Surface Water-Groundwater Interactions in a Catchment Impacted by Longwall Mining

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Summary

A conceptual model of surface water (SW) – groundwater (GW) interaction has been developed for a catchment impacted by longwall mining-induced subsidence. The model is based on a theoretical knowledge of surface and groundwater hydrology, GW level and flow in fractured sandstone aquifers; and measured flow data and GW level changes in boreholes from several mining impacted catchments in the Southern Coalfield of New South Wales. The model incorporates the important role of geology, topography and channel morphology in understanding SW-GW interconnectivity. The paper discusses changes in surface flow and loss of water into the subsurface, uppermost Hawkesbury Sandstone aquifer during various flow scenarios, which mostly depend on the distribution of fractures, fracture zones and bedding planes. An increase in permeability and porosity of the fractured aquifer system due to subsidence-related fracturing enhances recharge to the aquifer from surface flow. As the subsidence front approaches, cracking and fracturing of the riverbed causes the GW level to decrease. The maximum decrease occurs when the permeability in fractures, joints and bedding planes are increased, transmitting larger volumes of water into the deeper part of the aquifer. This phase is also related to the extensional stress of the rock mass. The occurrence of fractures and parted bedding planes in riverbeds and rockbars allows SW to enter an aquifer, with the possibility to re-appear later downstream. Several possible scenarios are discussed based on the hydrogeology of fractured aquifer systems; from a single system with single recharge-discharge zone, to a complex system with multiple recharge-discharge zones. The capacity of an aquifer to retain the recharged SW during mining depends on the depth of the water table, fracture aperture, and the horizontal and vertical extension of fractures. The volume of SW intercepted by the aquifer through the fractured system during mining varies and depends on different phases of SW-GW interaction; including baseflow discharge, reversal of the hydraulic gradient, and disconnection of the SW-GW system.

Key words: Longwall mining, surface water-groundwater interaction, fractured aquifer

1. Introduction

The process of SW-GW interaction is complex and requires knowledge of climate, landform, geology and hydrogeoecological framework (Sophocleous 2002). The interaction is further complicated when a catchment is impacted by human activities such as mining. Longwall mining beneath surface waterways causes SW and GW to interact differently, as longwall mining-induced subsidence causes enlargement of existing, and development of new fractures and fracture zones. There are several techniques that can be applied to assess SW-GW interaction, including monitoring SW flow upstream and downstream of longwall mining panels; monitoring SW and GW levels along a waterway upstream of longwall panels, along the impacted area, and downstream of longwall panels; and application of hydrochemical methods, such as environmental isotopes, hydrochemistry, and tracers (dyes, gases and isotopes). Mining-induced changes in hydraulic gradient, diversion of SW flow into subsurface routes from riverbed cracking, or both can dominate the hydrology of streams.

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SW and GW were traditionally researched separately, even though there is hydraulic connectivity between them in some catchments. The increasing importance for the proper management of water resources and importance to maintaining river system function has stemmed from the observed SW-GW connectivity in areas where GW use from alluvial aquifers led to declines in river baseflows. Management of SW and GW as a single resource with respect to water quantity and quality is currently increasing worldwide (Fullagar, 2004; Brodie et al. 2007b). Interaction between a river and GW can occur in three ways: river gains water from inflow of GW via the riverbed; stream loses water to GW by outflow via the riverbed; and both are gaining in some segments and losing in other segments of a river (Winter et al. 1998).

Several river-aquifer relationships are possible depending on climate, geology, geomorphology and topography. A river can be: connected gaining, connected losing, disconnected with a shallow water table, disconnected with a deep water table, and flow-through (Dingman, 2002; Evans, 2007; Fetter, 2001; SKM, 2006; Sophocleous, 2002). In many situations, the interaction between SW and GW is affected by the position of surface waterways in relation to topography and geological characteristics of their beds (Winter, 1999). Lower GW levels in a connected gaining situation near a river may induce additional recharge and decrease rates of baseflow discharge, whereas higher GW levels increase baseflow discharge and reduces river recharge (Braaten and Gates, 2003).

Larkin and Sharp (1992) classified river-aquifer systems connectivity with respect to the direction of regional GW flow components. Three systems dominate SW-GW connectivity: underflow-component dominated by the GW flux longitudinally to a river and in the same direction as the river flow; baseflow-component dominated by the GW flux moving laterally to or from a river depending on whether the river is gaining or losing; or a combination of both, making mixed components. Both flow paths into the river create 3-D physico-chemical patterns controlled by the flow pattern (Brunke and Gonser, 1997).

Several tools can be used to assess SW-GW connectivity. The best knowledge will be gained when multiple tools are used to complement each other. The most common and accepted tools are field observations, seepage measurements, ecological indicators, hydrogeological mapping, geophysical surveys, hydrographic analyses (Brodie and Hostetler, 2007; Brodie et al. 2007a), hydrometric analyses, hydrochemical studies (Baskaran et al. 2007b; Crandall et al. 1999), temperature studies (Baskaran et al. 2007a; Constantz, 1998; Constantz et al. 2002), artificial traces, and water budgets (Ransley et al. 2007; Brodie et al. 2007c). The best quantitative assessment is through application of chemical, isotopic, gas or dye tracers. Widely used tracers currently used are radon-222 (^{222}Rn) (Cook et al. 2003; Crandall et al. 1999; Ellins et al. 1990), CFC-11, CFC-12 (Cook et al. 2003; Rademacher et al. 2003), stable isotopes deuterium and oxygen-18 (McCarthy et al. 1992), dissolved gases such as sulfur hexafluoride and helium, and dyes such as fluorescein and rhodamine WT.

There are still knowledge gaps in understanding SW-GW connectivity, such as the volumetric relationship between GW pumping and river losses in different hydrological systems, time lag between GW pumping and SW impacts, and the broad understanding of the geographical location of gaining and losing streams (SKM, 2006).

There are even more knowledge gaps across Australian catchments and less understanding of SW-GW interactions in mining impacted catchments. Studies are very scarce and monitoring data is limited.

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Lack of systematic and comprehensive studies using different tools is not widely available.

2. Surface Water - Groundwater Interaction in Mining Impacted Catchments

Mining-induced subsidence causes topographic modifications to a river's channel valley floor. Subsidence above longwall panels is typically up to 1.4 m and upsidence on valley floors is typically up to 0. 5 m, expanding a well-developed network of fractures, joints and bedding planes. Vertical subsidence and horizontal rock movements change flow and interconnectivity in hydraulic systems; causing changes in surface flow, GW level, and enhancing SW-GW interaction. In areas of high relief, horizontal movements are approximately 40% of the maximum vertical movement (Holla, 1997). Horizontal movements of up to 25 mm have been observed 1.5 km from the edge of the longwall panel (Reid, 1998). During subsidence, the strata undergoes fracturing, opening of joints, separation of bedding planes, reactivation of faults, and creation of new fractures.

The SW-GW interaction increases during mining compared to the natural system due to enhanced fracture porosity and permeability changes. This can alter hydraulic gradients close to the SW-GW interface and cause leakage between hydrogeological units in the shallow subsurface. The dilation-compression sequence causes changes in pore-water pressure, decreasing, and later increasing, hydraulic head.

Mining-induced development of joints and fractures can occur by vertical displacement of a single fracture or multiple fractures, horizontal displacement of a single horizontal shear or complex shear, vertical slips, compression and tension related upsidence, and complex deformations on bedding planes. Detailed field observations and analysis of geological, fracture, and subsidence data indicates that in the Southern Coalfield of NSW, bedding planes produce horizontal pathways for GW, and reactivated or newly developed fracture and joint patterns are major pathways for the vertical movement of water. Vertical fractures are often wider than bedding planes. This causes rapid vertical infiltration and movement of water, followed by horizontal distribution into bedding planes.

The hydraulic effects on GW systems are predictable. An increase in rock permeability and storage occurs in the entire vertical profile of the subsidised area, with some variations due to local rock characteristics and initial distribution and opening of fractures and joints (Booth et al. 1998). Changes in aquifer hydrology can alter and create preferential pathways for GW flow, diverting SW into subsurface flow, rerouting SW and GW flows, and modifying their interactions (Sidle et al. 2000).

3. Results and Discussion

Mining-induced subsidence in the Southern Coalfield of NSW causes significant changes in the stream topography and alteration in channel and drainage morphology. Significant fracturing of riverbeds and rockbars causes SW to reroute to subsurface flow (Jankowski and Spies, 2007; Kay et al. 2006; TEC, 2007).

SW flow in mining-induced areas due to fracturing and cracking of riverbeds above longwall panels results in water loss, either temporarily or permanently. Permanent water loss can occur in areas where longwall mining produces a hydraulic connection between SW and the mine. Influx into a mine typically occurs when there is an absence of low permeability material that can limit or restrict inflow into mines, with inflow through a well-developed system of fractures, joints and voids. Temporary water

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loss occurs in areas were a longwall mine is separated from the ground surface by a low permeability seal that prevents any inflow into the mine. The Southern Coalfield mines are sealed by low permeability material (claystones within the Narrabeen Group) that underlies the fractured sandstones, mostly preventing inflow of SW into mines. However, vertical movement of water from the ground surface to the base of this sandstone is possible as fractures, displacements, and deformations of the rock mass cause a relatively good hydraulic connection between different bedding planes, through the reactivation of existing, and development of new, fractures, joints, veins and fractured zones.

Figure 1 shows the presence of recharge and discharge zones developed and/or reactivated due to subsidence related enlargement of fractures and bedding planes. Recharge into the subsurface system can occur through infiltration via vertical fractures enlarged due to subsidence (Fig. 1a). Theses fractures have a well-known pattern at 90^o, which is common for the Hawkesbury Sandstone (Tammetta and Hewitt, 2004). Very often these fractures are reactivated along old joints partially cemented by precipitation of carbonates or by weathering of aluminosilicates. Large cavities termed “silica karst” (McKibbin and Smith, 2000) commonly occur across sandstone outcrops and can provide an excellent flow pathway from the ground surface into vertically and horizontally orientated fractured zones and bedding planes (Fig. 1b). Observed cavities are not only related to dissolution of silica, but very often are developed during dissolution of siderite and reductive dissolution of iron-oxides/hydroxides (Fig. 1b). The most common discharge mechanism is drainage under gravity where the sandstones are exposed in gorges and cliff faces. However, discharge in river channel from the shallow aquifer in mining impacted area occurs in two ways: (1) from fractures where water discharges under artesian pressures, and (2) from bedding planes initiating surface flow downstream of the longwall panel (Fig.1c and 1d). Interaction between SW and GW can occur laterally and longitudinally along a river, from the upstream non-impacted part of a river, through the impacted part, to the downstream part below the main subsidence impacted area.

3.1. Lateral Surface Water-Groundwater Interaction

The conceptual lateral flow model of SW-GW interaction in a mining-impacted river is shown in Figure 2. Flux of water into the subsurface occurs mainly along vertically outcropping fractures, joints, and veins that provide dominant pathways for SW to infiltrate an aquifer. Depending on opening, length, and position of fractures, interaction can be permanent or temporary. Permanent interaction occurs along a riverbed when there is water in the river; however, temporary connection is related to the presence of fractures above the main river channel and only occurs during high flows. Flow through fractures, cavities, and some bedding planes intersecting a riverbed is distributed vertically along vertical fractures and horizontally along horizontal bedding planes. The location of SW flux depends on the interconnectivity between horizontal and vertical fractures and bedding planes, and their 3-D extension. Due to the extensive impact from mining-induced subsidence on sandstones and the combined impact of subsequent panels, vertical flow can move to deeper depths as long as low permeability material does not occur, eg. a claystone formation that will limit vertical flow. Horizontal inflow of SW depends on the extension of bedding planes and their opening. Some large opened bedding planes can be used as preferential pathways for GW flow.

Because the interaction between SW and GW depends on topography, riverbed morphology, and the water level of both SW and GW (hydraulic gradient), several

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different SW-GW connections can develop during pre-mining, mining, and post-mining periods (Figure 3):

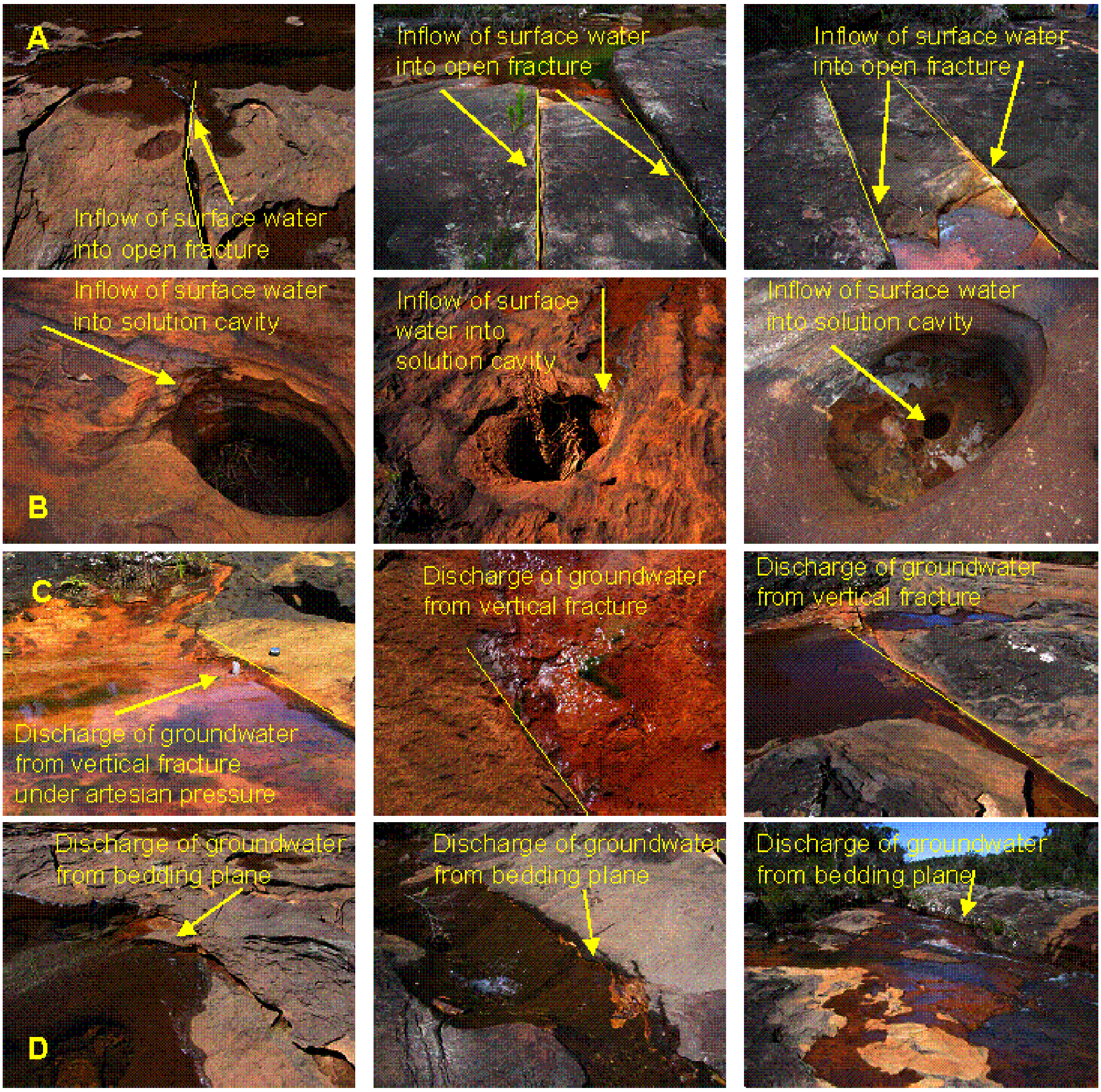

Figure 1. Recharge to, and discharge from, the sandstone during surface water-groundwater interaction in a catchment impacted by longwall mining.

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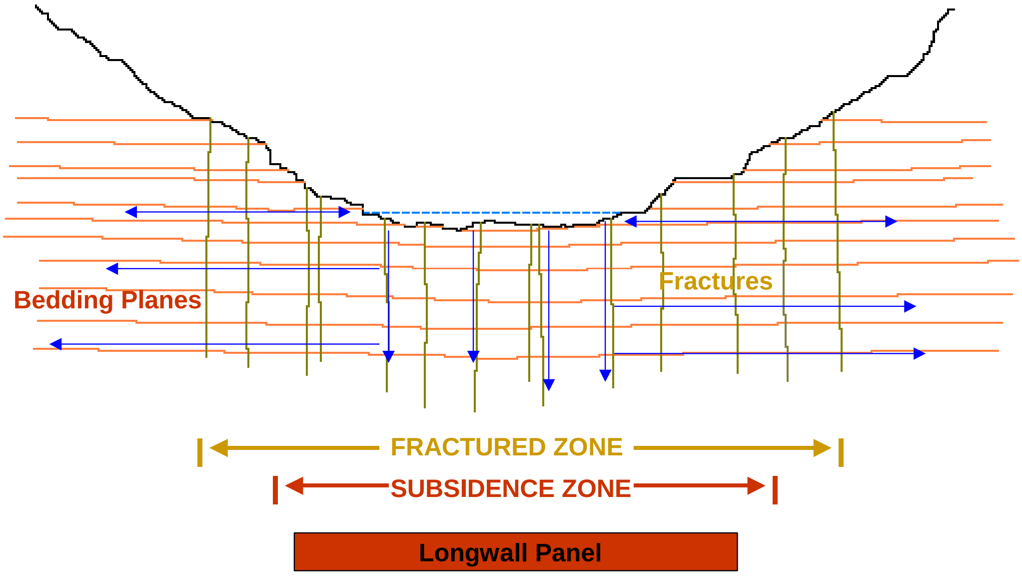

Figure 2. Concept of lateral SW-GW interaction in a longwall mining impacted catchment.

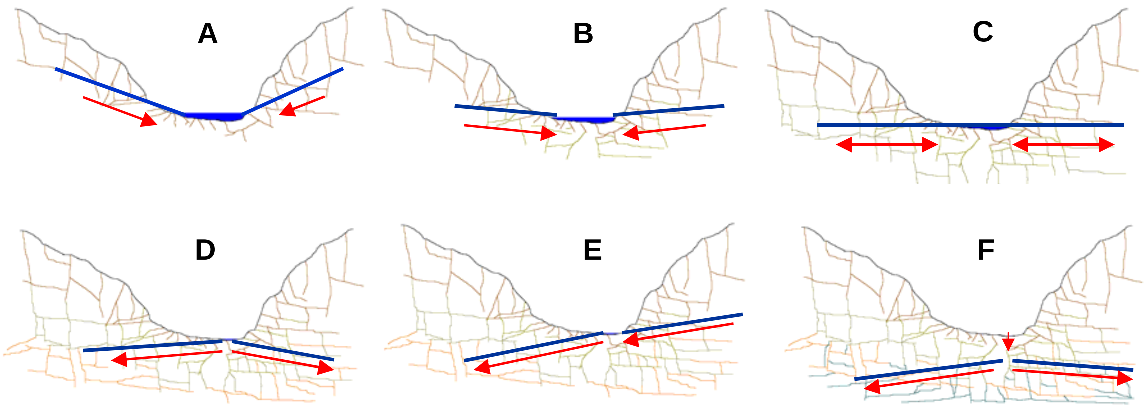

Figure 3. Conceptual model of various scenarios of SW-GW interaction in a longwall mining impacted catchment. Time scale scenarios from natural system (A) to possible final impacted system (F).

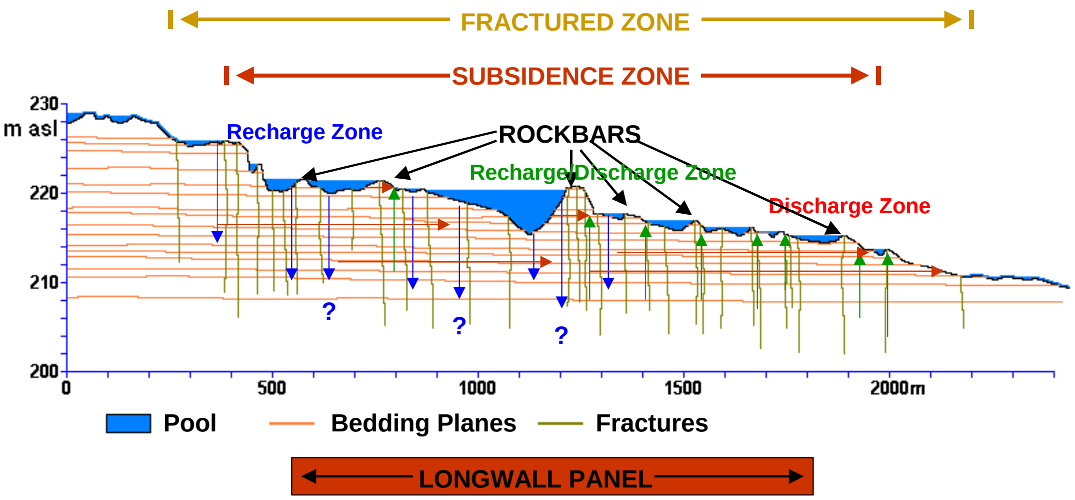

Figure 4. Simplified concept of longitudinal SW-GW interaction in a longwall mining impacted catchment.

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A. GW flow towards a river with baseflow discharge and steep hydraulic gradient – connected gaining river.
B. GW flow towards a river with reduced baseflow discharge and nearly flat hydraulic gradient – connected gaining river.
C. SW-GW interaction in both directions, with flat water table and possible flow through a river.
D. Reversed hydraulic gradient, where SW recharges the GW system and GW flow is away from the river – connected losing river.
E. Hydraulic gradient towards a river from one side and reversed hydraulic gradient on the other side – gaining river on one side and losing river on the other side.
F. GW table below the riverbed with no flow of SW, with the river recharging GW following rainfall – disconnected and losing river.

3.2. Longitudinal Surface Water – Groundwater Interaction

Due to mining-induced subsidence, the morphology of a river channel is modified. Cracks across and along the riverbed cause SW to be diverted from surface routes to subsurface flow. Because some fractures and bedding planes are well connected and others are not, a complex flow pattern with flow in some part of the channel and a lack of flow in another part is created, particularly during low flows. Figure 4 presents a simplified concept of the longitudinal flow pattern in a mining-impacted catchment. Several recharge-discharge zones are present along the riverbed, causing SW to disappear into the subsurface and reappear downstream as SW flow. Cracks in rockbars add more complexity to the system. As there are no detailed studies on how subsidence modifies SW flow, it is necessary to develop a concept that is based on hydrogeological flow principles in fractured aquifer systems.

Many scenarios can by drawn from this simplistic point of view; simple SW-GW interactions and complex/multiple interactions/flows with several recharge-discharge zones and mixing points (Figure 5):

A. A simple shallow flow system along a river with multiple separate subsurface flow paths, developed along preferential bedding plane(s).
B. A simple deeper flow system along a river with multiple separate subsurface flow paths, developed along preferential bedding plane(s).
C. Complex SW-GW interaction with shallow and deeper subsurface flow paths, developed along preferential bedding planes with many mixing points of SW and GW.
D. Complex SW-GW interaction with multiple recharge-discharge and mixing points, where flow occurs along a single preferential bedding plane pathway.
E. Complex SW-GW interactions with multiple recharge and mixing points, and a single discharge point where the flow path occurs along a single preferential bedding plane.
F. Complex SW-GW interaction with a single recharge point and multiple discharge points, where the flow path occurs along a single preferential bedding plane.
G. Complex 3-D SW-GW interaction with multiple recharge and mixing points, and flow paths occurring along several preferential bedding planes. No discharge zone is present; GW can discharge further downgradient into storage, to a neighbouring catchment, or leak into a lower aquifer system.

4. Conclusions

A few conclusions can be drawn from this analysis of the SW-GW interaction in a catchment impacted by mining-induced subsidence:
1. Longwall mining-induced subsidence enhances SW-GW interaction laterally and longitudinally.
2. Horizontal and vertical extension and enlargement of fractures and bedding planes

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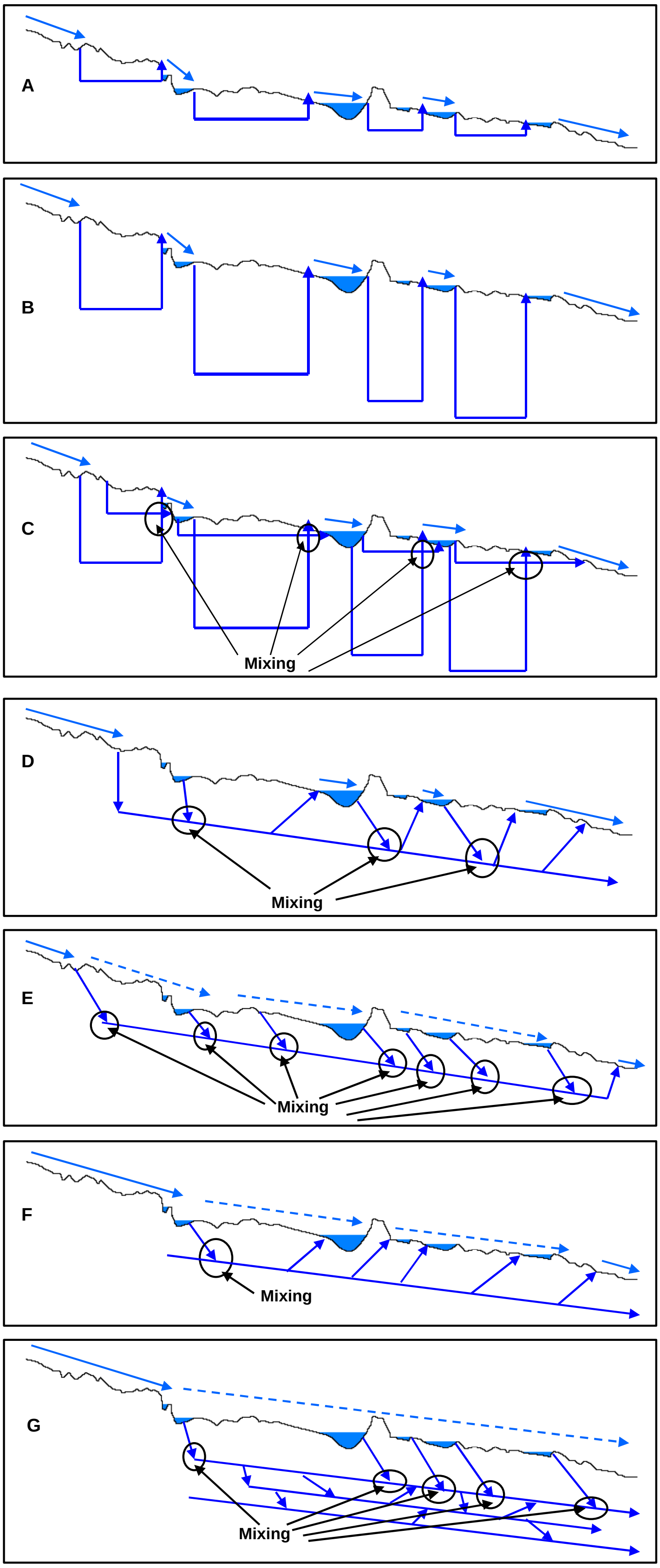

Figure 5. Possible scenarios of SW-GW interaction along a river depending on the level of subsidence-induced fracturing and bedding plane distribution.

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networks cause a more intensified interaction away from the river and deeper in the aquifer system, creating a complex 3-D pattern.
3. Several conceptual scenarios of lateral SW-GW interaction are possible depending on the GW level near the river.
4. Longitudinal SW-GW interaction depends on the number of fractures and bedding planes present across the river. Scenarios can range from a simple single recharge-discharge system to a complex 3-D multiple recharge-discharge system, with mixing zones, variable vertical extension, and connection with a number of fracture systems and bedding planes.

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