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Methodological proposal for conceptualization and classification of interactions between groundwater and surface water

Bruno J. Ballesteros-Navarro, Elisabeth Díaz-Losada,
José A. Domínguez-Sánchez and Juan Grima-Olmedo*

Department of Research on Geological Resources, Geological Survey of Spain, Cirilo Amorós 42, 46004, Valencia, Spain
**Corresponding author. E-mail: j.grima@igme.es*

Abstract

Water management plans require comprehensive knowledge of physical processes and principles controlling water resources. These mechanisms, subject to limitations, can interact in complex ways, which makes it challenging to design guidelines to achieve optimum water resources use, taking into account economic, social and environmental factors. The relationship between rivers and aquifers defines different forms of interaction between superficial water and groundwater. These processes have great relevance in inland water management and protection against pollution, as well as dependent ecosystems. Under the current legislative framework in Europe, i.e., the Water Framework Directive 2000/60/EC (WFD) and the Groundwater Directive 2006/118/EC, calculation of flow direction and exchange rates between groundwater bodies and associated surface systems are key aspects of river basin management plans. This paper examines conditioning factors of exchange processes, related basic physical principles, and criteria for establishing different conceptual models, providing a typology for systematic classification of groundwater–surface water interactions.

Keywords: Continuity; Exchange; Hydraulic connection; Stream–aquifer relationship; Typology; Water Framework Directive

Introduction

Water management is critical to satisfy human and environmental needs. This objective is partly achieved through hydrological planning. Climatic aspects, hydrogeological features and anthropic effects are important factors to be considered within the planning process. Particular limitations, and their interactions, makes the task of providing guidelines for sustainable use of water resources very difficult. Environmental sustainability is the driving force for the intervention of humans in the water cycle, modifying the natural hydrologic regime. To increase guaranteed supplied level, important hydraulic

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infrastructures have been implemented, with the result of changing substantially characteristics and conditions to which surface and groundwater are exposed, in terms of both volume and quality of resources.

The main conclusion is the need of a detailed analysis of the mechanisms governing behaviour of water resources as an additional input to improve knowledge. Decision-makers frequently reveal insensitivity biases for decision analysis (de Carvalho *et al.*, 2017) so reliable information is a keystone. Proof of this is the existence of cases in which ignorance of essential aspects of the water cycle has had an extremely negative consequence for the environment, creating additional problems. The river–aquifer relationship provides a link between surface water (rivers, lakes and wetlands) and groundwater, and it is based on water exchange between groundwater and surface watercourses that run on or near to permeable formations. Nevertheless, regardless of its importance, interactions between surface and groundwater have not been studied extensively nor are detailed references available.

This process has great relevance in the management and protection of inland waters against pollution, as well as associated ecosystems. In fact, the European Directive 2000/60/EC, whose main objective is to achieve good ecological status of water bodies, proposes lines of work aimed at addressing selection and definition of characterization methodology. In particular, in section 2.2 of Annex II, on further characterization of groundwater bodies, it is required to perform calculations on directions and rates of exchange between groundwater bodies and associated surface systems.

Approaches and literature review

Study of stream–aquifer relations

Since the middle of the last century, an attempt has been made to analyse the relationship between groundwater and surface waters, since both are often hydraulically connected (Winter, 1995). However, their interactions are difficult to observe and measure, so they have been overlooked or undervalued in the management of resources of a water system systematically. There is also a duality between surface and underground hydrology experts.

Some authors have addressed the scientific treatment of this phenomenon. Some explore large-scale interactions and quantitative analysis, as well as ecological implications or effects of human activity (Hancock, 2002). Others focus in more detail on the study of interactions between groundwater ecosystems and connected rivers (Brunke & Gonser, 1997; Wroblicky *et al.*, 1998) and the dominant component of underground flow involved and possibility of classifying alluvial aquifers from such relationships (Larkin & Sharp, 1992). Some authors try to evaluate the volume of resources involved in interaction from estimation of transfer rates, either through study of the hydrograph, analytical solutions (Sahuquillo, 1986) or other methods (river water balances, infiltrometers, aquifer mass balances, hydrochemical methods, etc.). There are also numerous studies on the typology of rivers or specific hydrogeological landscapes, such as those associated with karst aquifers (Bailly-Comte *et al.*, 2009).

A classification based on water transfer between surface water and groundwater, which differentiates between gaining rivers or effluents and losers, has traditionally been used (Winter *et al.*, 1998). According to this criterion, a number of studies have been carried out in order to explore conditioning factors involved in the relationship (Tóth, 1970; Winter, 1995). Similarly, classification of riparian wetlands according to the role they play in flood lamination and control and, in general, in the hydrological regime of surface courses, as well as recharge and drainage elements of aquifers, have been done (García Rodríguez, 2003).

One of the most interesting works to establish different types of river–aquifer relationship is the one made by the US Geological Survey (Winter *et al*., 1998), which gathers basic information from different scenarios, both from the physical environment and hydrochemical perspectives. Thus, movement of surface and groundwater, its interconnections in different environments, relationships between groundwater, rivers and lakes, chemical processes and influence of human activities are analysed. The author details basic interaction concepts: surface and groundwater movement within the hydrological cycle, interconnections in different environments, groundwater relations with rivers and lakes, chemical processes and influence of human activities.

More recently, in the work carried out by Murillo (2016), different types of stream–aquifer interrelations are classified according to flow direction, spatial distribution of the relation and existence of hydraulic continuity (or discontinuity). Based on this criterion, and in the nature of the aquifer, different forms of direct or indirect relationship are defined according to the relative position of water levels in the river and in the aquifer.

However, despite the aforementioned work and some remarkable studies, like that of Mas-Pla *et al.* (2012), and the widely accepted idea about the importance of the interaction between groundwater and surface water in the scope of water planning, there is no adequate systematic approach to establish detailed forms and characteristics of mechanisms involved in this relationship. In order to cover this gap and knowledge needs identified in this field, this paper provides a schematic description of the different types and proposes a systematic characterization and classification according to different river sections or elements of the water cycle.

The final purpose is to establish a practical and useful tool to support the decision-making process, frequently neglected by the lack of qualitative–quantitative methodologies (de Carvalho *et al*., 2018) for integrated water resources management with specific attention to achieving policy objectives.

Factors that condition water exchange processes within the framework of stream–aquifer relationship

Dynamics of hydrological systems usually involves two main components, groundwater and surface water, which interact with each other in a wide diversity of physical and climatic conditions. In this context, river–aquifer relationship is defined as the process that allows the transfer of water resources between a riverbed and a permeable geological formation (PGF) due to the existence of a geological–hydrological mechanism.

To understand interactions, it is necessary to identify conditioning factors and their influence. Tóth (1970) states that it is necessary to define what he calls the hydrogeological environment, determined by topography, geology and climate. According to the author, each component responds to specific and measurable parameters, such as slope, permeability of rocks or precipitation, which in turn control groundwater conditions, volume variations, spatial distribution of the underground flow and its velocity, as well as chemical composition and temperature. Winter (1999) addresses this issue and indicates that the interaction of groundwater with streams, lakes and wetlands is conditioned by the position of surface water bodies with respect to groundwater systems, geological characteristics of their beds and climate regime. Accordingly, the following key factors are identified: position of the channel with respect to the aquifer, relief-geomorphology, geological and hydrodynamic characteristics, and climate regime.

Geomorphology is very useful to characterize large-scale interactions between surface water and groundwater. Larkin & Sharp (1992) classify river–aquifer systems, depending on the regional flow component, as:

- predominant underflow component, with underground flow pointing in the river direction;
- predominant baseflow component, with underground flow pointing perpendicularly or obliquely to the channel, towards or away from it;
- mixed.

In addition to topography, flow pattern also depends on hydraulic conductivity in rocks and soil, and climatic regime. On these aspects, Woessner (1998) argues that precipitation events and seasonal models modify hydraulic potential and induce changes in flow direction. In addition to the main movements identified – influent and effluent – other authors include:

- flow through the river bed, when piezometric level in one margin of the river is greater than in the other, the reason why groundwater moves perpendicular to river flow, so the channel becomes a mere transmitting element;
- river section of parallel flow, which happens when surface water potential of the river equals the piezometric level of the aquifer (Wroblicky *et al*., 1998; Woessner, 2000).

On the other hand, very variable flow regimes can alter hydraulic conductivity of riverbed sediments, by erosion or deposit, and thus affect the intensity and direction of exchange. Spatial distribution of the underground flow system also influences the intensity of natural groundwater discharge. According to this, Tóth (1963) states that groundwater moves within a flow system in which, depending on its spatial distribution, there are three ranges, local, intermediate and regional, conditioned by topography and hydrodynamic characteristics of aquifer formations, which may overlap within the same hydrogeological structure.

Woessner (2000) establishes the following elements of large-scale interchange between surface and groundwater: (i) distribution and magnitude of hydraulic conductivities, both in channel and sediments of the associated floodplain; (ii) relationship between level of water in the channel and hydraulic potential of groundwater; and (iii) geometry and position of the channel with respect to the alluvial plain. Thus, direction of the exchange processes varies with hydraulic load, while magnitude of transfer depends on hydraulic conductivity of sediments. Guyonnet (1991) determined that even small thickness layers in the channel bed, with low or high hydraulic conductivity, have a substantial effect on transfer from surface water to the aquifer or vice versa.

As explained throughout this section, many factors influence the processes of interconnection and cause them to occur in a certain way and with greater or lesser intensity. Therefore, they can be grouped into four types: geological, geomorphological, hydrological and hydraulic.

Geological factors. Tectonic–stratigraphic arrangement is the driving force of the interaction process between river and aquifer. Thus, a riverbed can flow over a permeable formation (so there will be a connection), or over an impermeable one. As a result, the layout and nature of geological formations affect the way in which underground flow is established, since changes in lithology determine the existence of interconnected groundwater (or disconnected) with surface water and the extent of exchange.

The nature of permeable geological formation (PGF) conditions predominant flow mechanism, i.e., detrital connections tend to be diffuse, whereas carbonate or crystalline formations have the effect on the connection to be localized and linked to fractures or discontinuities.

Geomorphological factors. Channel geometry is the starting point for morphodynamics and sedimentology studies of river processes (Pedraza, 1996) and influences the river–aquifer relationship. Leopold & Wolman (1957) differentiate three river models depending on whether the channel geometry is rectilinear, meandriform or braided. The difference between the first two is based on sinuosity index, which is the relationship between water path length along the talweg and rectilinear distance from initial and final points. Braided typology is defined for channels with high sinuosity depending on the multiplicity or diversification of the stream. Among most common methods, the one developed by Rust (1977) also includes a fourth type: the anastomosed, with low sinuosity and multiple channels.

Larkin & Sharp (1992) establish that the dominant component of regional underground flow can be inferred from geomorphological parameters, such as channel slope, sinuosity of river, degree of penetration of the channel, channel width–depth relation and character of associated fluvial depositional system. Thus, channel slope has a significant influence on river–aquifer relationship, since low values produce higher residence times and, therefore, it favours infiltration of resources from river to aquifer. As regards dimensions, the greater the channel wet surface the more the exchange of resources. In this sense, sinuosity factor has the same implications, since greater sinuosity diminishes flow velocity and enhances interrelation, if this does not imply deposition of fines.

Regional component of underflow is clearly predominant in systems with high slope or gradient and low sinuosity channels, high width-to-depth ratio and low bed penetration. It is prevalent as well in fluvial depositional systems with transport of sediments along the bottom of a waterway. In contrast, systems with predominance of baseflow component have the typical characteristics of a fluvial system with transport of suspended solids. Mixed flow systems occur when a valley's longitudinal gradient and channel slope are virtually the same and the slope of the valley's sides are insignificant (Larkin & Sharp, 1992).

Hydrological factors. Climate plays a fundamental role in the stream–aquifer relationship, since the rainfall regime generally conditions availability of water. It controls fluvial regime, depth and fluctuation of piezometric surface in aquifers. In this sense, fluvial regime affects the relation depending on whether it is:

- permanent: baseflow is (more or less) continuous, so the river is normally effluent seasonally; water transport only at certain periods of the year, and is both effluent and influent depending on the season;
- torrential or ephemeral: the water table is always below the channel, so it is exclusively influential when there is flow in the surface channel (Gordon *et al.*, 1992).

River regime determines flow rate and velocity of surface runoff, jointly with channel slope and sinuosity, factors that also influence water residence time in the channel and, consequently, time for interrelation. When the water table is close to the surface, evapotranspiration processes come into play and can intercept part of the groundwater draining into the rivers. Even areas of depressed piezometry can draw resources from riparian areas (Meyboom, 1966).

Hydrodynamic factors. Aquifer type is another factor that allows the existence and intensity of a hydrological relationship. Thus, aquifers can be free, confined or semi-confined. In the first case, there is a relation with the channel above it with few limitations, while in the third one it is restricted. The second instance implies nonexistence of a relationship.

There are a number of physical principles involved in the relationship between a surface course and an aquifer, based on the hydrodynamic properties of geological formations, such as hydraulic conductivity, hydraulic conductance, hydraulic potential, etc. They are discussed in the following section.

Basic physical principles of the exchange process

Physical principles underlying water exchange processes between a surface watercourse coming into contact with an aquifer are limited to those related to hydrodynamic parameters of permeable geologic formations of the riverbed (hydraulic conductance) and those related to their hydraulic potential. The former defines general characteristics and framework of the relationship, while the latter determine direction and intensity of flow.

Streambed conductance and hydraulic potential. Hydraulic conductance is the basic physical principle that defines river–aquifer relationship. This concept represents the resistance of the bed of a channel to the transfer of water. For a given river section, its value is defined by the following expression (Murillo, 2016):

$$C = KLW/T \tag{1}$$

where C is streambed conductance (m^2/d); K is vertical hydraulic conductivity of riverbed sediments (m/d); T is estimated average thickness (m); L is length of river section (m); W is average width (m).

From Equation (1), the greater the permeability of the geological formations involved, or the wet surface, the greater the transferability. On the contrary, the transfer of water will be more restricted as thickness of formations increases. On the other hand, storage coefficient of the PGF, whose value in a free aquifer equals effective porosity (in semi-confined or confined is a combination between porosity, compressibility of water and granular structure of the formation), may have importance on occasions, such as storage in banks. In those cases, higher storage coefficients imply greater volumes of water capable of being stored, increasing the possibility of exchange.

One of the fundamental principles in hydraulics is the postulate by Bernoulli in 1738, which enunciates that energy in a fluid flow line remains constant along its entire path. Therefore, water tends to move towards areas with less energy. When there is hydraulic connection between a river and an aquifer, the difference between hydraulic potential of the water sheet in the river and water within the aquifer determines the direction of transmission (Figure 1). Hydraulic potential also influences the intensity of exchange flow, increasing it as hydraulic head increases. This can be summarized as:

$$Q = C(Hr - Ha) \tag{2}$$

where Q is magnitude of flow (m^3/d); C is conductance (m^2/d); Hr is river level (m); Ha is piezometric level (m).

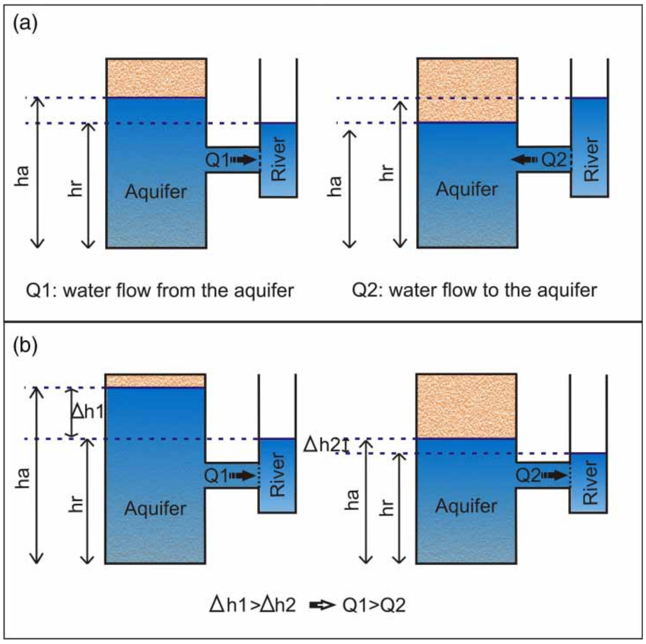

Fig. 1. Hydraulic potential and direction of flow.

Positive values imply the river gives water to the aquifer, while negative ones indicate that groundwater seeps out into the stream.

In the case of the influent river, the greater the height of the water column in the channel the greater the pressure at its base and, therefore, the flow transfer to the aquifer. On the contrary, in effluent rivers, higher height of the water column will imply a reduction in the contributions of the aquifer to the river. This operating scheme assumes that when there is a change in the relation of hydraulic load, an inversion of the sense of resources transfer happens, so influential rivers become effluents and vice versa.

Hydraulic connection and continuity. A clear understanding of concepts handled when describing the link between a river (or a lake) and an aquifer is to be addressed first. Most of them are correctly applied. However, during the review of the state-of-the-art, they are used without distinction, originating ambiguity. It is quite possible that this confusion is due to the lack of detailed studies of the mechanisms that control interrelation between surface water and groundwater.

According to the U.S. Geological Survey (Winter *et al.*, 1998), a losing river and an aquifer may be connected through a saturated zone, or be disconnected if there is an unsaturated zone between both. This definition is opposed to the principle that there must always be hydraulic connection for a relationship between a river and an aquifer to exist. Other authors (Peterson & Wilson, 1988; Stephens, 1996; Bailly-Comte *et al.*, 2009) have taken the same position, and admit definition of hydraulic connection (and disconnection) is related to the presence (or absence) of a saturated zone. According to them, a river is hydraulically connected to an aquifer if its water sheet is intercepted by the aquifer's piezometric level. On the contrary, the system is hydraulically disconnected if there are unsaturated sediments between surface water and groundwater. In contradiction and against this conception of hydraulic connection, a river–aquifer connection is needed to study the physical process and reproduce it mathematically, despite the presence of non-saturated sediments in between. This conclusion is supported by Peterson & Wilson (1988), using numerical modelling. Along similar lines, other authors also consider losing rivers as having hydraulic connection when there exists a geological formation of permeable unsaturated materials between them. On the other hand, the Water Resources Forum in 1997 defines hydraulic continuity as ‘interconnection between aquifers and surface water’. From the definition itself, this concept implies making equivalent the concepts of hydraulic connection or ‘interconnection’ and hydraulic continuity.

From the above, it is gathered that in the current bibliography regarding river–aquifer relationship, the terms ‘hydraulic connection/disconnection’ and ‘hydraulic continuity/discontinuity’ are often inappropriately applied, which may lead to ambiguities and conceptual errors. This is visible when a detailed study of the relationship and characterization of its different types is addressed, since in doing so, the need to define both terms immediately arises. In fact, they can be distinguished from definitions, since different physical processes are concerned. The stream–aquifer relation implies the existence of a geological–hydrological mechanism that allows transfer of water resources between a river channel and a permeable geological formation via a physical connection without which such relationship could not exist. Consequently, there will be hydraulic connection between river and aquifer when there is an interconnection mechanism, either occasionally or permanently. On the contrary, hydraulic disconnection happens when there is no access route.

On the other hand, hydraulic continuity, applied to river–aquifer relationship, is defined as that situation in which the aquifer saturated zone and the water sheet of the surface channel are in direct contact. In contrast, hydraulic discontinuity occurs when there is an unsaturated or partially saturated zone between an aquifer’s piezometric level and water sheet of the surface element. This concept has application only to the underground environment so, in order to differentiate it from the surface hydraulic continuity, it has been termed as underground hydraulic continuity.

In Figure 2, these concepts are visualized. A pipe connects two deposits. There is a hydraulic connection between both tanks, but hydraulic continuity exists only when a fluid (Figure 2, right) saturates the system.

Conceptual clarification of such processes is essential in hydrogeology, since the existence of hydraulic continuity (discontinuity) is one of the key factors for the spread of pollution. Hydraulic continuity between river and aquifer facilitates transport of polluting substances to one or another element, since contact always occurs in the saturated zone. In contrast, hydraulic discontinuity increases residence time within the unsaturated zone, favouring processes of self-purification.

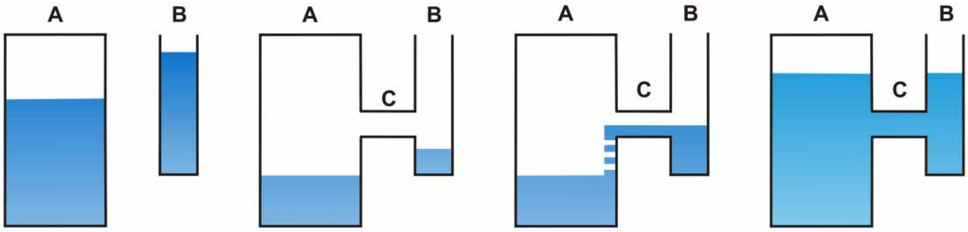

Fig. 2. Hydraulic continuity.

Results and discussion

Classification proposal: criteria and characterization

Exchange of water resources between river and aquifer produces two situations according to flow direction, between winning and losing channels. These relationships are due to natural factors, linked to geological and hydrological characteristics of the territory. Such processes and mechanisms can be better characterized from five criteria (Table 1). The three most important are direction (only criteria considered to date), continuity/discontinuity shape and spatial distribution. A fourth criterion allows providing information of interest on the river–aquifer relationship and it is the volume of water exchange in one direction or another. Finally, it is also essential to know the temporal nature of the process, that is, whether it occurs at all times or if it takes place in a seasonal or occasional way, as proposed by Gordon *et al.* (1992).

One issue to consider is that along the course of a river there may be various forms of relationship with groundwater or, simply, no relationship at all. Therefore, the first thing to do is to establish sections in which there is an exchange of resources due to interchange mechanism. To do this, it is necessary to find the optimum work scale best suited to the objectives pursued. It is worth mentioning that the basic criterion of classification is the direction of the relationship.

With these considerations, a methodology is proposed aimed at typological characterization of the river–aquifer relationship.

First criterion: water direction. The existence of relationship assumes transmission of water resources, which generate a loss–gain situation. It is by far the most relevant criterion, since it defines whether the water exchange is established in favour of surface runoff, and consequently towards the river network, or to aquifers.

Table 1. Summary of classification criteria.

	Criterion	Types
1	Water direction	Effluent or winner channel (G)
		Influent or loser channel (L)
		Neutral (N)
		Reversible channel (R)
		Channel with composite relationship (C)
2	Underground hydraulic continuity	Hydraulic continuity
		Restricted hydraulic continuity
		Hydraulic discontinuity
		Transient hydraulic continuity
		Multiple hydraulic continuity
3	Configuration of the spatial relationship	Localized punctual
		Localized multiple
		Diffuse
		Mixed
4	Volume of exchange	Flow range
5	Temporal evolution of the process	Permanent
		Seasonal
		Occasional

Among other aspects, detailed knowledge of exchange areas provides information on the pollution risk of ground or surface water. In the case of spills in streams, it allows assessment of the potential risk of contamination of underground resources. Likewise, contaminated aquifers drained by rivers have the capacity to alter the water quality of surface courses, whereas this does not happen in influential rivers. Once the direction of the relationship is characterized, it is possible to evaluate potential affectation of related aquifers and contribute in selecting suitable areas for artificial recharge.

Typology. There are five types: effluent channel, influent channel, neutral, channel with reversible relation and channel with compound relation (Figure 3).

Effluent or winner channel (G): It is fed by the underground runoff, so it receives partially or totally its water resources from one or more PGFs. Hydraulic potential of formation is always greater than potential of water sheet of the connected stream. This situation is representative of headwaters, where volume of exchange usually corresponds to its base flow, as well as the final sections, although in this case, importance of the underground component is somewhat smaller.

Influent or loser channel (L): Transfers, partially or totally, its flow to one or more PGFs and, consequently, recharges the aquifer. It is then necessary that hydraulic potential of PGF is smaller than that of channel ($h_{PGF} < h_{river}$). It happens in intermediate and lower courses of rivers.

Neutral (N): In this case, despite the existence of connection and underground hydraulic continuity, there is no water exchange between river and aquifer due to the predominance of underflow component (Larkin & Sharp, 1992) in which underground flow is parallel to the channel.

Reversible channel (R): It has an alternate regime of losses or gains, either seasonally or occasionally. It occurs when the piezometric surface of the PGF fluctuates temporarily above or below the water level of the surface channel or, on the contrary, when the water level in the river fluctuates above or below the aquifer level. This type occurs most frequently in the middle and lower sections of watercourses.

A particular case of a river with a reversible relationship is known to be storage in banks or slopes (Winter *et al.*, 1998). This process occurs in effluent streams, in which during flood periods the water level rises above the aquifer piezometric level. The lithology of these aquifers is such that they allow storage of water close to the channel, so they become fed by rivers. With decline in channel level, the direction of relationship is restored and transferred water returns to the river. This type occurs most frequently in middle and lower sectors of watercourses.

Channel with composite relationship (C): It takes place in those streams in which any of the previous types occur simultaneously, because of particular geological–hydrological situations. Various combinations are possible:

- Streams flowing over a formation to which they yield (or receive from) their resources, but at the same time, fed by springs.
- Channels in which part of the riverbed behaves as a winner and part as a loser. It is usually due to tectonic causes. This situation occurs mainly in alluvial aquifers located in valleys with low slopes and rivers with high sinuosity, although it can also appear in headwater basins.
- Winners or losers with regard to a given formation with a reversible relationship.

Second criterion: underground hydraulic continuity. Transfer of resources between river and aquifer happens under different forms of hydraulic continuity/discontinuity. They range from clear and open underground hydraulic continuity to discontinuity.

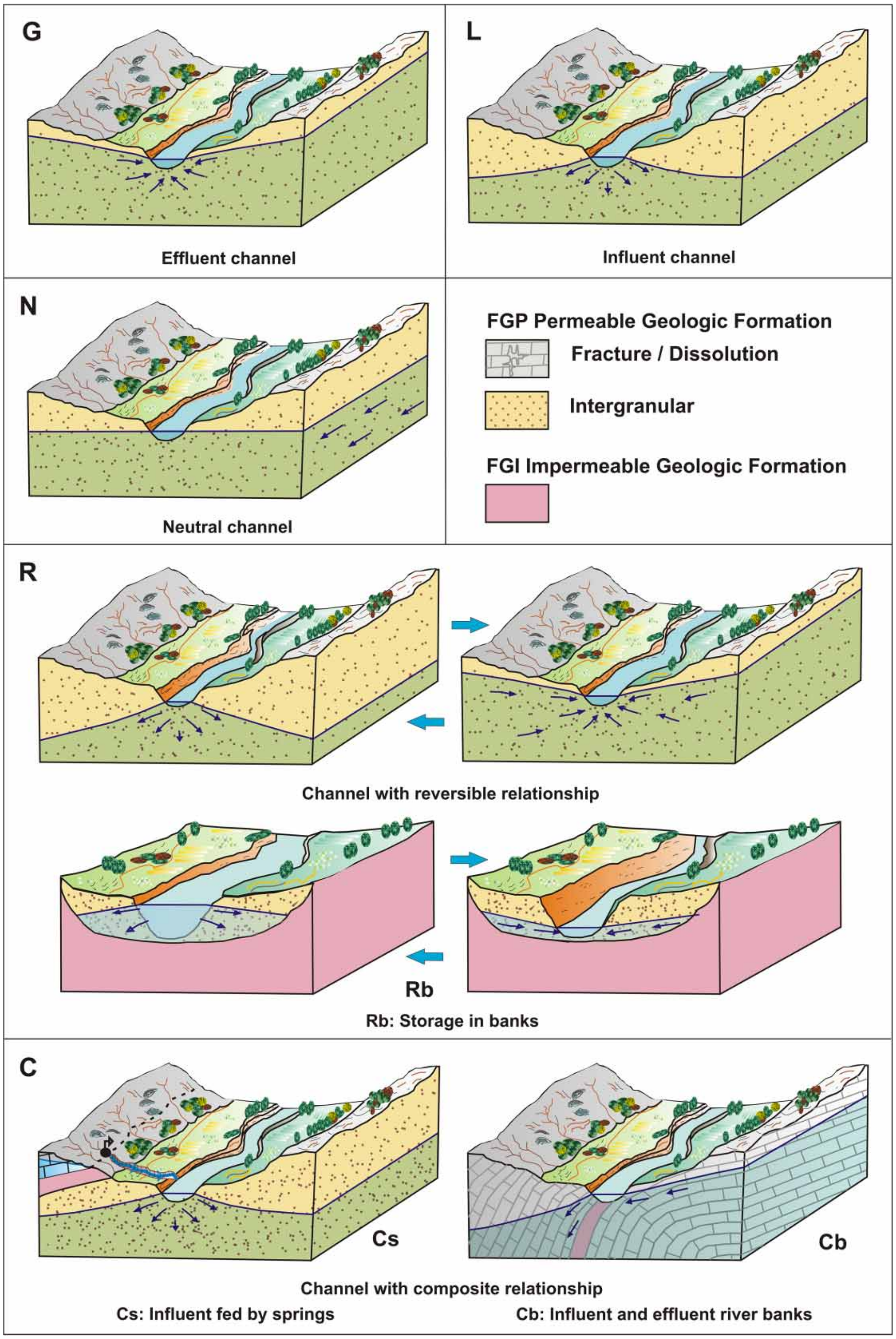

Fig. 3. Classification based on water direction.

It provides relevant information on groundwater vulnerability. Hydraulic discontinuity assumes the existence of an unsaturated zone between channel and piezometric level of the aquifer that favours soil self-depuration process. As thickness of the unsaturated zone increases, so does the potential for pollution prevention of the underground water resources.

Typology. Five different models can be defined: hydraulic continuity, restricted hydraulic continuity, hydraulic discontinuity, transient hydraulic continuity and multiple hydraulic continuity (Figure 4).

Watercourse in underground hydraulic continuity with an aquifer (C): There is always hydraulic continuity between an aquifer saturated zone and sheet of water, so the channel is totally or partially penetrating in the formation. Consequently, interaction can occur in both senses.

This situation is frequent in final river sections, especially in alluvial valleys where piezometric levels are very shallow. Within this category, as a particular case, it is the relation between an aquifer and a superficial channel through another aquifer of much smaller entity and, normally, of different nature, interposed between both elements (Murillo, 2016). A typical example is a formation linked to alluvial deposits, which normally have a small extent and are placed on aquifers of much greater relevance. The formation stays as a transmissive element of underground flow to the main aquifer. When this happens, hydraulic continuity is of indirect type, whereas when the transfer of resources between a river and an aquifer is completed without intermediate elements, it is of direct type.

Watercourse in restricted underground hydraulic continuity with an aquifer (R): Hydraulic continuity between river and aquifer is difficult or restricted by concurrence of specific hydrogeological circumstances. For example, there may be an aquitard between aquifer and streambed or aquifer hydrodynamic characteristics are poor. In both cases, a reduced volume of water resources is supplied to the river.

Also included are situations in which a relationship is established through dikes or fracture lines crossing an impermeable geologic formation interposed between waterway and aquifer. Therefore, transfer of resources between them is still possible, but limited by specific physical conditions of this mechanism. The first type can be described as low permeability effect and the second as fracture effect. They often happen in large sedimentary basins, usually related to deep or regional underground flow and, therefore, to effluent rivers with low exchange ratio.

Watercourse in underground hydraulic discontinuity with an aquifer (D): There is an unsaturated zone between an aquifer's piezometric level and water surface course, but a mechanism of connection between them (open with no restrictions) exists. In this case, relationship usually occurs in one sense, with two situations:

- *Discontinuity between aquifer and influent (or loser) river*. The riverbed is raised with respect to the piezometric surface without contact. The channel loses flow in favour of the aquifer. It is known as shower effect, when it is produced through porosity permeability formations or as sink effect, within secondary permeability formations. It happens more frequently in intermediate sections of hydrological basins.
- *Discontinuity between aquifer and effluent (or winning) river*. The river receives water resources from a contiguous geologic formation whose hydraulic potential is greater. Generally, the formation is placed in an elevated topographic position (with respect to the surface course), without being in contact, and contributes by means of springs close to the channel. It can be named 'spring effect'. This is a typical case of headwater areas of rivers, where natural drainage of aquifers of mountain areas contributes to feeding surface courses and forms baseflow.

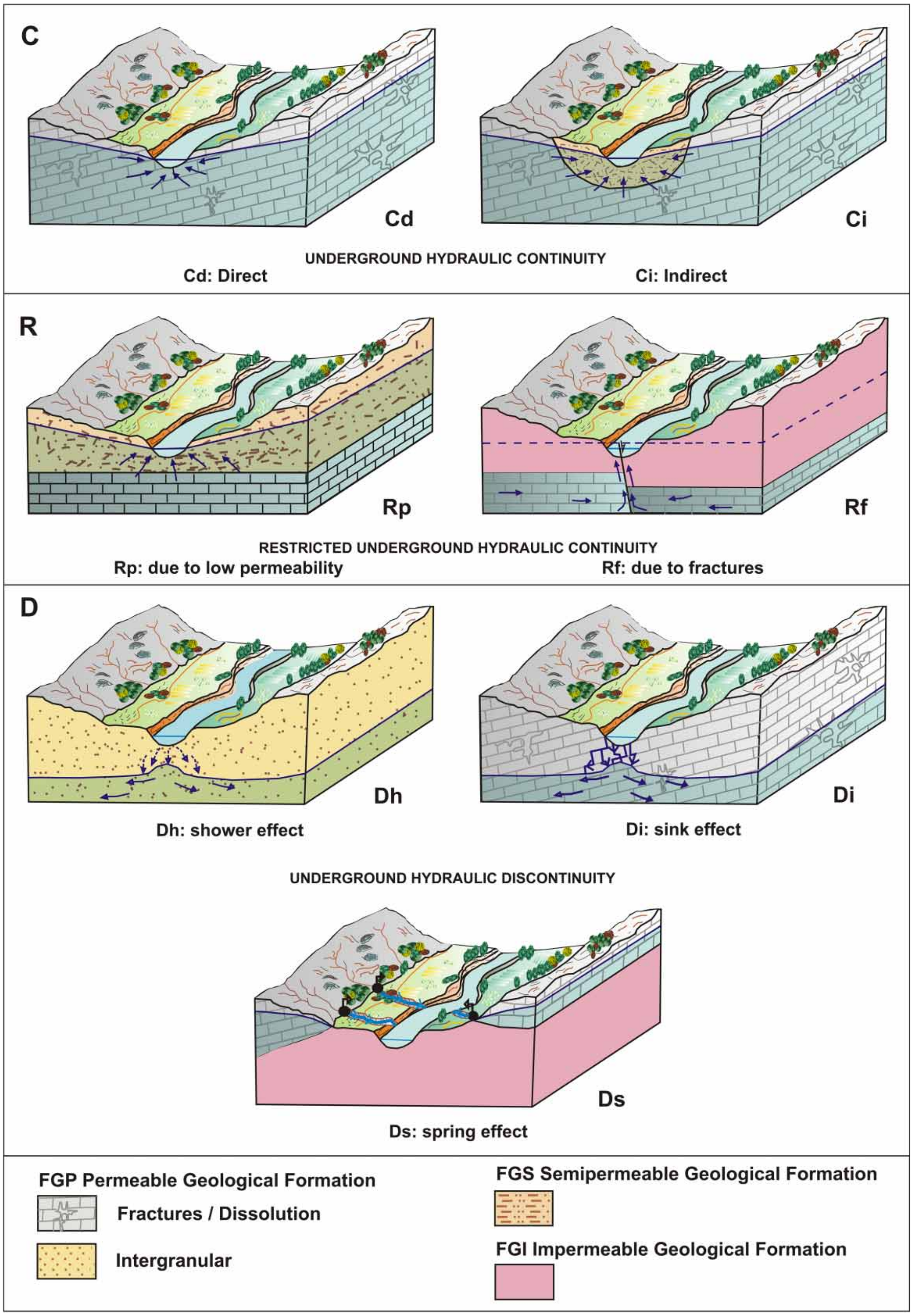

Fig. 4. Underground hydraulic continuity.

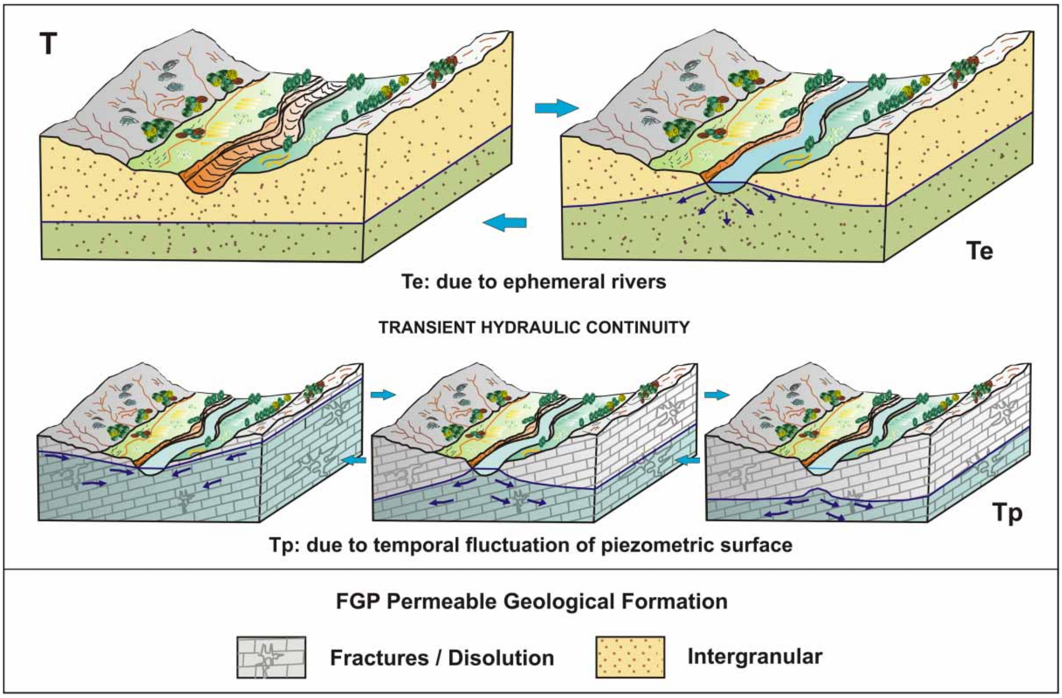

Fig. 5. Transient hydraulic continuity.

Watercourse in underground transient hydraulic continuity with an aquifer (T): Hydraulic continuity and discontinuity between river and aquifer happens alternately, during a certain time. The aquifer-saturated zone is usually very shallow. Two different situations exist (Figure 5), as follows:

- Permanent water courses in which temporal fluctuation (seasonal or occasional) of piezometric surface causes hydraulic discontinuity between surface course and aquifer.
- Ephemeral rivers (seasonal or occasional runoff) connected to an aquifer such that its saturated zone reaches the water sheet when it transports water.

The first can be described as transient continuity by piezometric fluctuation and the second as transient continuity by ephemeral rivers.

Watercourse in multiple underground hydraulic continuity with an aquifer (M): Two or even more of the above situations concur. It could be a gaining river in discontinuity with spring effect and, additionally, presenting hydraulic continuity with a formation on which it is located (and whose piezometric level coincides with the water level of the river).

Third criterion: configuration of the spatial relationship. From a spatial perspective, relationship can be established in different ways depending on the location and extent of the area where the exchange takes place. It can take place through visible emergences or sinks located along the channel, whether isolated or distributed in groups, or can be gradually diffused along the channel.

Spatial configuration of these exchange zones is strongly conditioned by aquifer nature. In detrital ones diffuse relation predominates, whereas in fissured aquifers, punctual (or group) interactions predominate. Because of it there is no morphological configuration characteristic of a particular river section, although, since alluvial plains are more frequent in lower courses and steepest reliefs in headwaters, it is more usual to find diffuse relations in the first case and punctual or group in the second. The importance of this criterion is because it allows critical points in which the relationship is substantiated to be identified, and its implications in terms of vulnerability. It aims, in short, to design actions and adequate protection measures, whether they are springs, sinks or areas with flow losses (or gains) in rivers.

Typology. According to this criterion, four types are defined, according to Gordon *et al.* (1992) and Murillo (2016): localized punctual, localized multiple, diffuse and mixed (Figure 6).

Localized punctual relation (P): It takes place through a single place in a visible form.

Localized multiple (G): Relationship occurs through several points close to each other, or groups of them perfectly differentiable.

Diffuse (D): Gain or loss of river flow cannot be allocated to specific points in the channel, and it is non-visible.

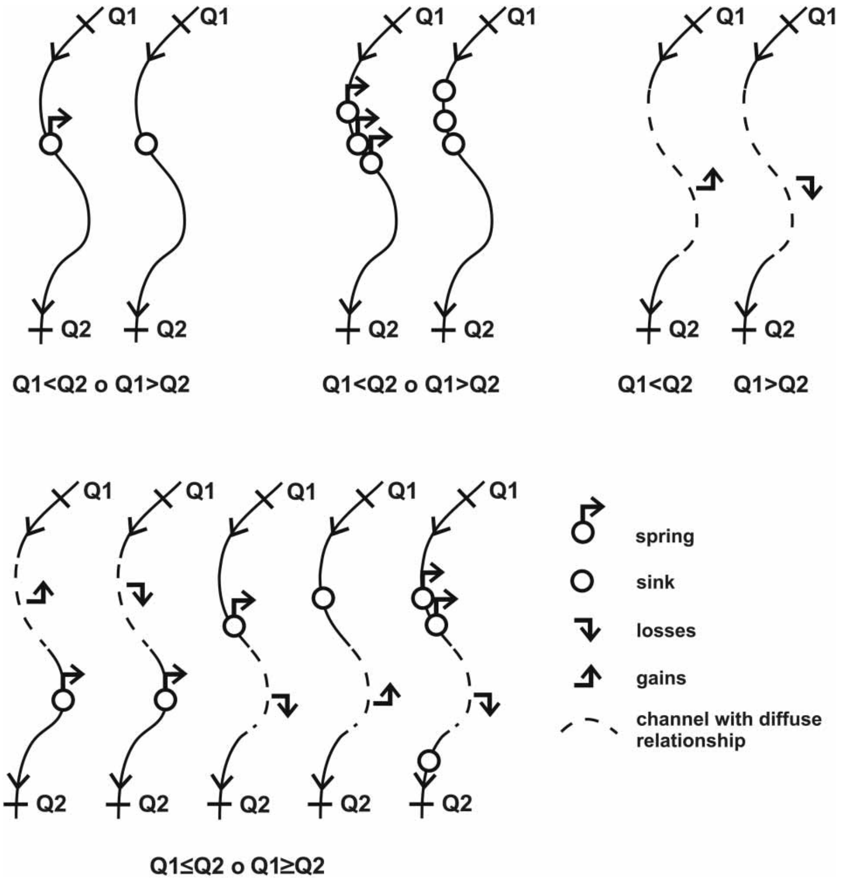

Fig. 6. Spatial relationship.

Table 2. Classification based on volume of exchange.

Order number	Volume of exchange (hm^3/y)	Order number	Volume of exchange (hm^3/y)
1	<1.0	6	25–50
2	1.0–2.5	7	50–100
3	2.5–5	8	100–250
4	5–10	9	250–500
5	10–25	10	>500

Mixed (M): Transfer of water resources occurs in localized and diffuse ways simultaneously. It is the case of a winning channel that, in turn, presents emergences or groups of localized emergences. Likewise, in a channel there can be (at the same time) entirely identified sinks and losses (or gains) not localized, that is, diffuse.

Fourth criterion: volume of exchange. One essential aspect of the river–aquifer relationship is the water volume involved. During the first stages of work, it is of interest to outline the order of magnitude of such exchange. Among other aspects, a quick overview of distribution and magnitude of surface water–groundwater interaction allows planning and selection of priority actions. To achieve this aim, the establishment of ten flow ranges (annual average volumes) are proposed, shown in Table 2.

Zero code will be used for underground flow parallel to the river in which there is no water exchange (underflow), or when the result of the final balance of the exchange volumes is zero or tends to zero.

Fifth criterion: temporal evolution of the process. Water exchange between a river and an aquifer occurs in different ways over time, that is, it can takes place only on certain occasions, depending on hydrological conditions, namely, hydrological regime of the rivers, behaviour of piezometric surface and associated springs to the channel with which they interact.

Knowing the duration of periods in which relationship is established and magnitude of volume involved, provides additional information on specific capacity of river–aquifer interaction (volume exchange/time). It provides indications about infiltration capacity of a riverbed (or part of it). A permanent relationship usually involves a greater volume of resources, while an intermittent one implies the opposite. In a sense, it provides data on aspects of interest in water management, since it allows times to be identified in which there is greater or lesser volume of exchange and, consequently, the possibility of carrying out actions to increase available resources.

Typology. According to this criterion, there are three types of temporal relationship (Figure 7): permanent, seasonal and occasional.

Permanent (P): It is continuous in time. This is the case of rivers and springs in permanent regime.

Seasonal (S): It occurs in springs of seasonal behaviour. This is the case of channels without surface runoff during dry seasons. During high waters, this exchange is established in either direction, by the presence of water in the river, or by elevation of the piezometric level in certain aquifers.

Occasional (O): In dry channels that, in response to exceptional rainfall or rapid thawing, maintain sporadic water exchange with an aquifer for a (more or less) short period. This is the case of ephemeral rivers with fluvial-torrential regime, or fed by rapid-response aquifers that originate sporadic but very important emergences, such as karst with overflow springs, which briefly feed surface courses.

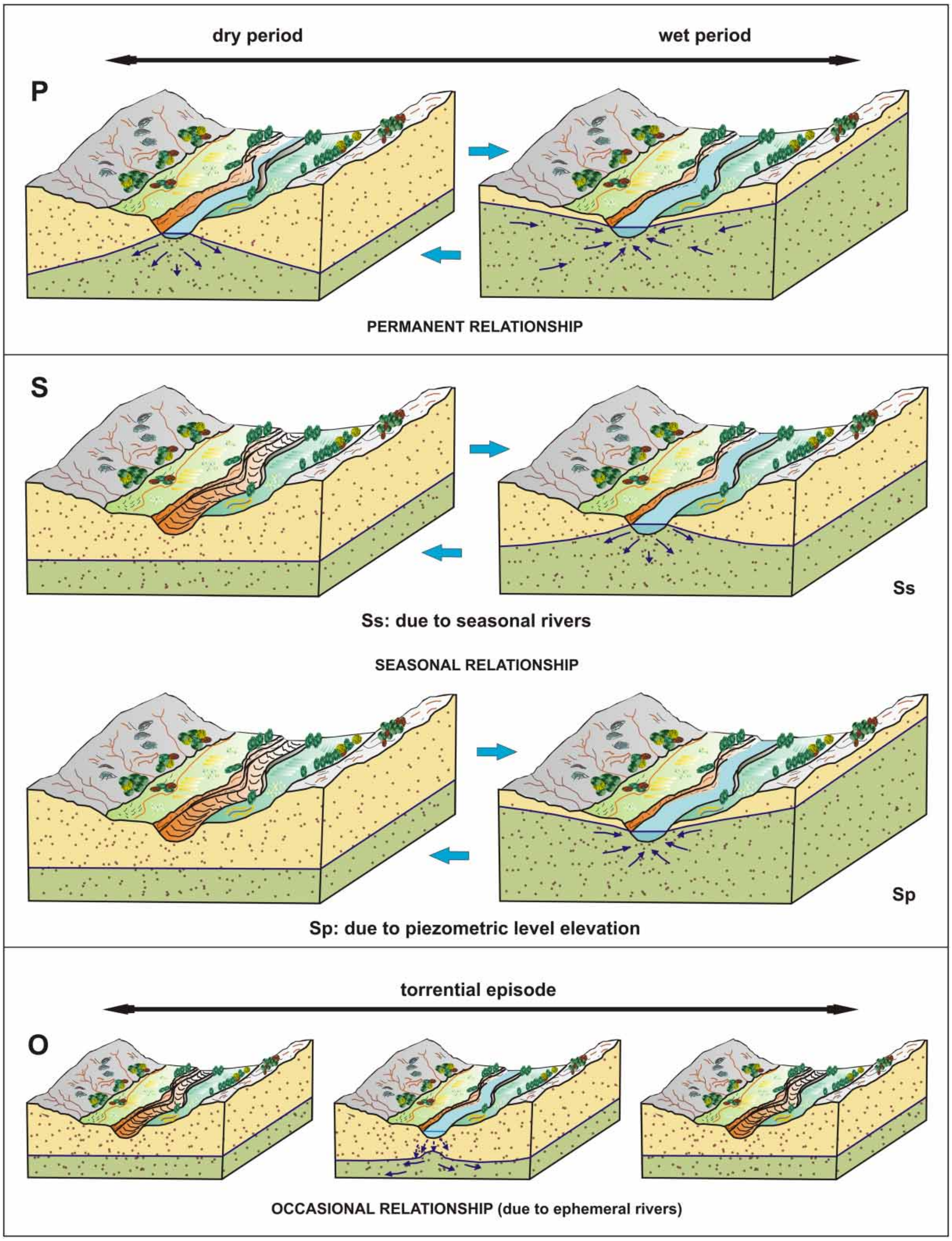

Fig. 7. Classification based on temporality.

As in the previous case, another less usual form of relationship is the one caused by important piezometric fluctuations that allow occasional hydraulic continuity between river and aquifer.

Classification system and codification

The existence of a classification system to characterize river–aquifer relationship in a hydrological basin makes it possible to objectify situations and constraints associated with every case. Among other aspects, it allows the establishment of benchmarks and priority actions to solve problems that may arise. In short, it is an important tool to support decision-making and management of water resources, and very useful in the implementation of specific directives, such as the Water Framework Directive.

Information generated is structured around a typological basis of a few classification parameters. It will also help in the preparation of emergency plans in situations such as droughts or overexploitation, and will be a key indication when assessing potential danger of pollution processes, especially those caused by accidental spills. From another aspect, it is also an important contribution in studies for determination of ecological flows.

Once the different types are defined, a classification of river–aquifer relationship can be established for each channel (or specific section) by assigning an alphanumeric code composed of three letters and an order number associated with another letter, according to the five defined criteria. As an example, two cases follow:

- Typology channel GCD 4P: Effluent channel, in hydraulic continuity with the aquifer through a mechanism of diffuse exchange, which contributes to the river flow between 5 and 10 hm^3/y throughout the year.
- Typology channel LDP 3S: Influential channel with no hydraulic continuity with the aquifer and loses in a concrete point (sink) between 5 and 10 hm^3/y only during the wet season.

As can be seen, this codification makes it possible to characterize and identify in a simple and instantaneous way for each river section: direction of the relationship, hydraulic settings, spatial and temporal form in which it takes place, and order of magnitude of volume of transferred resources. On the other hand, river–aquifer characterization can be established both in natural and influenced regimes, according to the objectives.

In general, code U may be entered for criteria not allocated due to lack of information. It is equivalent to undetermined or unknown criteria. It highlights the need for evaluation or avoids giving unverified information that may lead to improper actions.

Conclusions

Hydrological planning and EU Directives aimed at sustainability of water resources and restoration of good ecological status of water bodies demand studies and methodologies to identify sensitive areas. Obtaining this information helps to establish priorities for action and helps optimize efforts, in terms of both human and economic resources.

Efficient management of water resources must encompass both surface water and groundwater. In this sense, accurately establishing river–aquifer relationships becomes a necessity since, for example, defining river sections that constitute preferential ways to recharge aquifers (or those that behave as effluents) allows management sectorization, establishing areas with greater and lesser possibilities (space–time) of exploitation or, on the contrary, areas in which recharge actions are analysed. In this way, the proposed methodology provides valuable information to stakeholders or experts to serve as a starting point for the application of different strategies aiming to carry out sustainable management, based on simple methods, like indicators, or others more contrasted such as the Delphi method.

In the case of river–aquifer relationship, the absence of characterization, as well as adequate classification systematics, makes studies and work proposals that demonstrate depth in this matter of great interest. Accordingly, concepts like connection and underground hydraulic continuity, used indistinctly so far, have been defined clearly, as well as conditioning factors of river–aquifer relationship: geological, geomorphological, hydrological and hydraulic. In this sense, this paper contributes to fill the gap in some of these aspects and helps to understand the exchange between surface water and groundwater, while establishing, as a result, a generic methodology, based on five elemental criteria to aid in clarification and better visualization of the different processes involved, both as regards availability of resources and ecological status.

Application of the systematic proposal to hydraulic planning will allow having relevant information that can be used as a tool to support decision-making, for management of water resources and requirements for actions in emergencies (droughts, floods, etc.) or any circumstance that may endanger good groundwater status or cause risk to populations.

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