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REVIEW ARTICLE

What maintains the waters flowing in our rivers?

Rethinking hydrogeology to improve public policy

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Abstract This article discusses how new contributions from hydrogeological science in the 20th and 21st centuries have allowed for a better understanding of the processes that affect the maintenance of river flows. Moreover, the way in which this knowledge has been conveyed beyond academia and has been gradually incorporated into public policy for natural resource management is also discussed. This article explains the development of several approaches used to understand the relationships among the management of aquifers, vegetation and river flows, including water balance, aquifer recharge, the piston effect, seasonal effects, and safe and sustainable yields. Additionally, the current challenges regarding the modeling of hydrological processes that integrate groundwater and surface waters are discussed. Examples of studies applied in Brazil that demonstrate these processes and stimulate thought regarding water management strategies are presented. In light of the case studies, it is possible to propose different strategies, each adapted for specific hydrogeological context to maximize aquifer recharge or base flow maintenance. Based on these strategies, the role of infiltration ponds and other artificial recharge techniques is re-evaluated in the context of the mitigation of environmental impacts on the maintenance of river flows. Proposals for the improvement of public policies regarding the payment of related environmental services to stimulate investment in aquifer recharge and the maintenance of base flow, for which the goal is to attain win–win–win situations for the environment, farmers and water users, while preventing land speculation, are discussed. Lastly, a conceptual model for the dissemination of hydrogeological knowledge in public policies is provided, and its challenges and possibilities are discussed.

Keywords Hydrology · Hydrogeology · Environmental management · Public Policies · Water resources management

Introduction

The human need for water for drinking and production purposes has been a primary motivation for the study of water resources since the beginning of civilization. Although naturalists have studied water processes in natural environments for centuries, and practical builders have acquired the empirical knowledge necessary to provide the water needed by society throughout human history, hydrology was first recognized as a specific academic field after the seventeenth century (Jones and McDaniels 1963). Since that time, hydrologists have developed its mathematical and experimental principles based on the results of hydraulic studies initiated by physicists, thereby increasing the technical knowledge necessary to create water works for surface and groundwater supplies (Bras 1999; Dooge 2004). Later, in the 20th and 21st centuries, a dramatic increase in the amount of systematic data available and the modeling capabilities of computer systems enabled further advances in the understanding of hydrological processes.

However, to understand the earth's water cycle, the study of water alone is not sufficient. Because water circulates through the earth's atmosphere, biosphere, soils and rocks, it is necessary to understand how these systems absorb,

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store and release water. To advance these frontiers, hydrology has interacted with many other sciences (Jones and McDaniels 1963, p. 3), including meteorology, climatology, geology, geomorphology, agronomy and biology. In accordance with this broad scope, in the twentieth century, hydrology was formally defined as "the science that treats of the waters of the Earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things. The domain of hydrology embraces the full life history of water on the Earth" (Federal Council for Science and Technology 1962, p. 2).

A specific aspect of the water cycle has intrigued many researchers throughout history: what feeds rivers after runoff from rainfall has ceased? Homer (1000 BCE), Thales (650 BCE) and Plato (427–347 BCE) suggested that water from oceans flowed to mountain springs in underground channels, whereas Aristotle proposed an alternative explanation: atmospheric vapor in underground caves condenses, which results in capillary flow through fine veins, leading in turn to springs (Todd and Mays 2005, p. 3). Vitruvius (27–17 BCE) proposed a connection between precipitation, water infiltration and stream flows, stating that forest shade protected streams from evaporation. Pliny the Elder (77–79 CE) recognized the relationship between the evapotranspiration of trees, changes in land use and water flow in springs (McGuire and Likens 2011, p. 3–4). Tolman (1937) reported the popular belief that underground rivers fed surface springs, which was common before the twentieth century. The veracity of the theory of groundwater infiltration was the subject of an intense debate among academics from the seventeenth century to the early nineteenth century (Meinzer 1934, p. 12). After the nineteenth century, the development of geology and its dialog with hydrology provided a basis for the understanding of water storage and flow in the pores of soil and aquifers.

During the twentieth and twenty-first centuries, global economic development has increased the demand for water resources, particularly in growing urban centers and for irrigation. In addition, the environmental impacts of pollution and changes in land use have resulted in alterations in the water cycle, often in unforeseen ways. The need to manage water resources emerged in many public policies that were aimed at mediating conflicts and planning sustainable water use. Faced with these challenges, research on the relationships between river flows, groundwater and changes in land and water use has improved our understanding of the processes related to the maintenance of river flows. As the consensus among academic groups has grown, the transmission of that knowledge to society has occurred in various ways, which has influenced how certain groups have dealt with environmental conservation and natural resource management.

The objective of this article is to re-examine these developments while addressing the challenges to the dissemination of hydrogeological knowledge and the sustainable management of water resources. A review of the history of hydrogeology before the twentieth century is beyond the scope of this article. Rather than undertaking a general review of the state of hydrogeological knowledge, this paper focuses on the emergence of selected concepts and paradigms regarding the relationships between aquifers, vegetation and rivers, particularly those that significantly influence current water management policies, such as water balance, aquifer recharge, the piston effect, seasonal effects, and safe and sustainable yields. Using examples from Brazil, this article discusses these hydrogeological theories and investigates how they can be used in water management policies. As a conceptual contribution of this article, the analysis of these cases leads to a discussion of new opportunities for the use of public policies to mitigate the impact of human activity on groundwater flow by intervening to increase rainfall infiltration and methods of stimulating sustainable water infiltration that are based on payments for environmental services. Lastly, a conceptual model of the dissemination of hydrogeological model in public policies is discussed, using a multidisciplinary approach to address its challenges and potentialities.

Interlinking riparian vegetation, aquifer recharge and discharge and public policies for land and water use

Environmentalist movements and the conservation of rivers

Social concerns regarding environmental conservation and ecology began to intensify in the 1960s (Gonçalves 2008). Among the concerns regarding the conservation of forests and wildlife, concerns about air and water pollution were also present. Although the terrestrial environment has more often been the banner of environmental movements, the aquatic environment has gained some degree of attention. The concern with "saving our rivers" has been especially associated with preserving the native vegetation surrounding springs, rivers and lakes. Therefore, several countries have developed legal mechanisms and public policies that protect riparian vegetation and wetlands or stimulate their regeneration.

The spatial contiguity between riparian vegetation and rivers has facilitated the transmission to the public that the "health" of rivers depends on this vegetation. In addition, there have also been frequent popular narratives stating that streams and rivers that were once had abundant water are drying, which is possibly due to deforestation (Santos et al. 2006). Popular narratives play an important role in the social dissemination of environmental concerns, but these narratives make it difficult to separate the hydrological fact of flow reduction from the utopian position that could impart favorable appearances to an idyllic past in contrast with the current challenges presented by the narrators. It is also interesting to note that the popular perception of the "death" of rivers is, in many cases, due not only to reduction in water flow, but also in large part to the sedimentation of riverbeds, even if there is water in embedded in the sediment layer added to the riverbed. Further, such phenomena are usually undifferentiated in personal narratives. Nevertheless, this concern has led to the initiation of several academic studies seeking evidence for the causes of these environmental impacts in light of the hypothesis of decreased river flow, as discussed in the following sections of this paper. These studies have provided new contributions to the understanding of hydrological processes.

Water balance and aquifer recharge

As the understanding of hydrogeological processes has been developed and disseminated during the second half of the twentieth century, more attention has been paid to the importance of the understanding of the contribution of groundwater flows to the maintenance of rivers and springs, particularly during dry seasons. This concept was combined with the idea that the hydrological cycle could be understood through the "water balance" as an accounting between input and output of water in its surface flow, subsurface flow (soil) and deep flow (aquifer) systems. Water isotope analysis corroborated the hypothesis that water moved more slowly in aquifers than in surface runoffs, emerging into rivers after periods of up to thousands of years (Balek 1988). Because of the slower flow rate from aquifer discharge, river flows were ensured during dry seasons, when the influence of surface runoff had ceased.

Interestingly, in the most simplistic water balance diagrams, it became the convention to consider vegetation to be an element that removes water from circulation through evapotranspiration. From the perspective of the amount of flow within the water system, vegetation would be a negative element, although from the perspective of water quality, vegetation would still play an important role as a buffer against the contamination and sedimentation of watercourses. In addition, the ecological value of the native vegetation and its role in sustaining native wildlife were not diminished.

There has also been concern regarding the impacts of changes in land use (such as deforestation and its replacement by pastures, crops or urban areas) on the separation between infiltration flow and surface runoff. The decrease in the infiltration of groundwater due to certain changes in the soil cover also decreases the aquifer flow in rivers, at times even reversing the flow; i.e., the river could start losing more water to the aquifer to balance the water deficit in the latter. Although any surface that is not impermeable can contribute to the recharge of subsurface and groundwater flows, there are certain areas with special environmental characteristics that are more important for the recharge of aquifers, such as flatter areas, sandy and deep soils, areas over porous aquifers and areas with less soil compaction, among others (Vasconcelos 2013b). From a watershed perspective, aquifer recharge processes predominate in more elevated areas, whereas in the areas near springs and rivers, the recharge processes predominate. Between these two areas, there can be sections in which neither of these two processes predominates; instead, the transport of groundwater flows predominates (Souza and Fernandes 2000). Therefore, in both the technical field and academia, by convention, certain spatial portions are designated as "recharge areas", which deserve special attention regarding the maintenance of water infiltration processes (Martins Junior et al. 2006).

However, another turn of thought was yet to come. Based on the hypotheses proposed by Beven (1989), Kirchner (2003) analyzed the variation in geochemical dating tracers along rainfall post-event periods and observed that most of the immediate post-rain flow increase consisted of "old" water from the deep aquifer and not, as conventionally expected, water from the surface or subsurface runoff. Furthermore, after a rainfall event ceased, most of the flow consisted not of water from the deep aquifer, but of water from the subsurface soil flow. Kirchner's interpretation, which is called the "piston effect", states that, similar to a system of communicating vessels, precipitation in the recharge areas of the basin causes pressure on the aquifers, which directly effects on their discharge into rivers. In turn, in valley lowlands, clay soils with more organic matter cause the subsurface flow to be slower and diluted over a longer period of time. The proposal by Kirchner (2003) was later corroborated by the study of Gonzales et al. (2009).

Seasonal influence of vegetation on watercourse flows

Throughout the second half of the twentieth century, several studies were conducted at both the soil profile and watershed scales that sought to improve the understanding of and to quantify the effects of vegetation and changes in soil use on river flows. In addition to the simplified water balances estimated for one hydrological year as a reference time unit, these new studies have shed light on seasonal effects and the effects of even finer time scales. Such detailing at the temporal scale has fundamental importance in water management because in periods of greater rainfall, the maximum flow rates can cause damage by flooding, while in dry seasons, the minimum flow rates are the most critical period for allocation among the several demanded water uses.

After an extensive literature review of the studies on the influence of forests and deforestation in seasonal river flow, Bruijnzeel (2004) summarized the key findings. The various studies corroborate the hypothesis that forests in a successional climax state consume a portion of the waters in the annual hydrological cycle due to evapotranspiration, but ensure greater flow during the dry season because they allow greater water infiltration into the soil and contribute to the increase of soil organic matter. Soils with greater organic matter content can retain up to 20 times more water than soils without organic matter (Shaxson and Barber 2003), and this water is released more slowly in subsurface flows. Changes in vegetation cover from forests to other types of vegetation or soil use tend to increase annual river flows, but decrease the flow during dry seasons. In contrast, Bruijnzeel (2004) noted that in vegetation in early successional stages, when the specimens are still undergoing accelerated growth, the demand for water via evapotranspiration and incorporation into plant tissues is much higher and can reduce the flows even during dry seasons.

Later, Wickel (2009) and Wickel and Bruijnzeel (2009) presented new syntheses of experiences that corroborated these hypotheses and extended the focus of the hypotheses proposed by Bruijnzeel (2004) from forests to other forms of native vegetation. The conceptual model described by these authors is that every form of native vegetation would naturally be adapted to function within the hydrological cycle of the land (within their surface and groundwater processes) and that human intervention on this native vegetation would negatively impact the hydrological cycle.

The conclusions of Bruijnzeel (2004), Wickel (2009) and Wickel and Bruijnzeel (2009) have contributed to the understanding that the preservation of riparian vegetation can help to sustain river flows during dry seasons, which opposes the concepts of simplified water balances in which these forests would always have a negative effect due to evapotranspiration. Interestingly, the legal and administrative instruments designed to protect riparian vegetation and wetlands are again, in this conception, important for the maintenance of the hydrological cycle during dry seasons.

Considering the effect of groundwater use on river flows

Discovering that groundwater moves

In parallel to the research on the effect of vegetation on the hydrological cycle, another line of research was developed regarding the management of groundwater use and the effects of that use on river flows.

Throughout the 19th and early 20th centuries, groundwater was legally treated in the same manner as mineral resources. In the laws of several countries, such as India (Cullet 2006, 2007), the owner of a piece of land had rights over the waters that were underground. In other countries, such as Brazil, where mineral rights were detached from soil property rights, the exploitation of groundwater for commercial purposes was also regulated by the institutional agency that granted rights for mining exploration.

Over the last decades, the legislation concerning surface water resources has increasingly considered the integrated drainage network character of such resources and the need to consider public welfare (such as ensuring urban water supply or the basic human right to water) above private assets. However, the rights to groundwater, as well as the effects of its interaction with surface waters, were usually associated with the rights to surface water for two reasons. First, conflicts over water use were typically initiated by the depletion of surface waters, which are easier to capture. Second, the dynamics of groundwater circulation have been harder to understand and monitor, which makes it difficult to regulate. An example of the persistence of these contrasting approaches in the management of surface and groundwater is that in many countries, including Brazil, the laws on surface water basins that cross internal federal units (more than one state) attribute management to the Union (the federal government), but the management of groundwater remains restricted to State management (Vasconcelos et al. 2013a).

As the view that groundwater moves from one part of the landscape to another was consolidated, along with the view that uptake in one part of the landscape affects the other parts, technical procedures and legal mechanisms were developed to resolve these conflicts. The most basic procedures consist of testing the effect of interference on well yields in cases in which wells are to be installed near existing wells. Although such tests provide information to understand the interaction between two wells, the tests still do not enable an understanding of the effect of extractions on aquifers, the ecological impacts of wells or their interaction with surface water resources.

Modeling and managing aquifers in their interaction with rivers

As the geological and hydrogeological knowledge base has expanded, it has become possible to identify certain aquifer sets in which systems of rocks that bear water could be incorporated into water-balance calculations. In addition, the monitoring of these aquifers has shown that, in many cases, groundwater was being over-exploited, leading to the decline of groundwater reserves.

Based on the water-balance paradigm, the simplest models maintained the input of water into the aquifer (from rainfall) as constant averages, and the users of wells should then be limited to annually withdrawing only what could be recharged by rainfall, a limit defined as "safe yield" (Lee 1915). Thus, the depletion of groundwater reserves was prevented. These were the first groundwater management models, which were typically developed by new departments within the government institutions that already managed surface waters.

These groundwater management models were harshly questioned by Bredehoeft et al. (1982) in the article "Groundwater—The water-budget myth". Using the theoretical bases of the water balance themselves and comparing them to the existing groundwater modeling equations, these authors showed how, if the recharge from rainfall remained constant, the use of groundwater in general would eventually lead to a corresponding decrease in the waters that flowed from the aquifers to the rivers or to ecological impacts on the riparian vegetation that uses the subsurface waters for evapotranspiration. In this process, as illustrated in Fig. 1, the wells initially affect the drawdown of the aquifers more strongly, but gradually begin to exploit the water flowing in rivers. However, for management purposes, it is important to note that this process, depending on the water transmission speed in the aquifer and the proximity between the well and the river, could take from a few days to thousands of years.

Thus, in a watershed already subject to conflicts over the use of surface water, the exploitation of groundwater would decrease the river flow even more and thus exacerbate these conflicts, in addition to aggravating the environmental impacts on riparian vegetation (Fig. 2). Therefore, the need for joint management of groundwater and surface water became clear. Sophocleous (2000, 2012) reported how Kansas was a pioneer in this integrated management, developing a management system that, to obtain minimum desired flow rates in the watercourses, jointly managed the groundwater and surface water extraction rights.

Thus, the discussion of groundwater management showed that it was necessary to go beyond the concept of "safe yield" and embrace a new concept called "sustainable yield". Beyond preventing aquifer drawdown, the extraction of groundwater should now consider the maintenance of the river flows and riparian vegetation, as well as the economic and social effects of different extraction scenarios (Alley and Leake 2004). From a managerial perspective, sustainable yield should no longer be defined simply based on quantitative water modeling, but instead by a participatory process in which the various users enter into an agreement regarding the possible uses of water resources and their various environmental, social and economic impacts over different time horizons (Maimone 2004). Interestingly, this broadening of the "safe yield" to the concept of "sustainable yield" was concomitant (and in dialog) with the expansion of the concept of "water management" to "integrated management of water resources", which also gradually began to incorporate an approach that integrates the management of surface water, groundwater and the interactions of these water resources with other environmental, economic and social systems (Al Radif 1999; Thomas and Durham 2003).

Challenges for the construction of hydrological-hydrogeological models

The effectiveness of the integrated management of groundwater and surface water resources depends largely on the technical and operational feasibility of building reliable models that incorporate the entire water system,

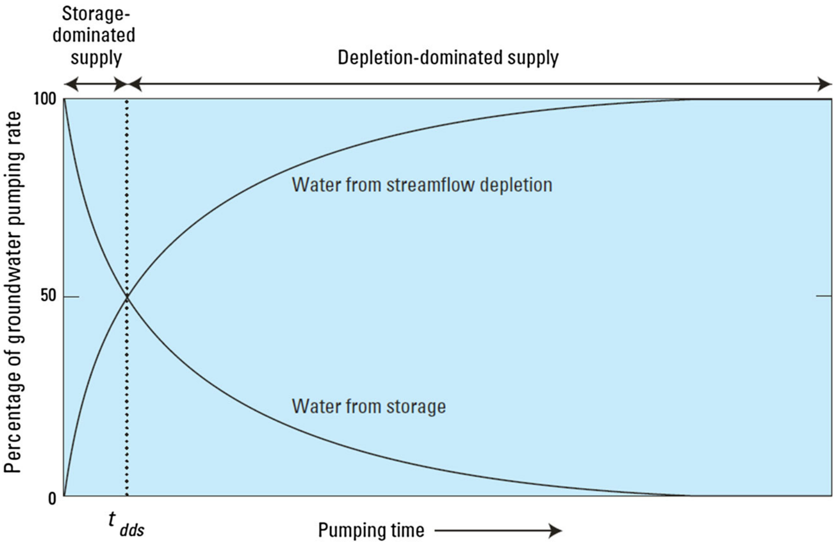


Fig. 1 Relationship between the depletion of groundwater reserves and river flows over the life of a well. Source: Barlow and Leake (2012, p. 14)

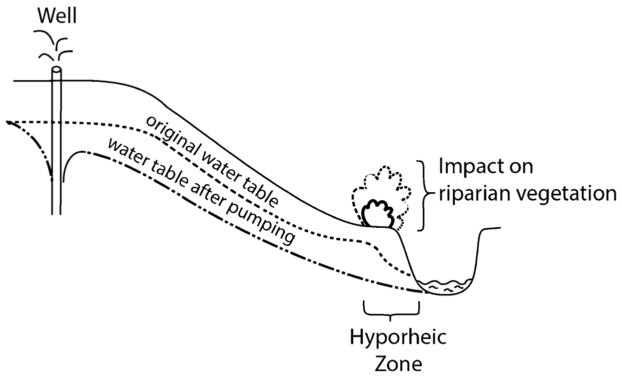


Fig. 2 Long-term impact of groundwater extraction on the water table and riparian vegetation. The water table level is a simplification, and shows the average level rather than seasonal variation. In the figure, the aquifer level after pumping decreases below the river water level; then, instead of sending water to the river, the aquifer begins to receive water from the river. When going through riparian vegetation, the average groundwater level decreases due to evapotranspiration by hydrophilic plants (Sophocleous 2002), although, as noted by Wickel and Bruijnzeel (2009), the riparian vegetation contributes to maintaining a minimum river flow rate during the dry season

integrating both surface water and groundwater. Originally, the groundwater models were usually built using assumptions for porous and homogeneous aquifers, making it difficult to apply these models to aquifers in fractured or karstic rocks. In addition, the simplest models assumed a direct connection with rivers, i.e., not considering clay deposition on riverbeds, which hinders the interaction between these rivers and the aquifers.

As the models evolved, they began to incorporate several optional modules that propose to model aquifer heterogeneity (such as barriers or changes in properties along the aquifer) as well as its interaction with the heterogeneity of the riverbed material. However, as these models become more complex, they begin to require detailed field information, which in many cases was operationally unviable, and such information was often replaced by more assumptions, estimates and calibrations, making the model results very unstable (and consequently less reliable) (Vermue 2009). Konikow (1986) and Balleau and Mayer (1988) demonstrated how different modeling options can generate completely different results in models of interaction between groundwater and surface waters.

In addition, the construction of these models is based primarily on the knowledge of hydrogeologists, focusing on the hydraulic aspects of rocks and sediments, but paying little attention to the interaction with ecosystems, particularly hydrophilic and hygrophilous riparian ecosystems. Sophocleous (2002) indicated how the lowering of the water table and decrease in flow in soils near rivers (called the hyporheic zone) causes ecological damage to riparian vegetation. Combining this conception with the studies by Bruijnzeel (2004), Wickel (2009) and Wickel and Bruijnzeel (2009), it can be seen that the degradation of riparian vegetation reduces the organic matter content in these soils and leads to an even further decrease in the ability to maintain river flows during dry seasons.

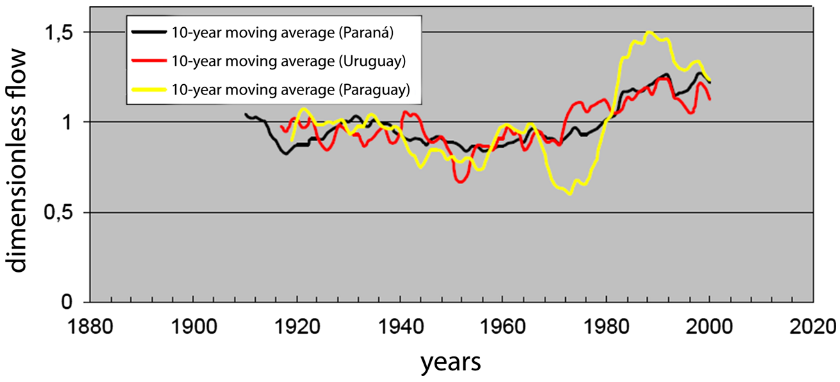
Discussion of Brazilian case studies

The purpose of this section is to illustrate selected case studies of the processes discussed in this article. The results of studies conducted in Brazil are analyzed using the concepts and theories presented in the earlier sections of this article.

Tucci (2002) revealed that, consistent with the proposals of Bruijnzeel (2004), the progressive deforestation of the international Prata River basin after the 1960s, with replacement by seasonal crops, increased in the annual average flow of its sub-basins (the Paraguay, Uruguay and Parana Rivers) (Fig. 3). The study attributed part of these effects to the changes in land use and partly to climate variability. This study is important because Bruijnzeel (2004) warned of the lack of studies investigating the effects of vegetation on the flow of watercourses at large temporal and spatial scales.

Another relevant study was conducted by Neves (2011), who monitored the flow rate of *veredas*, a type of hygrophilous riparian vegetation typical of springs in the Cerrado

Fig. 3 Ten-year moving average of the flow of the Paraguay River in Pilcomayo, Uruguay River in Paso de Los Libres, and Paraná River in Posadas. Adapted from Tucci (2002)



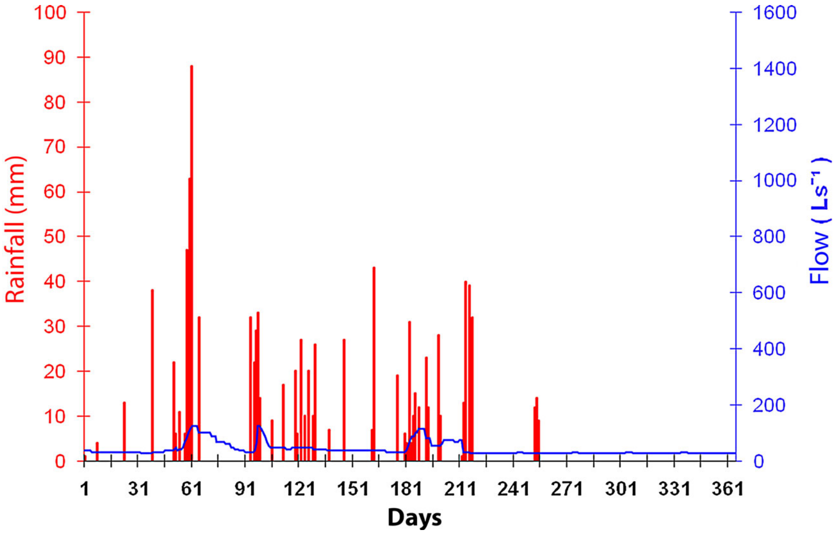


Fig. 4 Flow rates of a non-degraded vereda in response to rainfall events. Almescla Vereda, Pandeiros Environmental Protection Area, Minas Gerais, Brazil, hydrological year of September 2009 to August 2010. Source: Neves (2011)

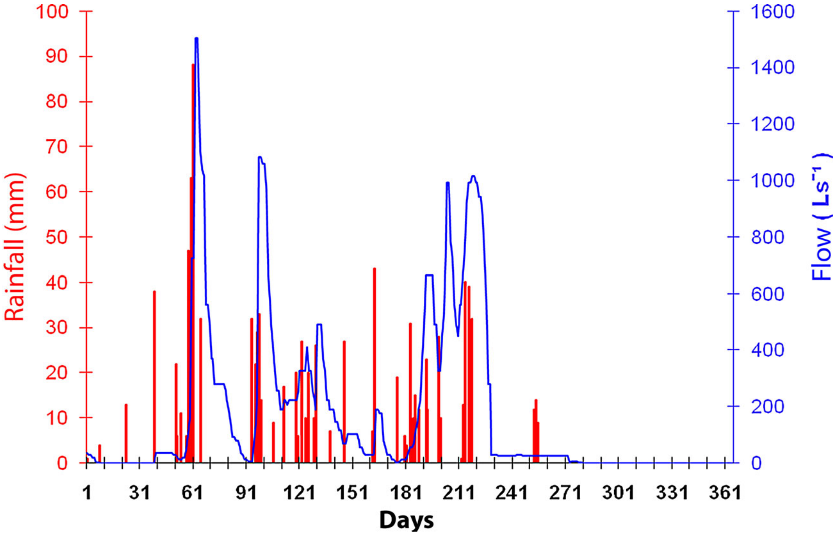


Fig. 5 Flow rate of a degraded vereda in response to rainfall events. Pindaibal Vereda, Pandeiros Environmental Protection Area, Minas Gerais, hydrological year of September 2009 to August 2010. Adapted from Neves (2011)

biome (Brazilian savanna). Daily monitoring of the flow of degraded and non-degraded veredas (Figs. 4 and 5) showed that although a non-degraded vereda has an annual flow several times lower than a degraded vereda, a non-degraded vereda can maintain an average flow rate of 3 l/s during the dry season, whereas a degraded vereda does not flow during virtually the entire dry season. The comparison of the two graphs allows an inference of how a large portion of the rainfall flow in the conserved vereda is consumed by vegetation evapotranspiration, although the conserved vereda also maintains the base flow during the dry season. The flow comparison studies of degraded and non-degraded veredas conducted by Maffia et al. (2009) and Pereira (2010) also described a similar pattern. Although these studies were conducted in small spring watersheds that were not subject to flooding, the contributions of these changes to the spring flow in a larger watershed comprising many of these degraded springs could lead to a significant intensification of flood hazards.

Figures 6, 7, 8, 9, 10, 11 illustrate the effect of soil texture and its organic matter content, as well as of the rock matrix texture of the aquifers, on river flows during the dry season for the Minas Gerais State in Brazil. Note the contrast between the two types of geosystems in northwestern and southern Minas Gerais. On one hand, in the northwest, the porous aquifers of sandstone and unconsolidated sandy sediments generate soils with medium to sandy textures and little organic matter, forming geosystems that, despite having the wells with the highest yields, have low specific yield contributions to the rivers during the driest periods ($Q_{7,10}$—lowest yield for a period of 7 days with recurrence of 10 years). On the other hand, in the south, over fractured granite, gneiss and schist aquifers, the yield of the wells is minimal, but the soils have a more

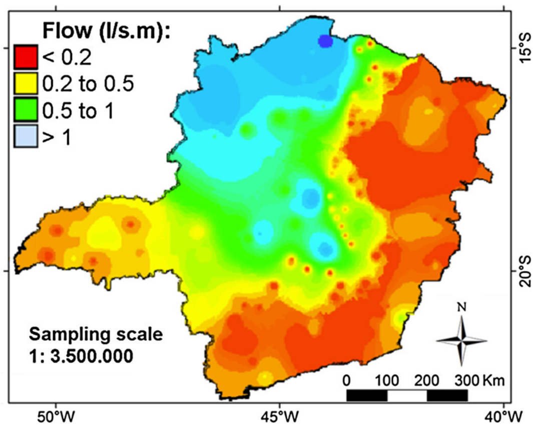


Fig. 6 Yields of wells in the state of Minas Gerais. Adapted from Ramos (2006)

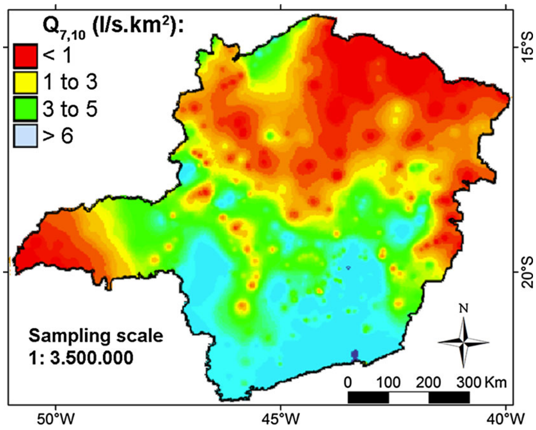


Fig. 7 $Q_{7,10}$ for the rivers in the state of Minas Gerais. Adapted from Ramos (2006)

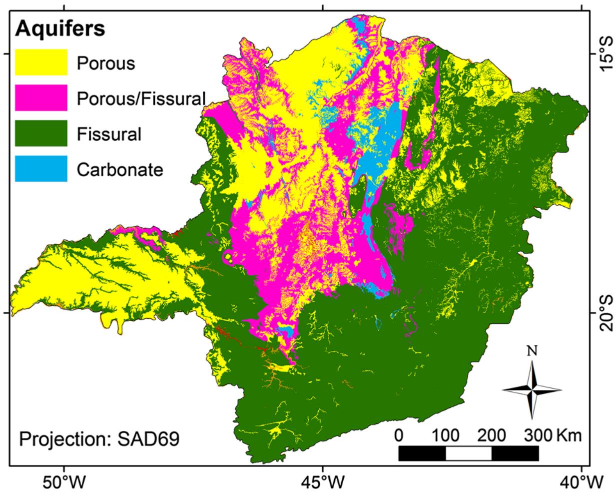


Fig. 8 Rock systems bearing aquifers in Minas Gerais. Adapted from Bomfim (2010)

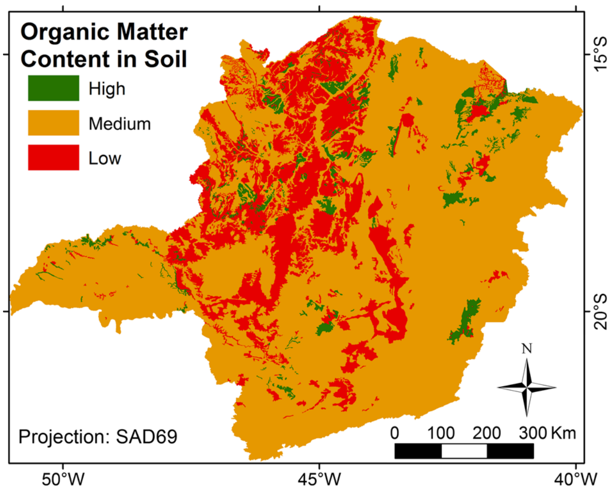


Fig. 9 Organic matter content in the soils of the state of Minas Gerais. Adapted from Minas Gerais (2007)

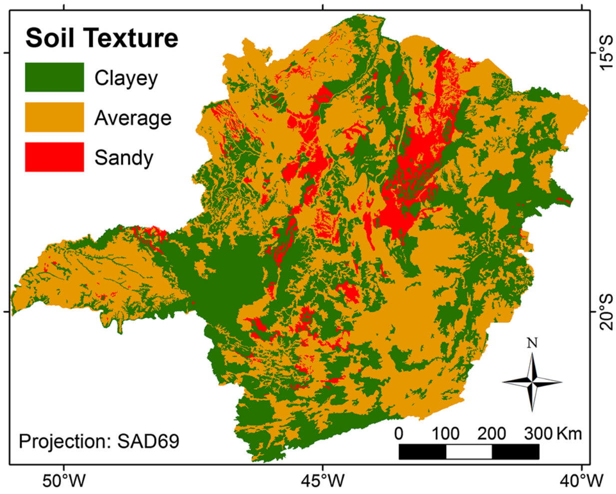


Fig. 10 Soil textures of the state of Minas Gerais. Adapted from Minas Gerais (2007)

clayey texture, more organic matter and a much higher $Q_{7,10}$. The northern and northeastern areas of the state have fractured aquifers and low rainfall, generating low capacity in both well yields and $Q_{7,10}$. In the far western part of the state, in addition to lower rainfall, porous aquifers form the recharge area of a much broader regional aquifer (the Guarani aquifer), resulting in high infiltration of the relatively abundant rainfall, but little contribution to rivers and little accumulation in local aquifers that could be viable for well exploitation.

Finally, the study by Vasconcelos (2014) in the Paracatu River Basin, in northwestern Minas Gerais, provides evidence of some interesting hydrological processes. Recursive signal filters were used to separate the quick flow

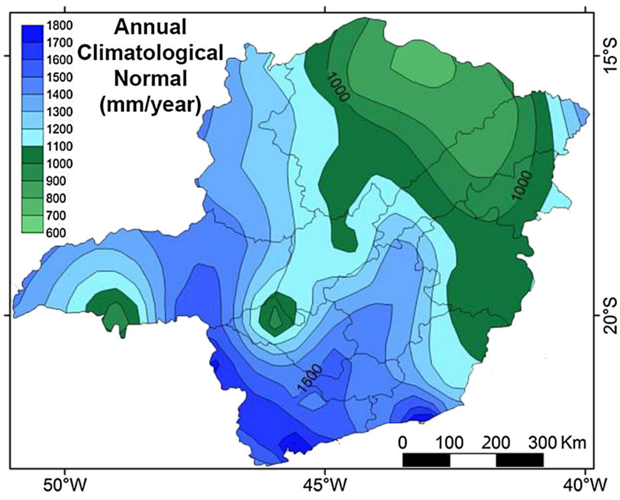


Fig. 11 Rainfall in the state of Minas Gerais. Annual Climatological Normal. Adapted from IGAM (2014)

(immediately post-rain), interflow (first weeks after the rain) and base flow (subsisting on the dry semester) patterns in nested sub-basins, subsequently dividing the flow rate values by the area of each section of the sub-basins to understand the differences in the specific flow of each section for each type of flow (Fig. 12). Comparing the geo-environmental characterization of the basin (Figs. 13, 14, 15), the areas with quartz-sand neosols over deep sandstone porous aquifers, though potentially the areas of highest rainfall infiltration, also provided the greatest contribution of quick flow to the rivers (followed closely by the areas with karstic aquifers), whereas areas with clayey oxisols and cambisols over fractured shale aquifers contributed the greatest maintenance of the base flows of the rivers. These patterns show coherence with the framework proposed by Kirchner (2003) for the piston effect and low flow contribution of clayey soils.

Rethinking the management of water infiltration

The analysis of Figs. 6 and 15 indicates that each type of geoform, soil, rainfall, or rock-bearing aquifer has different water use management potentials and needs. From a regional planning perspective, projects with greater groundwater use could be preferentially installed in areas with greater infiltration potential and deep, porous aquifers, ensuring the sustainability of groundwater reserves. In contrast, the sustainable management of land and water use becomes a priority in areas with clayey soils and rocks to avoid conflicts involving activities that depend on the flow during the dry season, such as irrigation and run-of-river hydroelectric plants.

In both areas of higher infiltration favorability and those where there is greater contribution to the base flow, the effects of soil and water management actions, including rainwater infiltration and retention dams, tillage and/or level planting and terracing, can be better used with an integrated management strategy for land use and groundwater and surface water resources.

However, as a transition between the initial paradigm of appreciation of recharge areas and the subsequent paradigm of the “piston effect”, actions such as the implementation of rainwater infiltration and retention techniques would be more relevant from the perspective of recharging the aquifer than for the maintenance of the base flows. Nevertheless, several monitoring studies of infiltration ponds[1] have shown that the retention of water typically lasts only a few weeks after the rainfall event. However, in the long term, the vegetation (natural or exotic) downstream of these dams becomes denser because of the extended availability of water and contributes more organic matter to the soil, which indirectly improves the base flow of the rivers during dry seasons (Barros 2006). The two complementary approaches are illustrated in flowcharts A and B (Fig. 16).

In this article, combining the concepts presented, we propose the possibility that the impacts of well exploitation on the base flow of rivers can be mitigated by the construction of infiltration ponds located between the well and the surface water body. This mitigation design becomes particularly useful in basins where there is already conflict over the use of surface water and groundwater. The mitigation design is shown in Fig. 17, in analogy with the impact of the extraction shown in Fig. 3. The number of infiltration dams to be built, along with their sizes, should be proportional to the amount of extracted water, but the exact number required to remedy the wells’ effect varies in each context according to the amount of water infiltrated in the ponds, which is a function of the rainfall volume captured, the soil type and the vegetation type. Other techniques to increase infiltration, such as terracing, could be used in an analogous manner.

Another instrument of interest for the joint management of land use and groundwater and surface water use is payment for environmental services. Although environmental payment arrangements directed to the maintenance of water sources for urban use of metropolises such as New York and São Paulo have shown some success (Kane and Erickson 2007; Padovezi et al. 2012), several attempts to use payment for environmental services in which the government compensates landowners for the simple conservation of native vegetation (i.e., without a previous delimitation of a specific user of the environmental services) have been

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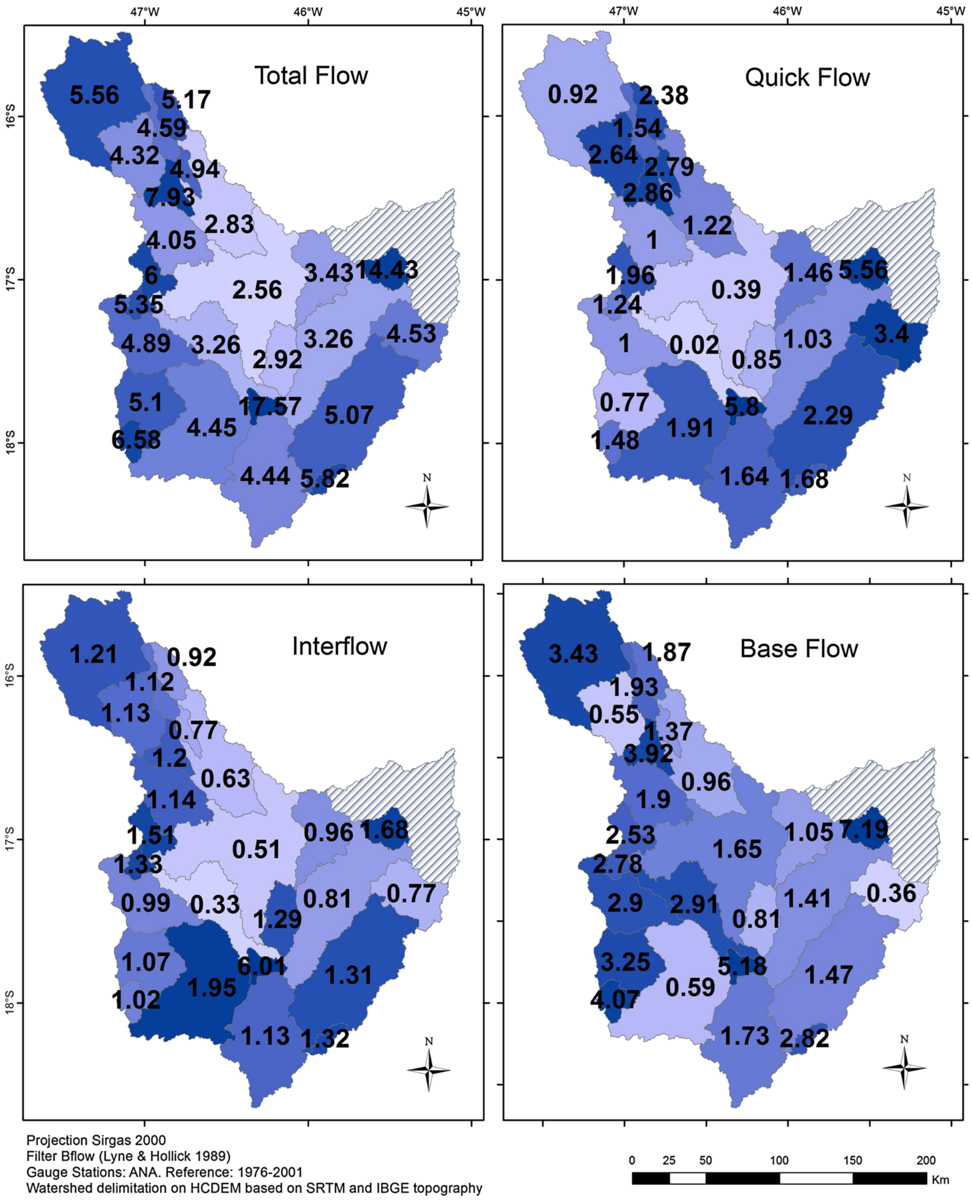
[1] The infiltration ponds discussed in this article are artificially carved ponds built to collect surface runoff during rainfall events and then to allow the water to slowly infiltrate the soil.



Projection Sirgas 2000
Filter Bflow (Lyne & Hollick 1989)
Gauge Stations: ANA. Reference: 1976-2001
Watershed delimitation on HCDEM based on SRTM and IBGE topography

Fig. 12 Specific flow rates of sub-basins in the Paracatu river basin, for total flow, quick flow, interflow and base flow

discredited or have stagnated in Brazil (Paolucci 2013) and other countries (Pattanayak et al. 2010), due to the low level of awareness of the population and the government regarding the cost-effectiveness of these programs. To counteract this, one interesting arrangement would require the landowner receiving the payment for the conservation of native vegetation to invest it in water and soil conservation infrastructures (Jourdain et al. 2014), such as terracing and infiltration ponds. This way, the farmer benefits from an improvement in productivity per hectare, while the other water users benefit from both aquifer recharge and the maintenance of the river's base flow. In addition, this arrangement avoids paying for environmental services to speculators who are not interested in producing on the land and would leave it unproductive even if they were not receiving payment for the environmental services. Finally, targeting these programs at areas that are already in conflict over water use would help to garner popular support to continue these programs.

Dissemination of hydrogeological knowledge

The diagram in Fig. 18 illustrates a simplified way of discussing the dissemination of hydrogeological knowledge, where academic hydrogeological research is gradually incorporated by broader societal groups.

However, the diagram in Fig. 18 does not represent a one-way linear path of knowledge dissemination. As discussed by Vasconcelos et al. (2013a), much of the

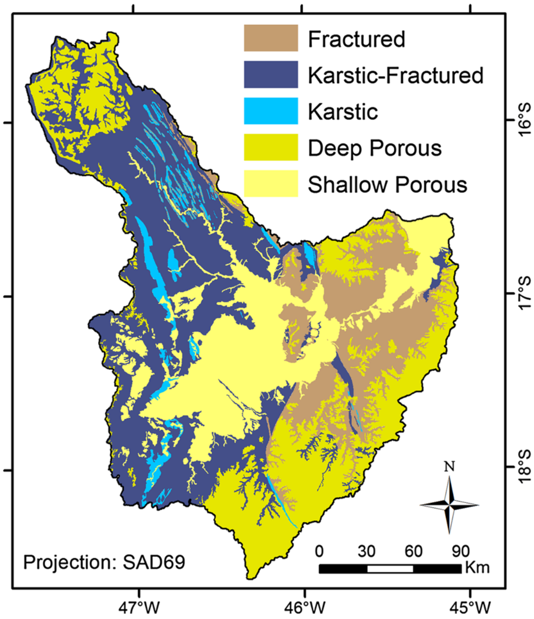


Fig. 13 Rock systems bearing aquifers in the Paracatu river basin. Base maps from Martins Junior (2006)

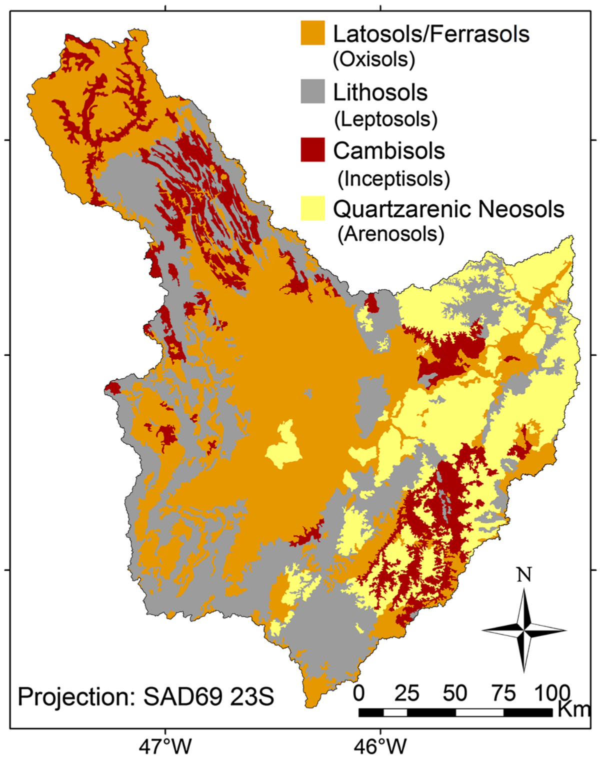


Fig. 14 Predominant soils in the Paracatu river basin. Base maps from Martins Junior (2006)

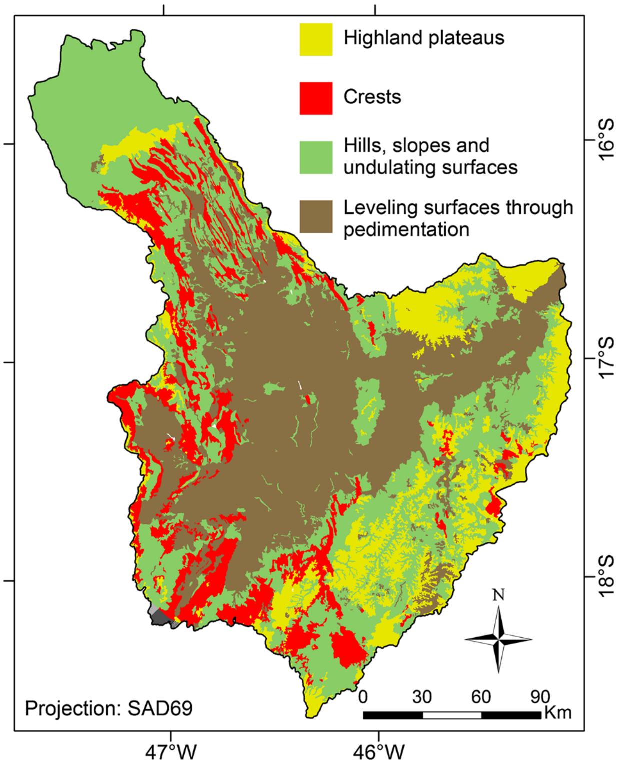


Fig. 15 Geomorphological systems of the Paracatu river basin. Base maps from Martins Junior (2006)

construction of hydrogeological knowledge has occurred due to interdisciplinary dialog. In addition, the methods of reasoning and of diffusing, incorporating and applying hydrogeological knowledge in practical terms depend on the educational and professional background of each of the shareholders participating in this process, who are involved in each of the following activities to varying degrees:

- academic research;
- opinion formation (media and education);
- formulation of laws and public policies;
- administration of public policies (government agencies);
- enforcement of laws (lawyers and judges); and
- consultation for enterprises that use water resources or that affect the quality or quantity of these resources.

As shown throughout this article, the understanding of the relationship between aquifer recharge and discharge has become more complex since the 20th century, while its gradual dissemination beyond the circle of hydrogeologists has become increasingly difficult. Lectures and training courses for other water resource professionals have allowed the transmission of basic concepts with relative ease. However, to move from a general understanding to the effective application of quantitative assessments in practical situations involving water resource-management policies, much more complete and costly technical training has been necessary. For other environmental professionals, the ease of incorporating assessments of the effects of environmental changes on groundwater and surface water resources has

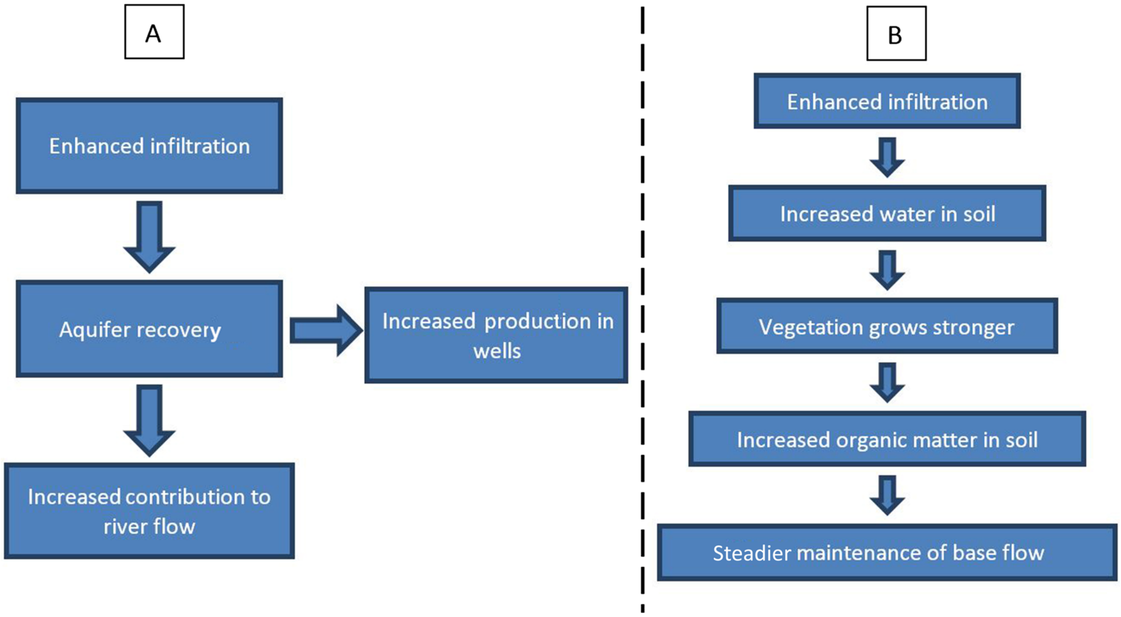


Fig. 16 Effects of induced aquifer recharge. **a** Direct effects. **b** Indirect effects

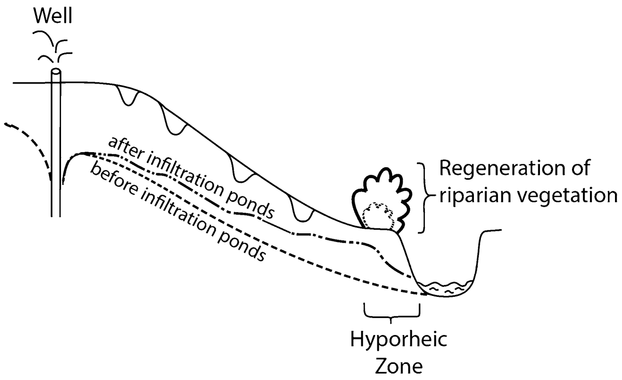


Fig. 17 Long-term effect of infiltration dams in mitigating the impact of groundwater extraction relative to the water table and riparian vegetation

depended significantly on their educational backgrounds and interest in this subject. If applying these assessments to isolated concrete cases was already difficult, their systematic incorporation for general implementation of environmental policies has become a much greater challenge.

The dissemination of knowledge about hydrogeological processes to the general population is a major challenge. First, explaining something that is not visible, but is just below the observable landscape makes it difficult to understand how water flows in soil and aquifers. In addition, as illustrated by the case studies discussed in this paper, the diversity of factors influencing the aquifer recharge process (rainfall, vegetation, slope, soil, aquifer porosity/fracturing, geological stratigraphy, groundwater level in relation to surface and water course levels, among others), which constantly interact with each other, generates a complexity that is difficult to convey in environmental education settings that typically require simple and synthetic teaching.

Conclusions

The popular perception of the "death of rivers" was one of the stimulating factors for the development of research on the interaction between groundwater and surface waters. These studies developed approaches such as water balance, aquifer recharge, the piston effect, and the relationship between hyporheic vegetation and river flows.

Hydrogeological research also facilitated the understanding that groundwater resources are not motionless mineral resources and has shown that their management should be integrated with that of surface water resources. It is also clear that the extraction of groundwater should not be limited only by the aquifer recharge potential, but should also include a broader perspective that considers the impacts on riparian vegetation and on the maintenance of river flows.

However, the modeling and management of the relationship between aquifers and rivers, without disregarding the water circulation through the hyporheic zone, remains a major challenge in terms of technical and operational complexity. Different geosystems with distinct soils, topography and aquifer-bearing rocks have different processes and different potentials for sustainability and multiple water and land uses.

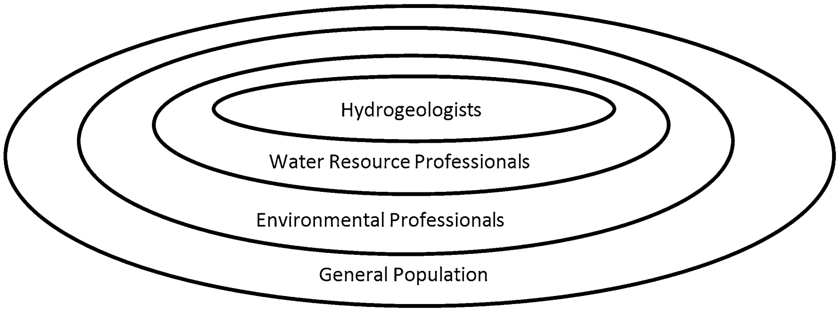


Fig. 18 Hydrogeological knowledge dissemination groups

Table 1 Outcomes of the analysis of each case study

Case study	Hydrogeological approach	Main outcomes
Paraná river basin	Water balance and influence of land use change on total stream flow	Changes from forest to seasonal crops increase annual stream flow, even in large basins
Veredas (spring wetlands) Almescla and Pindaibal	Influence of land use change and wetland degradation on seasonal flow	Degraded wetlands decrease base flow in the dry season and increase runoff in the rainy season
Hydrogeological diversity in Minas Gerais state	Effects of soil texture, organic matter content, and rock matrix texture of the aquifers on well yields and river flows during the dry season	Areas of sandy soils and porous aquifers provide good well yield, but poor base flow maintenance. Organic matter, clay and rainfall are essential factors for maintaining base flow
Hydrogeological diversity in the Paracatu river Basin	Effects of soil texture on flow components, piston flow	Sandy soils on porous aquifers favor piston flow, whereas clayey soils favor base flow maintenance

Table 2 Influence of hydrogeological knowledge on public policies for water management

Hydrogeological approach	Policy implications
Water balance	Groundwater could be managed by accounting for inputs (rainfall infiltration) and outputs (discharges into rivers, use by humans and vegetation)
Aquifer recharge	Land use management and structural measures could be implemented to increase rainfall infiltration and, consequently, groundwater availability
Piston effect	Conserving aquifers and soils containing more clay and organic matter is more important for the maintenance of river flows during the dry season, whereas aquifers and overlaying porous soils with faster flows are better suited to being managed as rechargeable reservoirs for groundwater use
Seasonal effects of changes in land use	Controlling the deforestation of forests and wetlands may improve the maintenance of river flows during the dry season and help regulate floods during the rainy season
Safe yield	Restraining groundwater use so that it remains within the limit of rainfall infiltration would prevent the depletion of groundwater reservoirs
Sustainable yield	The limits on groundwater use should recognize the influences on river flows and riparian vegetation, as well as the economic and social impacts

The case studies in Brazil illustrate how these emerging paradigms in hydrogeology can help to elucidate complex patterns of environmental information. Table 1 presents the main outcomes discussed for each case study:

Table 2 outlines the influences of the major developments in hydrogeology discussed in this article on public policies.

The construction of rainwater infiltration ponds can be used effectively as a mitigation strategy for managing environmental impacts on water circulation. Moreover, payment for environmental services programs can be adjusted to focus more directly on actions that ensure the maintenance of river flows, concentrating on areas where the demand for their use is higher, such as for urban water supply sources or basins with conflicts over water use.

Despite the developments in the understanding of hydrogeological processes and their management, perhaps the main challenge is still transmitting this knowledge beyond the hydrogeological academic environment. Training strategies for professionals in water resources and environmental fields, as well as the dissemination of simplified information to the general population, are healthy ways to achieve the sustainable management of water resources.

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