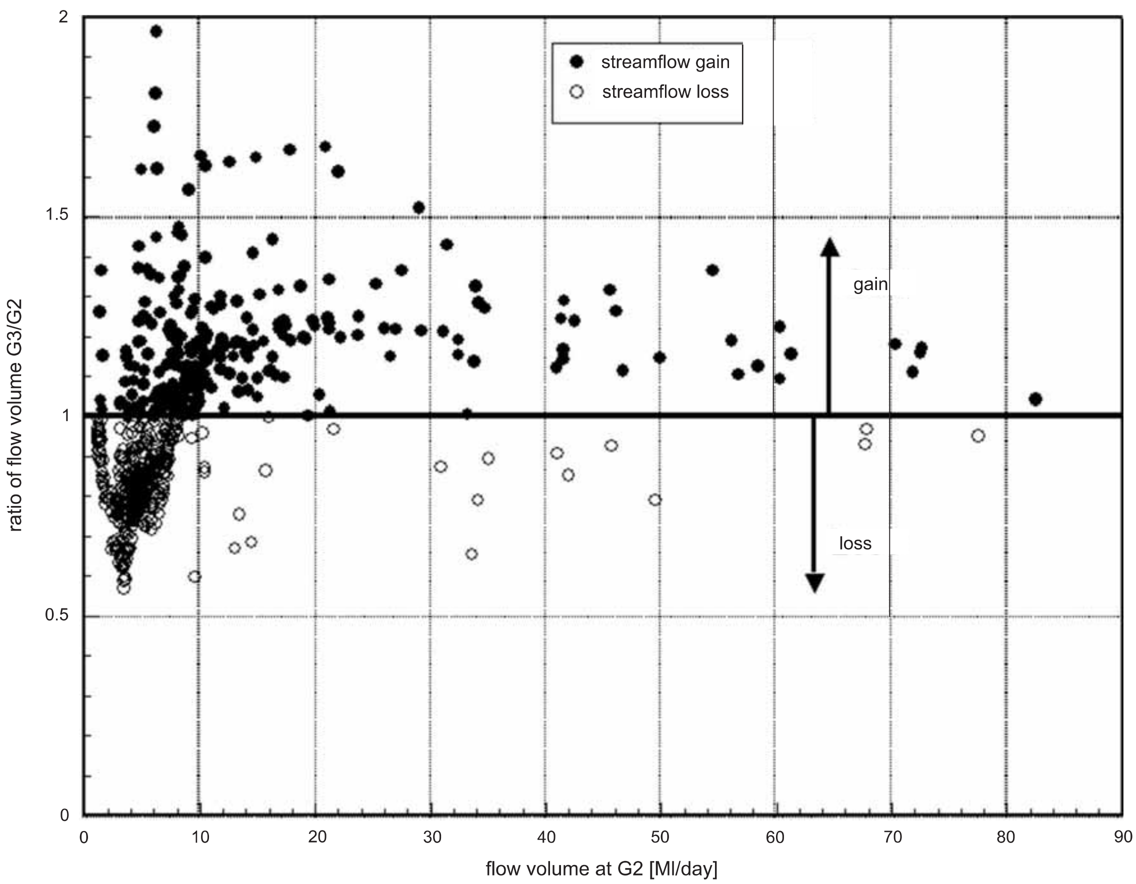

Fig. 6. Transmission losses downstream of the mining area (G3)

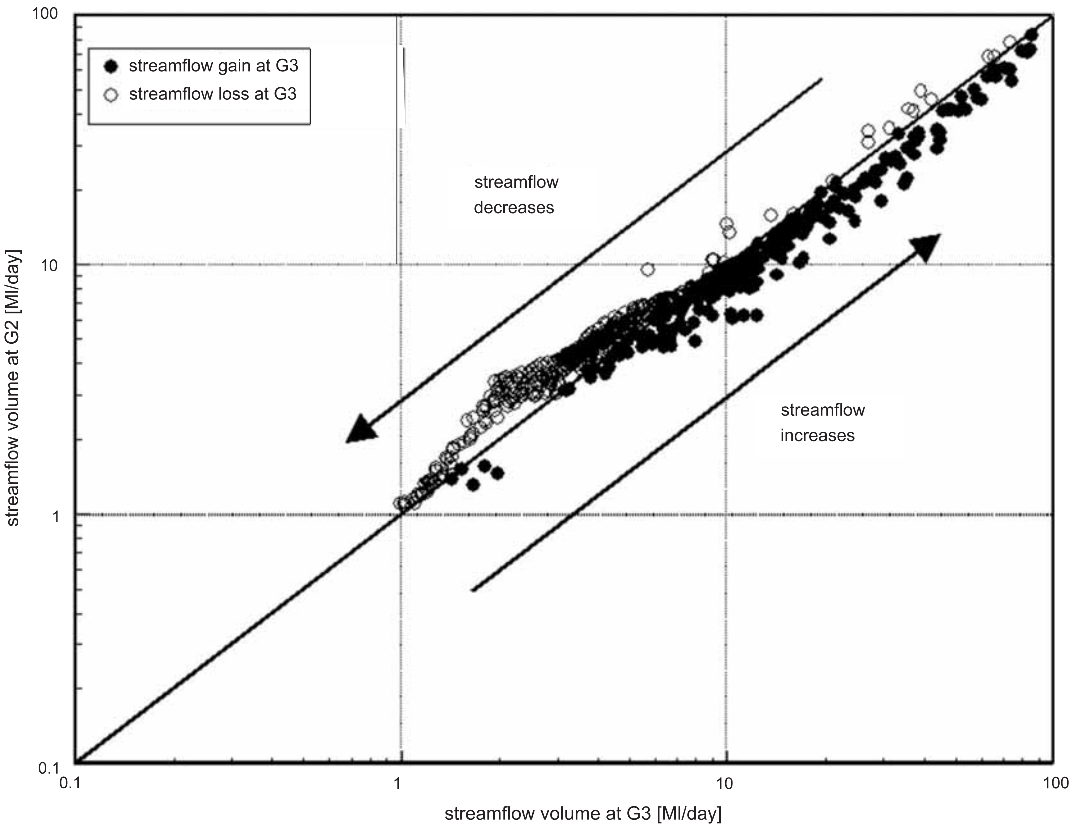

Fig. 7. Relationship between streamflow in the mining area (G2) and downstream of the mining area (G3)

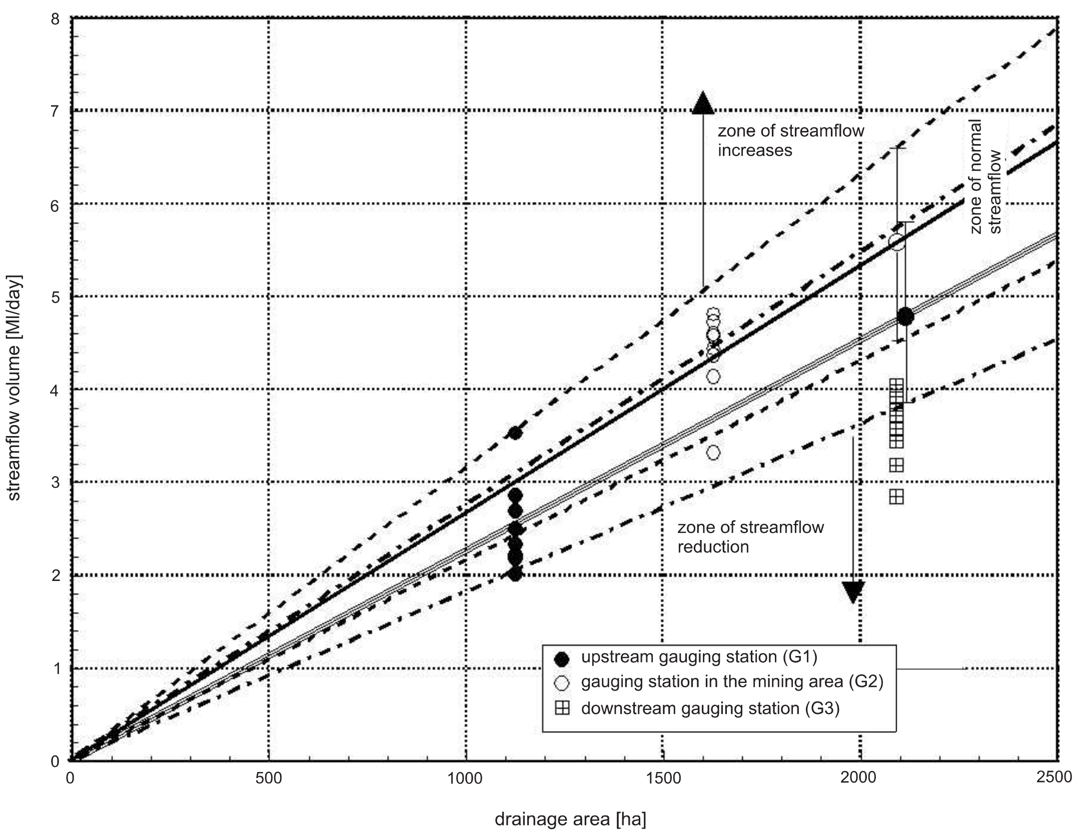

Fig. 8. Relationship between streamflow volume and drainage basin area (unfilled dot with ±10% error bar represents the theoretical downstream flow at G3 calculated from the average upstream flow (G1); filled dot with ±10% error bar represents of the theoretical downstream flow at G3 calculated from the average flow in the mining area (G2)

hypothesised that not only is there impact to the streambed, but the wider catchment area may also be impacted through mining-induced fracturing resulting in increased subsurface recharge/reduced run-off and increased aquifer storage/declined groundwater levels. As a consequence, reduced baseflow discharge to the main stream may result.

A plot of streamflow at each of the gauging stations versus the drainage basin area bounded by the gauging stations is shown in Figure 8. The large unfilled and filled dots represent the average theoretical flow at G3, calculated by using the average flow volumes based on drainage basin area at G1 and G2. Comparing these theoretical flow values with the actual flow data at G3, it is evident that there is lower flow at G3 than what would be expected if streamflow losses were not occurring. The difference in flow between the average actual flows at G3 and the average theoretical flows calculated from G1 and G2 are approximately 1.2 and 2.0 Ml/day respectively.

DISCUSSION

Analysis of the flow data indicates that the mining-enhanced fracture network within the sandstones resulted in increased hydraulic conductivity and storativity. However, the subsurface system is not capable of storing a large volume of water during high flow events. During high flows, the volume of flow increased along the stream, with flow at the downstream location (G3) higher than at the upstream locations (G1 and G2). Streamflow losses may have occurred, however the analysis undertaken is not suitable for identifying streamflow losses during high flows. During low stages, when most surface flow would be re-directed to subsurface routes, the baseflow discharge is reduced or ceased due to a reversal of the hydraulic gradient along the stream, causing the stream to be disconnected-losing with groundwater.

The volume of water that infiltrates the subsurface depends on the aperture of the new and existing fractures, and their vertical and horizontal extent, distribution and connectivity. The capacity of the groundwater system to receive surface flow is variable and changes during the mining of subsequent longwall panels. The change with mining is due to the tensional and compressional phases of subsidence, modifying the horizontal and vertical extension of fractures, joints and bedding planes, and the subsequent increase or decrease in connectivity between surface water and groundwater. The storage of the subsurface system is sufficient to receive water during low flows, resulting in a reduction and potentially cessation in surface flow. Some of the water lost into subsurface flow reappears downstream and discharges from horizontally-oriented bedding planes and sub-horizontal fractures intersecting the streambed.

The analysis undertaken suggests that the lost water does not return before G3 gauging station, however it is not possible to ascertain whether all lost water re-emerges further downstream or whether there is temporary or permanent water loss from the catchment. If the fracture system has significant vertical extension and intersects one or more bedding planes, it is feasible that some water could join the regional groundwater flow system and water can be permanently lost to a neighbouring catchment. Alternatively, water could discharge several kilometers northeast on the cliff escarpment, where springs are known to occur. Detailed information on the volume of water that recharges the aquifer and discharges downstream is presently not quantified. Winter *et al.* (2003) discusses the difficulties in determining the sources of baseflow discharge, whether originating from a distant source, such as from a neighbouring drainage basin.

One method for computing streamflow losses in the drainage basin is subtracting the upstream streamflow from downstream streamflow (Tieman, Rauch, 1987). Streamflow at the downstream location (G3) would be expected to increase compared with flow at the upstream locations, as the drainage area is increasing. However, this method cannot account for factors such as lag time between gauging stations and is likely to result in conservative loss values, as the method assumes there is no reduction in streamflow at the upstream location.

The complexity of the hydrology in mining-impacted catchments results in difficulties in assessing losses, as there can be decreases in surface runoff, reduction in baseflow discharge to tributary creeks and main stream(s), and leakage from the shallow aquifer to deeper regional aquifer flow systems. This system, dominated by surface water–groundwater interaction, is difficult to monitor. Vertical and horizontal ground movements result in the development of new fractures and the enlargement of existing fractures and bedding planes. Pathways are created, allowing surface water to recharge the shallow subsurface, causing a reduction in streamflow and decreased baseflow discharge to the main stream.

Losses from shallow (upper Hawkesbury Sandstone aquifer) to deeper regional aquifer (lower Hawkesbury Sandstone aquifer) have not been monitored or accessed. Reduction in streamflow depends on surface fracturing and the hydraulic connectivity between surface flow, shallow aquifer and deeper regional aquifer. Shallow piezometers located along the stream indicate that shallow groundwater close to the stream is affected by subsidence, causing the majority of groundwater levels to be below the streambed, causing the stream to be disconnected-losing with the diversion of surface water into subsurface voids. If the shallow aquifer becomes connected to the deeper regional aquifer, it is possible that this water will be lost from the immediate catchment to the neighbouring catchment, particularly in the fractured aquifer drainage basin through the inter-catchment groundwater flow in deeper Hawkesbury Sandstone unit.

The Hawkesbury Sandstone is the major regional aquifer in this area. This sandstone unit has a thickness between

100–185 m and is underlain by low permeability Bald Hill Claystone formation (thickness between 18–26 m). This unit create a hydraulic discontinuity between aquifer in the sandstone unit and deep groundwater systems as the Bald Hill Claystone stops the vertical flow of groundwater and acts as an effective confining layer. Deeper aquifers overlain by Bald Hill Claystone have a mining depressurisation effect and there is potential for water to flow towards mine workings. However, total inflow into mine measured by mining company is low.

CONCLUSIONS

The following conclusions can be made concerning the impact of longwall mining-induced subsidence on the hydrological flow regimes in the Southern Coalfield catchment discussed in this paper:

– the streamflow changes described in this paper suggests that longwall mining-induced subsidence has enhanced the surface water–groundwater interaction, both laterally and longitudinally;
– a vertical and horizontal extension and enlargement of fractures and bedding planes resulting from the longwall mining activity could explain the loss of flow due to a more intensified surface water–groundwater interaction, and to a greater depth, than would have occurred prior to mining;
– the flow system is both connected-gaining and disconnected-losing over various segments of the main stream;
– streamflow losses due to mining dominate during very low to low flow conditions, whereas streamflow losses during medium to high flows are masked by the large volume of streamflow;
– surface flow which has been redirected to the subsurface may reappear further downstream or be permanently lost from the drainage basin.

REFERENCES

BOOTH C.J., 2002 — The effects of longwall coal mining on overlying aquifers. *In*: Mine water hydrogeology and geochemistry (eds. P.L. Younger, N.S. Robins). *Geol. Soc. London, Sp. Publ*., **198**: 17–45.

BOOTH C.J., BERTSCH L.P., 1999 — Groundwater geochemistry in shallow aquifers above longwall mines in Illinois, USA. *Hydrogeol. J.*, **7**: 561–575.

CARVER L., RAUCH H. M., 1994 — Hydrogeologic effects of subsidence at a longwall mine in the Pittsburgh coal seam. *In*: Proc. 13th Conference on Ground Control in Mining (ed. S.S. Peng): 298–307. West Virginia University, Morgantown, WV, USA.

COSTELLOE J.F., GRAYSON R.B., ARGENT R.M., McMAHON T.A., 2003 — Modelling of flow regime of an arid zone floodplain river, Diamantina River, Australia. *Environ. Modelling Software*, **18**: 693–703.

DIXON D.Y., RAUCH H.M., 1988 — Study of quantitative impacts to ground water associated with longwall coal mining at three mines sites in the northern West Virginia area. *In*: Proc. 7th International Conference on Ground Control in Mining: 321–335. West Virginia University, Morgantown, WV, USA.

DIXON D.Y., RAUCH H.W., 1990 — The impact of three longwall coal mines on streamflow in the Appalachian Coalfield. *In*: Proc. 9th International Conference on Ground Control in Mining (ed. S.S. Peng): 169–182. West Virginia University, Morgantown, WV, USA.

JANKOWSKI J., 2007 — Surface water–groundwater interactions in a catchment impacted by longwall mining. *In*: Proc. 7th Triennial Conference on Mine Subsidence (eds. G. Li, D. Kay): 253–262. Wollongong.

JANKOWSKI J., 2009 — Hydrological changes due to longwall mining in the Southern Coalfield, New South Wales, Australia. *In*: Proc. IAH, NSW Branch Groundwater in the Sydney Basin Symposium (ed. W.A. Milne-Home): 107–117. Sydney, NSW, Australia.

JANKOWSKI J., 2010 — Surface water–groundwater interaction in the fractured sandstone aquifer impacted by mining-induced subsidence: 2. Hydrogeochemistry. *Biul. Państw. Inst. Geol.*, **441**: 43–54 (this volume).

JANKOWSKI J., MADDEN A., McLEAN W., 2008 — Surface water–groundwater connectivity in a longwall mining impacted catchment in the Southern Coalfield, NSW, Australia. *In*: Proc. Water Down Under 2008 (eds. M. Lambert *et al*.). Adelaide. CD-ROM.

KAY D., BARBATO J., BRASSINGTON G., de SOMER B., 2006 — Impacts of longwall mining to rivers, and cliffs in the Southern coalfields. *In*: Proc. 7th Underground Coal Operators Conference: 327–336. The Australasian Institute of Mining and Metallurgy, Wollongong, NSW.

LUCAS R., CRERAR J., HARDIE R., MERRITT J. KIRSH B., 2009 — Isaac River cumulative assessment of mining developments. *Mining Technology*, **118**: 142–151.

PENG F.F., SUN V.Z., PENG S.S., 1996 — Modelling the effects of stream ponding associated with longwall mining. *Mining Engineering*, **48**: 59–64.

SHEPLEY M.G., PEARSON A.D., SMITH G.D., BANTON C.J., 2008 — The impacts of coal mining subsidence on groundwater resources management of the East Midlands Permo-Triassic Sandstone aquifer, England. *Quart. J. Eng. Geol. Hydrogeol.*, **41**: 425–438.

SIDLE R.C., KAMIL I., SHARMA A., YAMASHITA S., 2000 — Stream response to subsidence from underground coal mining in central Utah. *Environ. Geol.*, **39**: 279–291.

SLAUGHTER C.B., FREETHEY G.W., SPANGLER L.E., 1995 — Hydrology of the North Fork of the Right Fork of Miller Creek, Carbon County, Utah, before, during, and after underground coal mining. *Water Res. Invest. Rep.*, 95–4025, USGS: 56.

TIEMAN G.E., RAUCH H.W., 1987 — Study of dewatering effects at an underground longwall site in the Pittsburgh seam of the northern Appalachian coalfield. *In*: Proc. U.S. Bureau of Mines Technology Transfer Seminar, Information Circular 9137: 72–89. Pittsburgh, Pennsylvania.

TIEMAN G.E., RAUCH H.W., CARVER L.S., 1992 — Study of dewatering effects at a longwall mine in northern West Virginia. *In*: Proc. 3rd Workshop on Surface Subsidence Due to Underground Mining: 214–221. COMER, West Virginia University, Morgantown, WV, USA.

WINTER T.C., RESENBERRY D.O., LA BAUGH J.W., 2003 — Where does the ground water in small watersheds come from? *Ground Water*, **41**: 989–1000.