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Disconnected Surface Water and Groundwater: From Theory to Practice

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Abstract

When describing the hydraulic relationship between rivers and aquifers, the term disconnected is frequently misunderstood or used in an incorrect way. The problem is compounded by the fact that there is no definitive literature on the topic of disconnected surface water and groundwater. We aim at closing this gap and begin the discussion with a short introduction to the historical background of the terminology. Even though a conceptual illustration of a disconnected system was published by Meinzer (1923), it is only within the last few years that the underlying physics of the disconnection process has been described. The importance of disconnected systems, however, is not widely appreciated. Although rarely explicitly stated, many approaches for predicting the impacts of groundwater development on surface water resources assume full connection. Furthermore, management policies often suggest that surface water and groundwater should only be managed jointly if they are connected. However, although lowering the water table beneath a disconnected section of a river will not change the infiltration rate at that point, it can increase the length of stream that is disconnected. Because knowing the state of connection is of fundamental importance for sustainable water management, robust field methods that allow the identification of the state of connection are required. Currently, disconnection is identified by showing that the infiltration rate from a stream to an underlying aquifer is independent of the water table position or by identifying an unsaturated zone under the stream. More field studies are required to develop better methods for the identification of disconnection and to quantify the implications of heterogeneity and clogging processes in the streambed on disconnection.

Introduction

The majority of hydrology textbooks discussing surface water-groundwater interaction show a conceptual illustration of a gaining, a losing, and a losing-disconnected stream, similar to Figure 1.[5] However, these textbooks limit the discussion to a qualitative description of this figure and only present the end members of possible flow regimes, although transitional states between losing-connected and disconnected also exist. A clear definition of the term as well as a description of the fundamental physics and the implications for management is often missing. In fact, there is no precise and generally accepted definition of the term, which results in an

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[5] The terms "Connected" and "Disconnected" refer to the interaction between surface water and groundwater, but surface hydrologists sometimes use the terms to describe whether or not there is surface water flow between the upstream and the downstream portions of a system (Nadeau and Rains 2007) or how human activities change the relation between rivers and the landscape (Wohl 2004). In this paper, we use the term connected exclusively to refer to the flow regime between surface water and groundwater.

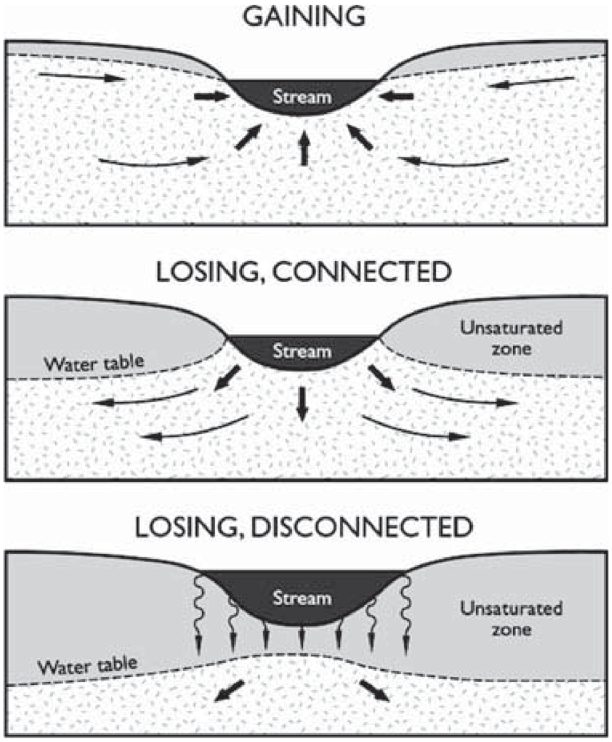

Figure 1. Different flow regimes between surface water and groundwater (figure based on Winter et al. 1998; Brunner et al. 2009a). In a gaining stream, the stream drains the aquifer. In a losing connected system, water flows from the stream to the aquifer. In both cases, the flow between the river and the groundwater remains fully saturated and in a losing disconnected system, an unsaturated zone between the river and the groundwater exists. Changes in the water table no longer affect the infiltration rate.

imprecise use even in the scientific literature. In addition to the confusion surrounding the definition of the term, there are other areas of misunderstanding. These can be broadly classified as:

Relationship Between Connection Status and Exchange Flux

The term disconnected has been criticized (Fox and Durnford 2003) because it may suggest a system where no exchange takes place. Indeed, the truth about the infiltration rate of disconnected systems is at odds with the intuitive understanding of the term. For given hydrogeologic conditions and surface water depth, a disconnected system loses water to the groundwater and the infiltration rates are higher than under a connected flow regime. There is an additional misunderstanding about the relation between connection status and infiltration flux. The infiltration flux of a disconnected system has also been referred to as a "*maximum losing condition*" (Parsons et al. 2008), implying not only that the flux is higher than in connected systems, but also that it can be treated as constant. However, Vazquez-Sune et al. (2007) and Sophocleous (2002) point out that river stage effects infiltration rates of ephemeral and disconnected systems. It is thus possible to further increase the infiltration flux by increasing the stage height of the river in a disconnected state.

Relationship Between Connection Status and Water Table Position

Covino and McGlynn (2007), Wald et al. (1986), and Kalbus et al. (2006) said that a river is disconnected if the water table is below the streambed. Referring to Bouwer and Maddock (1997), Braaten and Gates (2003) and Sophocleous (2002) said a stream is disconnected if the depth of the water table below the stream stage is greater than twice the stream width. Other approaches that define the state of connection by relating the depth to groundwater to geometric properties of the river (such as width or depth of the river) have also been suggested (State of Canterbury 2001). Recently, however, Brunner et al. (2009a) have shown that none of these relationships are correct, and can in fact be quite misleading because they neglect most of the important hydrological variables and do not define where the water table has to be measured.

Management Implications of Connection Status

It has been suggested that joint management of surface water and groundwater is only required for connected regimes (Australian National Water Commission 2009). This approach is presumably based on the belief that in disconnected systems the exchange flux is zero or constant. Braaten and Gates (2003) and Ivkovic (2009) indicate that pumping under a disconnected stream is unlikely to affect streamflow, giving further support to the notion that they can be managed separately. However, Fox and Durnford (2003) showed that pumping adjacent to a disconnected river will increase the length of river that is disconnected, and thus may affect the flow rates of the river.

This paper aims at summarizing the current state of knowledge concerning connection status between streams and groundwater systems. We focus our discussion on rivers but all the points raised in the paper apply equally to lakes and wetlands. We begin with a brief discussion of the history of the term disconnected, and then summarize the physics of the process, and the field methods for determining connection status. We conclude by discussing the implications of connection status for surface water and groundwater management, and by highlighting areas for future work.

Terminology and Historical Background

That different flow regimes existing between surface water and groundwater exist was recognized early in hydrological history. Mead (1919) recognized the existence of gaining and losing flow regimes but did not yet use the terms "losing" and "gaining." Probably, the first conceptual illustration showing all the possible flow regimes was published by Meinzer (1923). In addition to gaining and losing streams, Meinzer defined perched systems where the stream and water table are separated through an unsaturated zone. The first paper we could find that used the term "connected" was by Walton (1955) but the term disconnected was not yet introduced. Moore and Jenkins (1966) used the term "broken connection" to describe a disconnected system. Bouwer (1978) and Rahn (1968) also described disconnected systems, but did not use the term disconnected or any other specific term. Peterson et al. (1984) used the term disconnected for systems where the water table is several feet below the streambed, and this appears to be the first use of the term.

Even though not widely cited, a key study in the area of disconnected losing streams was carried out by Peterson and Wilson (1988). Peterson and Wilson (1988) differentiate between a disconnected stream with a deep and a shallow water table. In the more recent literature (Stephens 1996; Osman and Bruen 2002; Sophocleous 2002; Fox and Durnford 2003; Desilets et al. 2008; Brunner et al. 2009a, 2009b; Treese et al. 2009), the term "disconnected" is commonly used instead of "disconnected stream with a deep water table," and "transition" is used instead of the term "shallow water table." Transition refers to a state that is between connected and disconnected. An unsaturated zone can therefore be found in both transitional and disconnected systems. However, unlike that in transitional systems, changes in the water table do not affect the infiltration rate for disconnection systems.

Winter et al. (1998) also used the term disconnected and illustrated a disconnected system using a figure similar to Figure 1. The report by Winter et al. (1998) undoubtedly helped to make the term more popular, even though the term was not explicitly defined.

Peterson and Wilson (1988) remind the reader that the term disconnected should not be taken literally because it could lead to the wrong conclusion that the flow ceases between the river and the aquifer. Fox and Durnford (2003) call the term disconnected a misnomer and suggested instead that the term *perched* be used. It is noteworthy that the term perched stream (as originally used in Meinzer 1923) is used in some textbooks showing conceptual figures of disconnected streams, as in Dingman (2008). Also, the term *percolating surface water* is sometimes used as in Haitjema (1995). However, the term disconnected is most frequently used in the literature. We will use the term disconnected, but we acknowledge that the terms perched and percolating are also acceptable.

Physics

In gaining and losing connected systems, the porous material remains fully saturated, but in disconnected systems, an unsaturated zone exists between the streambed and the water table.

Fox and Durnford (2003), Osman and Bruen (2002), and Peterson and Wilson (1988) pointed out that under steady state conditions, unsaturated flow below the streambed requires the hydraulic conductivity of the streambed (subsequently called clogging layer) to be less than the hydraulic conductivity of the underlying aquifer material. Using a 1D analysis, Brunner et al. (2009a) presented an exact condition for disconnection and showed that a lower hydraulic conductivity of the clogging layer is a necessary but insufficient condition. Equations presented by Zaslavsky (1963) allow the derivation of the same condition, even though the link to disconnection was not made by this author.

A disconnection is theoretically possible without the presence of a clogging layer. Reisenauer (1963) showed that due to capillary effects, an unsaturated zone can develop under a stream above a homogeneous aquifer, even in steady state. In this case, the infiltration rate is limited by the hydraulic conductivity of the aquifer and the availability of surface water. The water table that separates the saturated and unsaturated flow regimes is called an inverted water table (Stephens 1996). However, we are unaware of field documentation of such a case, and Peterson and Wilson (1988) conclude that disconnection induced solely by capillary forces is unlikely to occur.

Sedimentary processes in streams often form a streambed with a hydraulic conductivity significantly smaller than that of the underlying aquifer material (Rosenshein 1988; Larkin and Sharp 1992; Sophocleous et al. 1995; Calver 2001; Fox and Durnford 2003). The clogging of streambeds can be caused through biological activity (Treese et al. 2009), sedimentary processes (Schalchli 1992), or the combination of both (Battin et al. 1999). Blaschke (2003) also discusses different types of riverbed clogging and measured the thickness of the clogging layer of undisturbed sediments in the Danube using a freeze-panel-sampling method. Packman and MacKay (2003) showed that even a relatively small amount of fine sediment can result in the clogging of the uppermost layer of the streambed. Of course, provided the hydraulic conductivity of the streambed is large but a layer of lower hydraulic conductivity is present between the streambed and the underlying aquifer, disconnection could occur between the aquifer and the layer of low hydraulic conductivity.

Figure 2 illustrates how infiltration and pressure under the clogging (low hydraulic conductivity) layer in the center of a river are affected by changes in the water table in the aquifer. A homogeneous clogging layer with constant thickness is assumed. In order to illustrate the basic physics, such simplifying assumptions have to be made. If the water table in a borehole adjacent to the river is above the river level (the head difference is negative in this case), surface water gains groundwater. No exchange takes place if the head difference is zero. If the water table is lowered below the river level, the surface water body loses water to the aquifer. If it is lowered sufficiently, an unsaturated zone begins to develop. As a result, the pressure below the clogging layer drops below zero, and the negative pressure at the interface increases the hydraulic gradient through the clogging layer. Because the hydraulic head beneath the clogging layer will be lower at the edge of the river than in the middle of the river, desaturation will occur at the edge of the river before

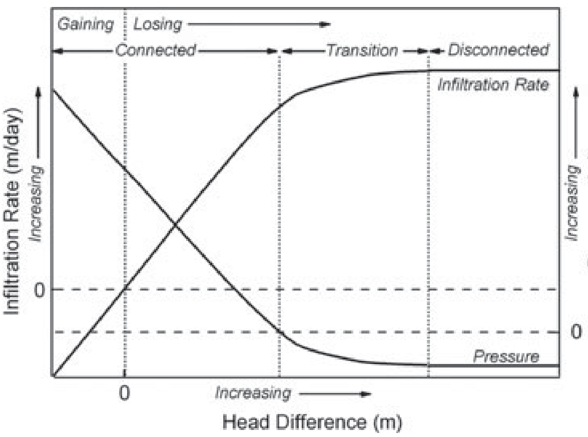

Figure 2. The flow rate between surface water and groundwater and the pressure head at the base of the clogging layer (both measured in the center of the river) as a function of the head difference between the river and an adjacent borehole. The graphs represent steady state values for a given head difference (from Brunner et al. 2009a).

it will occur in the center, and changes in the water table are no longer linearly related to the infiltration rate. By further lowering the water table, pressure at the bottom of the clogging layer approaches a constant value across the entire width of the stream.

Theoretically, the flux never reaches a maximum value as the water table falls, but rather approaches the maximum asymptotically (Brunner et al. 2009a). The maximum value can be estimated graphically (Osman and Bruen 2002) or numerically (Brunner et al. 2009a). This maximum flux is given by the hydraulic gradient through the clogging layer as well as its thickness and hydraulic conductivity. The gradient through the clogging layer is dependent on the depth of the surface water and therefore, the infiltration rate of a disconnected system will change in response to changes in depth and width of the surface water body. The infiltration rate of a disconnected system is therefore not constant, as it is dependent on the surface water depth.

In contrast to ideal systems as shown in Figure 2, river depth, clogging layer thickness and hydraulic conductivity will vary across real streams, and so the point at which disconnection occurs first is more difficult to predict. Nevertheless, it is clear that at the same time, the surface water might be disconnected at some locations across the stream but not at others. The infiltration flux will also vary across the stream width. For these reasons, defining disconnection in terms of the water table depth is problematic and it is more sensible to define the term through the total infiltration flux across the stream width.

Hence, we define a river to be disconnected if an unsaturated zone between the river and water table exists and the total infiltration flux across the stream width does not change measurably as the water table is lowered. A river is connected if it is fully saturated everywhere between the river and the aquifer. Any other situation is defined as transitional. A problem for any definition of disconnection, be it through the position of a water table or through an infiltration flux, is that theoretically the state of disconnection is never reached because the maximum infiltration rate or minimum pressure under the clogging layer is only approached asymptotically. Therefore, a transitional system can only be distinguished from a disconnected system by defining an arbitrary cutoff value where changes are considered negligible. It is also worth noting that the above definition refers to a particular location along the stream length, and it is possible (and even likely) for a river to be connected at one location and disconnected at another.

Even though lowering the water table at a specific point under a disconnected river will not increase the infiltration rate directly, it is incorrect to assume that additional pumping will not affect a disconnected river on a larger scale. Increased groundwater pumping will result in a widening of the cone of depression, and this can extend the length over which the river is disconnected. This effect was demonstrated in a conceptual study by Fox and Durnford (2003).

If we measure the water table depth in a borehole adjacent to the river, then we can define a critical water table depth where the system changes from transition to disconnection. Brunner et al. (2009a) carried out a sensitivity analysis on the relevant hydrological variables to assess the critical water table depth for a wide range of systems. For a given aquifer thickness and river width, the depth to groundwater where the system disconnects (measured in a borehole adjacent to the river) is approximately proportional to the stream depth and the hydraulic conductivity of the streambed sediments, inversely proportional to the thickness of these sediments and the hydraulic conductivity of the aquifer (and will increase as the distance of the borehole from the river increases). These proportions are only approximate, but highlight that approaches that only consider geometric properties of the river (e.g., depth and width) are incorrect. In addition, the application of the commonly used leakance term (vertical hydraulic conductivity of the streambed divided by the thickness of the streambed) is problematic in disconnection modeling and analyses. This is because both the clogging layer thickness and conductivity independently control the state of disconnection.

The discussion above is based on the analysis of perennial streams, but it is important to discuss some additional aspects relevant to ephemeral streams. Ephemeral streams are found mostly in semi-arid and arid areas where occasional flood events are an important source of groundwater recharge. The depth to groundwater under ephemeral streams is often sufficiently deep (e.g., tens of meters) that the available surface water during a flood event usually runs out before full saturation between the river and the groundwater occurs (and therefore becomes connected). Ephemeral streams therefore are frequently disconnected even in the absence of a clogging layer.

Even though the basic physics of disconnection are understood, important knowledge gaps remain. The influence of heterogeneity in the streambed of disconnected systems has so far not been explored systematically. However, new studies considering heterogeneities in losing streams are now being published (Frei et al. 2009) but the full impact is not yet understood. In addition, the influence of stream bathymetry and the impact of transient processes in the streambed on the state of connection are rarely considered in modeling and management approaches. A range of recent field studies has documented changes of the hydraulic properties of streambed in time (Springer et al. 1999; Doppler et al. 2008; Genereux et al. 2008; Hatch et al. 2010). Clearly, this transience is of importance to the state of connection and for surface water-groundwater interaction in general. Considering such complexity in regional models remains a field of research.

Modeling Approaches and Identification in the Field

Considering the fundamental importance of the state of connection on surface water-groundwater interaction, quantitative management tools should be designed to consider all possible states of connection. Among the first quantitative methods for predicting the impact of groundwater abstraction on streamflow were analytical models (Theis 1941; Hantush 1965). Analytical models are now being widely used for management purposes and built into conjunctive water management. However, these methods are based on fully saturated conditions and therefore implicitly assume that the river is connected over the entire length, and that it cannot disconnect. Management frameworks based on numerical models sometimes also assume full connection between surface water and groundwater (Başăaŏlu and Mariño 1999).

The exact physical modeling of a disconnected system as well as the transition from connected to disconnected requires a numerical model capable of simulating saturated as well as unsaturated flow. However, for most regional applications, modeling the transition between connected and disconnected regimes is not required, and the behavior of a disconnected river can often be approximated by neglecting the unsaturated zone as is done in, for example, MODFLOW (McDonald and Harbaugh 1988; Harbaugh 2005). MODFLOW assumes gravity drainage through the streambed for disconnected systems. Because the unsaturated zone is neglected, MODFLOW is fast and therefore can be used for regional applications. Nevertheless, the code is based on conceptual assumptions that in some cases can result in critical limitations (Brunner et al. 2010).

Identifying the state of connection in the field should precede the choice of the management model. As discussed by Brunner et al. (2009a), the suggestion that a river is disconnected when the water table depth is more than twice the stream width is incorrect. To test whether a system is disconnected or not, the physical definition requires lowering of the water table as well as monitoring of the infiltration rate. To the best of our knowledge, Moore and Jenkins (1966) were the first to demonstrate this behavior in the field. Moore and Jenkins pumped groundwater next to a river and showed that for areas where an unsaturated zone below the river existed, changes in water table had no measurable effect on the infiltration. A number of studies have documented changes in infiltration induced by pumping (Rahn 1968; Sophocleous 1988; Nyholm et al. 2002; Braaten and Gates 2003) and therefore demonstrate that the system is connected or in transition.

Even though it is possible to identify disconnection by showing that the flux does not change as the water table is lowered, the procedure is difficult and in most cases impractical. Installing a pump in order to lower the water table may be hard to implement, and measuring infiltration rates is challenging, despite the variety of available methods (for reviews, see Constantz et al. 2003; Kalbus et al. 2006). Further challenges are associated with identifying disconnection through pumping. Changes in infiltration and measurement errors can make this analysis difficult. Moreover, observing that the stream loss does not change during pumping is not necessarily a proof of disconnection because there might be a significant time lag between groundwater abstraction and stream response.

On the other hand, showing that a system is not connected (i.e., transition or disconnected) is much easier. The existence of an unsaturated zone beneath the stream confirms that the river is in transition or disconnected. The thicker the unsaturated zone under a river is, the more likely the system is to be disconnected. For most of the simulations carried out by Brunner et al. (2009a), the system was disconnected if the thickness of the unsaturated zone in the center of the river exceeded half a meter. However, an important reason why the presence of an unsaturated zone is not proof of disconnection is because small and large scale heterogeneity of the streambed might cause some portion of the river to be connected and another to be disconnected (Frei et al. 2009). Brunner et al. (2009a, 2009b) showed that for wide rivers, a significant drop in the water table is required to change the system from connected to disconnected.

Field studies that document unsaturated conditions under a river and thus show that the system is not connected have been published (Treese et al. 2009; Hatch et al. 2010). The only documented example of a pumping-induced unsaturated zone under the streambed that we are aware of is reported by Moore and Jenkins (1966) who installed observation bores in the streambed of the Arkansas River and observed that pumping caused the water table to drop below the streambed. If the water table is measured in a borehole adjacent to the river, then determining connection status is much more difficult. Braaten and Gates (2003) and Ivkovic (2009) mapped disconnected streams across large regions by assuming that streams are disconnected when the groundwater depth measured in boreholes within 1 km of the river is more than 10 m below the land surface. This may be a reasonable approach for regional assessment, but because variables such as the properties of the streambed, the distance between river and observation point or the depth of stream incision are ignored, the method is likely to result in inaccuracies at a local scale. It is clear that obtaining data to show that a river is disconnected remains one of the most significant challenges for disconnection studies and that many more documented field studies are required to demonstrate the ways in which this can be done in practice.

Conclusions

So far, no clear definition of the term disconnected as applied in describing the state of surface water–groundwater interaction has been published. Hydrology textbooks are often limited to an illustration showing an idealized, disconnected system. The implications for management, the influence of streambed heterogeneity, and the identification of disconnection in the field have not yet been fully explored by the hydrological community. The following points should be emphasized:

1. Identifying that a river is not connected (i.e., transitional or disconnected) is much easier than identifying disconnection but is less useful for management purposes. The observation of an unsaturated zone beneath a river is sufficient to conclude that a river is not connected. Larger values of the thickness of the unsaturated zone increase the likelihood of a system being disconnected. For the conceptual simulations of Brunner et al. (2009a), an unsaturated zone of half a meter thickness was sufficient for disconnection in most cases. However, currently the only way to prove that a river is disconnected is to demonstrate that the infiltration flux does not vary with water table depth. In practice, this can be difficult.

2. Spatial and temporal variations in connection status can occur. For example, groundwater pumping under a disconnected river may increase the length of the stream that is disconnected, which affects overall streamflow. This temporal and spatial variability has implications on the interpretation and use of field data. Any assessment of the state of connection may only be valid for a specific period and section of the river considered.

3. The infiltration rate of a disconnected stream is dependent on the depth and width of the surface water body. Therefore, surface water management will affect the groundwater system, independent of the state of connection. This suggests that surface water and groundwater should be managed conjunctively, irrespective of the connection status. It is only appropriate to manage these water resources separately if the exchange flux between surface water and groundwater is a small component of both individual surface water and groundwater balances.

There are many theoretical and practical challenges which remain in this area of groundwater management and research, and the prognosis for future research and application is healthy. The influence of heterogeneity and transient processes in the streambed on the state of connection is poorly understood. Regional scale modeling of disconnected systems using fully coupled surface water-groundwater models requires a considerable amount of input data, is computationally demanding, and remains an active area of research. Practical field methods that allow us to determine the state of connection and, in particular, allow for rapid identification of the disconnection state are lacking. More field studies dedicated to the state of disconnection are required to develop better, reliable and possibly more rapid and efficient methods. Such field studies are challenging and require a considerable amount of monitoring infrastructure that allows the behavior in both the surface water as well as the groundwater to be measured. The collection of data and the development of field techniques to identify disconnection remains one of the most significant practical challenges for this field of groundwater investigation.

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