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HYDROLOGICAL PROCESSES OF INTERACTION BETWEEN SURFACE WATER AND GROUNDWATER – A REVIEW

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ABSTRACT

The hydrological processes and factors involved in the interaction between surface water and groundwater are reviewed in this paper. Emphasis is placed on stream – groundwater interaction, as this is a common image of the interaction of surface water and groundwater. Different methods of assessing surface water – groundwater interactions are reviewed with the aim of providing insight into the scope of the studies and environmental problems associated with surface water – groundwater interaction. Problems that may be associated with the neglect of the nature of interaction are recognized and identification of where there is need for research made, with the aim of giving signals to where more understanding of hydrological processes on the basis of surface water – groundwater interaction are needed.

Key words: Groundwater recharge, groundwater discharge, surface water–groundwater interaction, surface water-groundwater assessment.

INTRODUCTION

The distinction between surface water and groundwater seems simple. Surface water is above the ground surface; groundwater is below the ground surface, in the saturated zone. This distinction, however, belies the complexity of the surface and subsurface environmental systems that often behave in a coupled manner and hence make surface water and groundwater interact in such an intimate way that the separation of the two, either in their study or in regulation, is unrealistic (Watson and Burnett, 1995; Kollet and Maxwell, 2006). Surface water can become groundwater and vice versa. Thus, the development and contamination of one commonly affects the other. The interdependence of surface water and groundwater, as well as the other components of the hydrological budget, are represented in the hydrological cycle. The nature of the interdependence however, especially as usually depicted in diagrams, has tended to be taken simplistically (Black, 1996). The simplification has been attributed to the discipline-oriented thinking, which essentially drove the studies of the different components of the hydrological cycle. Integrated studies involving many disciplines were lacking. As explained by Winter (2001), for example, surface water hydrologists knew that baseflow in streams was groundwater discharge, but they generally were unconcerned about the understanding of the groundwater flow paths that carried water to the streams - they just wanted to know if water was going to be there for human use. On the other hand, the groundwater hydrologists knew that surface water was a potential source to surface water, there was little concern for what different groundwater development practises might do to stream, lake and wetland ecosystems. Lack of integrated understanding of the surface water and groundwater interaction, until recently, has also been attributed to the difficulty and high cost of making adequate observations and measurements (Criss and Davisson, 1996). However, recent technological advances in instrumentation, ecological concerns, the need for better understanding and simulation of hydrological processes, especially for sustainable water resources management, consideration of water balance at different scales, and the global awareness for the protection of the environment, have raised the awareness and the need for better understanding of the interaction (Gardner, 1999; Lorentz, 2001). The classical simplistic relationship, in which infiltration is taken as dividing rainfall into two, with one part going through overland flow and stream channels to the sea as surface runoff, and the other, going into the soil and through the groundwater flow, to the stream or returned to the air by evaporative processes (Choley, 1978), no longer suffices, as a complex relationship, depending on a variety of factors, have been recognized. The factors include hydraulic properties, climate, landform, geology and biotic factors (Lorentz, 2001; Sophocleous, 2002; Salve and Tokunaga, 2002).

The understanding and description of surface water – groundwater interaction is necessary in order to identify and show the principal processes involved in the interaction and needed for effective water resources management. Kelbe and Germishuyse (2000) have identified four ways of conceptualisation of surface water – groundwater interaction, viz. according to the hydrological processes, the individual resources, the interdependencies of specific systems, and based on the existing regulations and control. A description based on the hydrological processes is preferred based on their findings that the hydrological processes sustain both surface water and groundwater and also the interaction itself. However, given the broad spectrum of the topic of surface water and groundwater interaction, Winter (1995) believes that an overview of surface water – groundwater interaction could be organized according to surface water type, landscape type, scale of hydrological systems, or field and analytical methods. Winter et al. (1999) prefer the use of a conceptual landscape, in order to emphasize that surface water and groundwater interact at many places throughout the landscape. The conceptual landscape defines the following types of terrain: mountainuos, river valleys (small and large), coastal, glacial, dune and karst. It is also possible to look at surface water – groundwater interaction in terms of their ecological implications (Gibert et al., 1997; Brunke and Gonser, 1997; Gardner, 1999). However, it can be observed that the conceptualization of surface water – groundwater interaction, either in the cases of Kelbe and Germishuyse (2000) classifications or on Winter (1995) and ecological bases, are dependent on hydrological processes. The hydrological processes concerned in surface water – groundwater interaction are not limited to a particular landscape or specific systems, neither are they restricted by regulations nor policy controls. They sustain the interaction in all the landscapes. This review is therefore concerned with the hydrological processes involved in the surface water – groundwater interaction, with emphasis on exchange between rivers and aquifers. This is considered apposite, as the most common image of the interaction of surface water and groundwater is that between streams and the contiguous aquifers (Winter, 1995). The review is not only concerned with the varieties of the hydrological processes that control the nature of the interaction between surface water and groundwater as already identified by researchers, but also examines how the processes exercise such controls and thereby contribute to the understanding of the interaction. Problems that may be associated with the neglect of the nature of the interaction between surface water and groundwater are recognized and identification of where there is need for research made, with the aim of providing signals to where more understanding of hydrological processes on the basis of surface water – groundwater interaction are needed.

INTERACTION BETWEEN SURFACE WATER – GROUNDWATER

Kelbe and Germishuyse (2000) identified the hydrological processes involved in surface water groundwater interaction as evaporation, transpiration, precipitation, runoff, infiltration, percolation and deep seepage. The processes can however be conveniently presented in terms of groundwater recharge and discharge (Fig.1).

Groundwater Recharge and Discharge

Groundwater recharge can be described as the water which percolates into the groundwater body, while groundwater discharge can be described as the emergence of groundwater to the surface as springs, water feeding rivers, swamps and lakes, water pumped from wells and water evapotranspired by deep rooted plants tapping water from the vadose and groundwater zones. The generalised flow path from precipitation to recharge is through infiltration from precipitation, or seepages from surface water bodies, into the vadose zone, followed by percolation to the water table into the groundwater system. The magnitude of the infiltration depends upon a variety of factors, such as the amount and intensity of rainfall, vadose-zone hydraulic properties, available storage volume in the vadose zone, channel geometry and wetted perimeter, flow duration and depth, antecedent soil moisture, clogging layers on the channel bottom and water temperature (Sophocleous, 2002). The understanding of water movement through the complete subsurface continuum by scientists from different disciplines has led to a number of concepts concerning the mechanisms (Fig. 2). The concepts range from: (**a)** overland flow over the entire hillside and absence of groundwater flow, to **(b)** overland flow at the base of the hillside and the absence of groundwater flow, to **(c)** overland flow at the base of the hillside as a result of groundwater reaching the land surface, to **(d)** subsurface stormflow, and to **(e)** complex flow in the unsaturated zone as a result of different permeabilities of soil horizons and complete absence of overland flow. In describing variations in groundwater recharge patterns in subterranean systems, however, the physical characteristics of the hydrological systems are classified by Kelbe and Germishuyse (2000) into four conceptual landscapes depicting extremes of hydrogeological features, viz:

1. Vertical flow system in a homogenous, uniform, porous media
2. Vertical and lateral flow system in a heterogeneous, non-uniform, porous medium
3. Complex interaction of matrix and fractured recharge systems distinguishable from the fractured and porous (matrix) systems
4. Thin soil mantle overlying fracture rock recharge zone above regional groundwater system

In Class 1, flow path is dominantly vertical along the line of least resistance through the soil matrix in the unsaturated zone, while lateral flow occurs in the saturated zone. This line of least resistance may have a lateral orientation and hence initiate lateral flow, but it is not likely to be significant to constitute pronounced or prolonged interflow to a stream discharge. This type of flow system is common in sedimentary rocks, especially in unconsolidated sediments typical of alluvial plains. In Class 2, unlike in Class 1, lateral flow that reaches a discharge point may occur in the unsaturated zone because of the heterogeneity of the hydraulic characteristics of the system, which encourages variable zones of moisture content that may lead to localized zones of saturation and flows in a lateral direction. Heterogeneity in terms of preferential flow of water through macropores or a rapid conducting material can also be included here. Lorentz (2001) has reported this phenomenon for Weatherly Catchment in the Northeastern Cape Province of South Africa, where lateral flow in the soil profile above the deeper groundwater table, and with little or no influence on the deeper groundwater, contributes to rapid runoff through macropore conductance during intense or large volume events. This was what Beven (1989), cited by Newman *et al.* (1998) and Sophocleous (2002), have defined as interflow and lateral subsurface stormflow, respectively, and what Dunne and Black (1970) have indicated can grade into return flow by which subsurface water can contribute to overland flow. Evidence of a lateral flow system in a heterogeneous, non-uniform, porous medium has also been observed in the basement complex area of southwestern Nigeria, where the occurrence of shallow level lateral subsurface flow between the depths of 45 – 60 cm in Agbogbo catchment, contributes to the establishment of an increasing gradient of moisture content downslope (Ogunkoya *et al.*, 2003). The subsurface water movement was sporadic and was associated with periods of heavy rainfall at the peak of the rainy season.

In Class 3, both vertical and lateral flows are involved in a case in which a perched intermediate recharge zones in the unsaturated layer impact on the interactive mechanisms for recharging the underlying fractured aquifer. Unlike in Class 3, no perched condition occurs in Class 4 as flow has vertical and horizontal paths in the unsaturated zone that are directly linked with the underlying fractured aquifer. Classes 3 and 4 are important in the crystalline basement complex areas where groundwater occurs in secondary aquifers and where fractures and dissolution channels may occur (Idowu *et al.*, 1998; Idowu *et al.*, 2001; Idowu *et al.*, 2004; Idowu *et al.*, 2007). At catchment scale, it is conceivable that responses may be dominated by a single mechanism out of the four or by a combination of mechanisms, depending on the magnitude of rainfall event, the antecedent soil-moisture conditions of the catchment, heterogeneity in soil hydraulic properties and geology.

In comparison to recharge, groundwater discharge in the four conceptual landscapes occurs through processes that are controlled by the laws of gravity and surface tension, entailing capillary rise in the vadose zone, evapotransipiration, lateral outflow through a surface boundary and direct abstraction (Sophocleous, 2002). Discharge of groundwater through evapotranspiration in areas where the water table is sufficiently high to be within the reach of plants, can be considerable and result in the surface water moving into the subsurface to replenish the evapotranspired groundwater and thereby affect the configuration of the groundwater flow system and how groundwater interacts with surface water.

Interaction between streams and groundwater

The interaction between groundwater and surface water can be put into three basic categories (Fig. 3): surface water body gaining water from inflow of groundwater (effluent), surface water body losing water to groundwater by outflow (influent), or the surface water body disconnected from the groundwater system (perched). Two other classes can be included with the three basic classes (Woessner, 2000), viz: flow-through and parallel-flow (Fig. 3). A flow–through condition occurs when the channel stage is less than the groundwater head on one bank and is greater than the head at the opposite bank, such that the surface water is gaining on one bank and losing on the other. A parallel-flow condition occurs when the channel stage and groundwater level head are equal. The direction of water flow can change in very short time frames as a result of individual storms causing focused recharge near the stream-bank, temporary flood peaks moving down the channel, transpiration of groundwater by streamside vegetation or groundwater pumping (Winter et al., 1999). The factors that control the hydrological exchange of groundwater and rivers have been reported by Sophocleous (2002) which include:

1. The distribution and magnitude of hydraulic conductivities, both within the channel and the associated aquifer,
2. The relation of stream stage to the adjacent groundwater level; and
3. Geomorphology, especially in terms of the geometry and position of the stream channel within the alluvial plain.

Distribution and magnitude of hydraulic conductivity

The variability and distribution of the hydraulic conductivities (heterogeneity) of streambed deposits and aquifer materials, act as the key factors determining the volume of large-scale and small-scale exchange processes, as well as the residence time of water within the riverine aquifer (Brunke and Gonser, 1997). The direction of the exchange processes varies with hydraulic head, which in turn is subject to influence by precipitation events and seasonal patterns, whereas water flow depends on the contrasts in the hydraulic conductivities of soils and rocks at different parts of the system, as well as the connectivity of the referential-flow-network (Faybishenko, 2000).

Related to the distribution and magnitude of hydraulic conductivity is the effect of the clogging by deposits located in stream channels. The clogging mechanisms have been identified as sedimentation of suspended solids induced by gravity, intrusion and consequent straining of fine sediments into the interstitial spaces because of mass flux from the river into the aquifer by infiltration (Wett *et al.*, 2002). The clogging mechanisms result in the formation of a fine particle layer with reduced hydraulic conductivity at the stream-aquifer interface. The clogging deposits can have such a low hydraulic conductivity that they can restrict seepage rates to values that are less than the saturated hydraulic conductivity of the underlying coarser materials, thereby causing the development of a perched stream situation because the materials below the clogging layer is unsaturated. It can be expected that the clogging materials can also affect groundwater discharge in gaining surface water body situations. However, the upward hydraulic force of the upwelling groundwater in gaining surface water bodies reduces siltation and thereby tends to maintain hydraulic conductivity (Brunke and Gonser, 1997). Winter *et al*. (1999) has observed that the restriction of seepage rates may lead to deficit in the evapotranpiration induced seepages to groundwater, thereby resulting in deep and steep-sided cones of depression common around lakes and wetlands. The clogging of the top layer of channel sediments is influenced by physical, chemical and biological variables (Brunke and Gonser, 1997). The physical variables include shear stress, representing the flow conditions; the suspended load grain size distribution and shape; the hydraulic gradient of seepage flow and its direction; while the chemical variables include types and quantities of dissolved organic matter controlling sorption processes. The biological variables concern the activities of epilithic micro-organisms, which develop a biological layer with adhesive capacities.

Relation of Stream stage to Groundwater level

The relation of streams to groundwater depends on the hydraulic connectivity between them. For groundwater to discharge to a surface water body (gaining), the altitude of the water table near the water body must be higher than the altitude of the surface of the water body so as to provide the necessary hydraulic gradient. Conversely, for surface water to seep to groundwater (loosing), the altitude of the water table near the water body must be lower than the altitude of the surface of the water body. Whether a surface water body is gaining, losing or perched has been shown by Winter (1999) to be dependent on physiography (geology and topography), which controls the local and regional groundwater flow systems, and climate, which controls the hydrological processes associated with the surface water bodies themselves, such as seasonally high or low surface water levels in response to precipitation, evaporation and transpiration.

Apart from the classes of surface water (streams) – groundwater interaction identified above, Sjodin *et al*. (2001) and, Chen and Chen (2003) among others, have identified a type of interaction between streams and groundwater caused by bank storage. This process occurs from storm precipitation or from the release of water from a reservoir upstream, whereby the loss of stream water to bank storage and return of this water to the stream in a matter of days, weeks or months tends to reduce flood peaks and later supplement streamflows. The flow paths can be lateral through the riverbank, or vertical over the flood plain. If the stream stage is sufficient to overtop the banks and flood over large areas of the land surface, widespread recharge to the water table can take place throughout the flooded area, in which case, the time it takes for the recharged flood water to return to the stream by groundwater flow may be weeks, months, or years because the lengths of groundwater flow paths are much longer than those resulting from local bank storage. The volume of the bank storage will depend on duration, height and shape of the flood hydrograph, as well as the transmissivity and storage capacity of the aquifer. A case in which flooding is the main groundwater replenishment mechanism to the floodplain and bank aquifers has been reported by Girard *et al*. (2003) for the Pantanal (a vast evaporation plain and sediment accumulation surface that floods annually) in the Upper Paraquay River Basin in Brazil. During the dry period, the aquifers drain into the Cuiaba River to maintain flow and contribute to the ecological stability of the river-floodplain system.

Geometry and positions of stream channel

Larkin and Sharp (1992) classified stream-aquifer systems as (1) underflow-component dominated (groundwater flux moves parallel to the river and in the same direction as the streamflow); (2) baseflow-component dominated (the groundwater flux moves perpendicular to or from the river depending on whether the river is effluent or influent; or (3) mixed. They explain that the dominant groundwater flow component, baseflow or underflow, can be inferred from geomorphologic data, such as channel slope, river sinuosity, degree of river incision through its alluvium, the width-to–depth ratio of the bankfull river channel and the character of the fluvial depositional system. The underflow component is predominant in systems with large channel gradients, small sinuosities, large width-to-depth ratios and low river penetrations; and in fluvial depositional systems of mixed-load to bed-load character, in upstream and tributary reaches and valley-fill depositional environments. Baseflow-dominated systems have characteristics typical of suspended-load streams with the opposite to the aforementioned geomorphic attributes for systems dominated by the underflow component (i.e. small channel gradients, big sinuosities, small width-to-depth ratios and high river penetrations). Mixed flow systems occur where the longitudinal valley gradient and channel slope are virtually the same and where the lateral valley slope is negligible.

ASSESSMENT OF SURFACE WATER-GROUNDWATER INTERACTION

The field of assessment of the interaction between surface water and groundwater is wide, covering hydrological, ecological, biogeochemical and geological, and involving different simulation techniques. This review deals only with the hydrological assessments. Kelbe and Germishuyse (2000) categorized the means of assessment into three, viz. hydrograph separation techniques, chemical and isotopic studies and physical measurements, while Winter *et al*. (1995) classed them into analytical, numerical, field and chemical methods. Sophocleous (2002) considered field studies and quantitative analysis. For the purpose of this review, the methods for hydrological consideration of the interaction between surface water and groundwater are classified into hydrograph analyses, water budgeting, field, chemical and modelling methods.

Hydrograph Separation/Analysis

The traditional approach to surface water analyses in order to demonstrate the level of interaction between surface water and groundwater is through hydrograph separation. Hydrograph analyses can be carried out to determine the groundwater component of stream flow and to determine groundwater recharge from stream flow. The primary interest of most studies however has been to determine the groundwater component of stream flow and in some cases, use this for estimating recharge (Mau and Winter, 1997). There are different methods of separating hydrographs (Viessman, 1989), including automated computer based techniques (Sinclair and Pitz, 1999). Four components that are traditionally referred to as channel precipitation, baseflow, interflow and direct surface runoff or quickflow can be identified in hydrograph separation techniques. The baseflow is the component that is taken to be composed of the water that percolates downward until it reaches the groundwater reservoir and then flows to surface streams as groundwater discharge. Idowu and Martins (2007) have estimated the recharge and baseflow to the Opeki catchment in southwestern Nigeria using the hydrograph analysis technique. The recharge varies between 3 and 20% of the annual precipitation (average of 1120 mm), while the baseflow range from 6 – 47% of the annual streamflow, with the MAR of 708 mm. In spite of the popularity of the hydrograph separation in the surface water – groundwater interaction studies, the sole use of hydrograph separation techniques for identifying the groundwater discharge or recharge component has been criticized by Hafford and Mayer (2000). They consider it as a poor tool on the ground that it is ambiguous because drainage from bank storage, wetlands and soils can exceed groundwater from the main aquifer store and also decrease exponentially during recession period.

Water Budgeting

In the water budgeting method, the interaction between surface water and groundwater is seen in terms of the deep percolation and groundwater discharge, which occur in consequence of the interchange between atmospheric water, surface water and groundwater. The deep percolation is taken as the residual of the applied water or inflow (irrigation and rainfall) minus surface runoff and evapotranspiration (Theodore *et al*, 1982). Accurate measurement of deep seepage rates at a single location is however difficult and complex. The problem may even increase many folds when an estimate is attempted on a regional basis (Sammis *et al.*, 1982) because of heterogeneity in soils and aquifer characteristics. The water balance approach has been employed by Ogunkoya (2000) to estimate the changes in the soil and groundwater storage in a small catchment (Agbogbo) in southwestern Nigeria. An overall decline of 0.3% (of the total rainfall of 4452 mm) in the soil and groundwater storage was reported over a three year period and attributed to the rainfall pattern and intensity of the dry season within the period of study. The water budget approach is highly subject to error and can lead to misunderstandings about the interaction between surface water and groundwater, especially when errors of measurements inherent in precipitation and particularly evapotranspiration, are considered. Further, as recognised by Winter (1976), only through careful field techniques can streamflow measurement errors be kept to relatively low values.

Field Studies

Field studies have resulted in increased understanding of surface water-groundwater interaction. These field studies usually involve monitoring of water levels and chemistry (in wells and surface water), temperature, soil water content and potential. The monitoring is based on the fact that indications of directions and amounts of water flow either from or to aquifers and surface water bodies can be made through them. The data are usually processed as maps, transects or profiles. Based on water level measurements in hand dug wells in Abeokuta city and environ, Idowu *et al.*(2004) and Idowu *et al.* (2007) determined the configuration of the water table and the groundwater flow direction, which enabled the identification of the recharge areas and answered why some areas experienced water logging, especially in the dry season.

Chemical Methods

Studies of the interaction of groundwater and surface water are often initiated because of the problems related to water quality. Many investigators have therefore used chemical characteristics of both groundwater and surface water to determine the interaction. Apart from the major cations and anions, stable isotopes of oxygen (^{18}O) and hydrogen ^{2}H in water molecules, radioactive isotopes such as tritium ^{3}H and radon ^{222}Rn have also been used in chemical methods. They can be used to determine source areas of water and dissolved chemicals in drainage basins, calculate hydrological and chemical fluxes between groundwater and surface water, calculate water ages that indicate the length of time that water and dissolved chemicals have been present in the drainage basin (residence times) and determine average rates of chemical reactions that take place during transport. With the analyses of the chemical properties (pH, EC, Ca, Mg, K, HCO_3, NO_3, Si and Cd) of the water collected from hand dug wells in parts of southwestern Nigeria (Abeokuta city and environs), Idowu *et al.* (2007) have been able to determine the spatial variation in the groundwater chemistry of the study area and consequently, identify two groundwater types (that feed the surface water bodies) whose sources coincided with the identified recharge areas. Using environmental isotopes of Oxygen – 18, Tritium, and Carbon (^{13}C and ^{14}C), Tijani (1997) provides evidences of mixing/ dilution of saline paleowaters in the groundwater systems of the Benue Trough with meteoric waters, through recharge from rainwater and surface water bodies.

Modelling

To realistically model the interrelatedness of groundwater and surface water systems, it is necessary to mathematically describe the transient effects on the water table configurations, so that water table is free to move in any direction in response to movement of water in unsaturated and saturated zones (Winter, 1984). To describe these effects necessitates the simulation of the combined saturated-unsaturated zones, including infiltration, seepage faces and fluctuations in the level of contiguous surface water bodies, all of which are complex and therefore requires simplifying assumptions. Both analytical and numerical modelling techniques have been used for analyzing the interaction between surface water and groundwater. Analytic solutions to one-dimensional flow to fully penetrating streams used before the advent of numerical modelling is still being used to estimate groundwater recharge from streamflow hydrographs. Automated computer-based techniques for using these analytical methods, including mathematical digital filtering, have been developed (Nathan and McMahon, 1990; Chapman, 1991). Although hydrograph analysis continues to be used, studies have used other analytical techniques and numerical modelling. For example, in a study involving the effects of pumping groundwater on streamflow, Spalding and Khaleel (1991) compared the results of several analytical solutions to a two-dimensional groundwater flow model and found that, simplifying assumptions, needed for the use of the analytical methods, resulted in differences in streamflow depletion from the numerical model that ranged from 20 percent (due to neglect of partial penetration) to 45 percent (due to neglect of clogging layer resistance). Numerical modelling of the interaction between groundwater and surface water is generally carried out using two techniques (Jorgensen *et al.*, 1989). The first is based on Darcy calculation (where discharge = hydraulic conductivity* hydraulic gradient*cross-sectional area) as well as highly idealized stream geometry, to transfer water (seepage) through the stream sediments, based on head differences between the surface water and groundwater. The second technique determines the amount of soil moisture in a profile by calculating infiltration and consumptive use. Flow to the water table is the residual or outflow term in soil-moisture budget. Examples of modelling of stream–groundwater interaction include Wett *et al.* (2002) in which numerical modelling of river-aquifer interactions, based on the effects of stream stage rise on an alluvial aquifer under the influence of a bank filtration well in Austria using MODFLOW (McDonald and Harbaugh, 1988), was carried out. They report that immediately after flooding, the portion of filtrated river water in the well decreases significantly despite the constant hydraulic conductivity of the riverbed. Two reasons are identified for this. One, groundwater recharge by precipitation and stream stage elevation during the flood increased the groundwater table. Two, increased groundwater head, under the influence of riverbed clogging, together with decreased stream stage after flooding resulted in a reduced hydraulic slope and seepage rate (about 50% of the mean value). It was also observed that both flood induced groundwater table elevation and groundwater recharge by rain, filled up the bank storage volume, but was depleted by the well operation during the following weeks.

RESEARCH NEEDS ON SURFACE WATER – GROUND WATER INTERACTION

Apart from hydrological processes, geologic, geomorphologic and biogeochemical processes also determine the nature of the interaction between surface water and groundwater. The processes are controlled by factors such as surface and streambed topography, distribution and magnitude of hydraulic conductivities in the clogging sediments/soils/rocks, position of the water bodies with respect to groundwater flow systems, climate (precipitation, evapotransipration), channel geometry, river sinuosity, degree of river incision through its alluvium, infiltration, soil moisture conditions, physicochemical gradients and the retention and metabolism of organic matter at the surface-groundwater interface among others. The varieties of these factors reveal the value and importance of understanding surface water and groundwater interactions. Gardner (1999) explains these values to include flow augmentation, provision of buffering capabilities, formation and maintenance of habitat and refugia and enhancement of the effectiveness of programmes to protect and restore water quality and quantity. Mismanagement and over-utilization of surface water or/and groundwater, failure of measures for regulating and protecting water quality and quantity, impairment of pathways connecting surface water with groundwater (which may result into drying up of streams or groundwater mining), water contamination, decline in the population and diversity of micro-organisms, macro-vertebrates, fish and wildlife that inhabit the transition zone between surface water and groundwater, are some of the problems that may arise from the neglect of the interaction between surface water and groundwater. Consideration of these factors, both in the theoretical and applied investigations, make for a better understanding and the appreciation of the spatial and temporal peculiarities of river water and groundwater interaction necessary for gauging anthropogenic changes and effective management of water resources.

Development and contamination of water resources occur in consequence of superimposition of human activities on the natural dynamic equilibrium that exists between surface water –groundwater interchange. Therefore, it is important that the interactions, both pre- and post-development, are well understood. In this regard, Bouwer and Maddock III (1997) have suggested both a predevelopment steady-state and a transient-state numerical modelling that can determine, for example, the reduction of groundwater discharge to gaining streams, the increased recharge from losing streams and the reduction of discharge to evapotranspiration from vegetation due to falling water tables. The range of human activities that affect the interaction between surface water and groundwater include agricultural development (especially irrigation and application of chemicals to cropland), urban and industrial development (for example, discharges of sewage), drainage of land surface, groundwater pumping, construction of reservoirs, removal of natural vegetation and atmospheric discharge and deposition (Winter *et al.*, 1999; Woessner, 2000).

By far the most important need for the understanding of surface water –groundwater interactions is in the area of effective water resources management (Woessner, 2000). It has been acknowledged that effective water resources management is best logically considered with the catchments as planning units (Global Water Partnership, 2000). In the same vein, Morrice *et al.* (1997) have demonstrated the need for comparison of catchment scale perspectives of surface water-groundwater linkage in order to establish catchment scale differences. It would therefore be more appropriate if assessments of surface water-groundwater interactions are tailored along eventual considerations and understanding at basin-wide or catchment scales. Naturally, this would require investigations at local scales for the necessary data collection required for adequate understanding of the interactions, and the necessary tools for extrapolating results from local to basin-wide or catchment scales. Sophocleous (2002) concludes that the choice of proper temporal and spatial scales for conducting such experiments is critical, because the particular site and time of the year in which experiments are performed are likely to dramatically influence results.

The hydraulic properties of streambeds and aquifer materials are difficult to measure directly, thereby presenting a limitation to spatially defining the hydraulic properties and spatial heterogeneities of a streambed and aquifer. In a stream-aquifer study, Sophocleous *et al.* (1995) ranked streambed clogging, stream partial penetration and aquifer heterogeneity as the three most significant factors in stream-aquifer problem, but as recognised by Sophocleous (2002), most analytical models ignore these factors. It is imperative that these factors are taken into consideration in future studies along with the three dimensional modelling needed for a better understanding of the stream-aquifer process, in view of the fact that exchange of stream and aquifer water occurs both vertically and horizontally and so, is inherently three dimensional. Groundwater exfiltration occurs diffusely or at discrete locations. There is the need for more research in the areas of identification of the stream reaches that interact intensively with groundwater and the quantification of the water fluxes. These would lead to better protection strategies of such systems. All these call for analytical and numerical models that are continually improved upon by the abilities to more realistically simulate field conditions. Proposing a solution to these research needs, Bouwer and Maddock III (1997) advised the use of regional numerical models, such as MODFLOW (McDonald and Harbaugh, 1988), for assessing basin-wide stream-aquifer interactions for the reason that complexities, that are usually neglected in simpler analytical and numerical models, can be accounted for. In addition, questions on hydrological and legal matters such as: (1) when will a well begin to deplete a certain amount of appropriable water, (2) how much water is being pumped by a certain water user group, and (3) how does this consumptive use affect other user and the environment, can be addressed.

CONCLUSION

Hydrological interaction between surface water and groundwater can be understood in terms of groundwater recharge and discharge. Surface water and aquifers exchange water both horizontally and vertically and therefore, flow dynamics are inherently three-dimensional. It is therefore important that research tools appropriately simulate the field conditions in three dimensions to better understand the stream – aquifer process. In view of the importance and complexity of the interactions between surface water and groundwater, a holistic approach, encompassing the understanding of the movement of water between the groundwater and surface water systems, the biogeochemical and microbial processes within the interface of the two, is necessary. Such an approach will engender sustainable utilization of water resources. The approach calls for the working together of not only surface water and groundwater hydrologists, but also geochemists, biologists and environmentalists in general. The challenge shall be the placement of the needed emphasis on the broader perspectives of surface water – groundwater interaction through cross-disciplinary collaborations and extrapolating results from small instrumented (local) reaches to stream-network, basin or catchment scales. As succinctly put by Winter (2001), “one of the foremost challenges in the coming years will be to put together the right mix of people who will address the physical, chemical and biological processes that link the hydrological compartments from the stream, to the hyporheic compartments, to the local groundwater, to the regional groundwater flow systems. It would be effective if these interdisciplinary teams worked at common field sites and in a way that would facilitate intersite comparisons, so processes common to some or all settings can be distinguished from unique to individual settings”.

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REFERENCES

Beven, K. J. 1986. Runoff production and flood frequency in catchments of order n: In alternative approach. In: V. K. Gupta, I. Rodriguez-Iturbe, E. F. Wood. (eds) Scale problems in hydrology. Reidel, Hingham, pp. 107-131

Beven, K.J. 1989.1nterflow. In: Morel-Seytoux H.J. (ed.) Unsaturated flow in hydrological modelling:theory and practice. Kluwer, Dordrecht, pp. 191-219.

Black, P. E. 1996. Watershed hydrology. Ann Arbor Press, Inc.

Bourg, A. C. M., Bertin, C. 1993. Biogeochemical processes during the infiltration of river water into an alluvial aquifer. Environmental Science and Technology, Vol. 27, pp. 661-666.

Bouwer, H., Maddock III, T. 1997. Making Sense of the interactions between groundwater and streamflow: Lessons for water masters and adjudicators. Rivers, Vol. 6, No 1, pp. 19-31.

Brunke, M., Gonser, T. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology, 37, pp. 1-33.

Chen, X., Chen, X. 2003. Stream water infiltration, bank storage, and storage zone changes due to stream-stage fluctuations. Journal of Hydrology 280, pp. 246-264.

Chapman, T. G. 1991. Comment on evaluation of automated techniques for baseflow and recession analysis by R. J. Nathan and T. A. McMahon, Water Resour. Res. 27 (7), pp. 1783-1784.

Chorley, R. C. 1978. The hillslope hydrological cycle. In: Kirkby, M. J. (ed) Hillslope Hydrology, John Wiley & Sons, pp. 1-42.

Criss, R. E., Davisson, M. L. 1996. Isotopic imaging of surface/groundwater interactions, Sacramento Valley, California. Journal of Hydrology, 178, pp. 205-222

Dunne, T., Black, R. 1970. An experimental investigation of runoff production in permeable soils. Water Resour. Res. 6, pp. 478-490.

Faybishenko, B. 2000. Vadose zone characterization and monitoring: current technologies, applications and future developments. In: Looney, B. B. and Falta, R. W. (eds) Vadose zone science and technology solutions. Battelle Press, USA. Vol. 1, pp. 589.

Gardner, K. M. 1999. The importance of surface water/groundwater interactions. US Environmental Protection Agency Issue Paper EPA-910-R-99-013

Gibert, J, Fournier, F., Mathieu, J. 1997. The groundwater/surface water ecotone perspective: state of the art. In : Gibert, J, Fournier, F. and Mathieu, J. (eds)Groundwater/surface water ecotones: biological and hydrological interactions and management options. UNESCO International Hydrology Series. 3-8.

Girard, P., da Silva, C. J., Abdo, M. 2003. River-groundwater interactions in the Brazilian Pantanal. The case of the Cuiaba River. Journal of Hydrology 283, pp. 57-66.

Global Water Partnership. 2000. Integrated Water Resources Management. Global Water Partnership Technical Advisory Committee (TAC) Background Papers, No 4. 67 p.

Halford, K. J., Mayer, G. C. 2000. Problems associated with estimating groundwater discharge and recharge from stream-discharge records. Ground Water 38 (3).

Idowu, O. A., Martins, O., Ajayi, O. 1998: Groundwater occurrence in southwestern Nigeria: a comparison of two geological environments, Water resources, Vol.9, pp 33-40.

Idowu, O. A., Martins, O., Ajayi, O. 2001. Factors influencing yields of boreholes in basement complex aquifers in parts of southwestern Nigeria, Nigerian Journal of Science. Vol. 34, No. 2, pp. 95-100.

Idowu, O. A., Martins, O, Adetona, M. A. 2004. Shallow aquifer characteristics in a tropical crystalline rock environment: A case study of Abeokuta city, southwestern Nigeria. ASSET Series A, Vol. 5 (1), 109 - 120.

Idowu, O. A., Martins, O., Gbadebo, A. M. 2007. Hydraulic and hydrochemical characteristics of the phreatic basement aquifers of parts of southwestern Nigeria. Journal of Mining and Geology, Volume 43, No 1, 71-78

Idowu, O. A., Martins, O. 2007. Hydrograph analysis for groundwater recharge in the phreatic basement aquifer of Opeki

River basin, southwestern Nigeria. Accepted for publication in ASSET, Series B, Vol. 6, No 1

Jorgensen, D.G., Signor, D.C., Imes, J. L. 1989. Accounting for Intracell Flow in Models With Emphasis on Water Table Recharge and Stream-Aquifer Interaction I. Problems and Concepts. Water Resour. Res.,25(4), pp. 669-676.

Kelbe, B.E., Germishuyse, T. 2000. Conceptualization of the surface water – groundwater processes in South Africa. Draft of Proceeding of a Workshop on Surface Water-Groundwater Interaction held in Pietermaritzburg, South Africa.

Larkin, R.G., Sharp, J.M. 1992. On the relationship between river-basin geomorphology, aquifer hydraulics, and groundwater flow direction in alluvial aquifers. Geol. Soc. Am. Bull 104, pp. 1608-1620.

Lorentz, S. 2001. Hydrological Systems Modelling Research Programme: Hydrological Processes. Water Research Commission, Pretoria, Report 637/1/01.

Mau, D.P., Winter, T. C. 1997. Estimating Groundwater recharge from streamflow hydrographs for a small mountain watershed in a temperate humid climate, New Hampshire, USA. Ground Water, Vol. 35, No. 2, pp 291-304.

McDonald, M.G., Harbaugh, A.W. 1988. A modular three dimensional finite-difference groundwater flow model. US Geol. Surv. Open File Rep. 83, 875 p.

Morrice, J.A., Vallet, H.M., Dahm, C. A., Campana, M.A. 1997. Alluvial characteristics, groundwater-surface water exchange hydrological retention in headwater streams. Hydrol. Process. Vol 11, pp. 253-267.

Nathan, R.J., McMahon, T.A. 1990. Evaluation of automated techniques for base flow and recession analysis, Water Resour. Res. 26 (7), pp 1465-1473.

Newman, B.D., Campbell, A.R., Wilcox, B.P. 1998. Lateral subsurface flow pathways in a semarid ponderosa pine hillslope. Water Resour. Res., Vol. 34, No 12, pp. 3485-3496.

Ogunkoya, O.O., Aina, P.O., Nurudeen, O. 2003. Temporal varability of soil water in a small catchment in Ile-Ife, southwestern Nigeria. J. Min. Geol., Vol. 39 (1), pp 53 – 59.

Ogunkoya, O.O. 2000. Water balance of a small catchment with permeable soils in Ile -Ife area, southwestern Nigeria. J. Min. Geol., Vol. 36 (1), pp 105 – 111.

Salve, R., Tokunaga, T. K. 2002. Seepage response along an alluvial valley in a semi-arid catchment in north-central California. Hydrological Processes. 16, pp. 65-86.

Sammis, T. W., Evans, D. D., Warrick, A. W. 1982. Comparison of methods to estimate deep percolations rates. Water Res. Bull. Vol 18, No 3, pp. 465-470.

Sinclair, K. A., Pitz, C. A. 1999. Estimated baseflow characteristics of selected Washington rivers and streams. Washington State Department of Ecology, Water Supply Bulletin No.60. 221 p.

Sjodin, A., Lewis, Jnr., W. A., Saunders III, J. F. 2001. Analysis of groundwater exchange for a large plains river in Colarodo (USA). Hydrological Processes 15, pp. 609-620.

Sophocleous, M. A., Kousis, A. D., Martin, J. L., Perkins, S. P. 1995. Evaluation of simplified stream-aquifer depletion models for water rights administration. Ground Water 33 (4), pp. 579-588.

Sophocleous, M. 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal 10, pp. 52-67.

Spalding, C. P., Khaleel, R. 1991. An evaluation of analytical solutions to estimate drawdowns and stream depletions by wells, Water Resour. Res. 27(4), pp. 597-609.

Theodore, W. S., Danniels, D. E., Warrick, A. W. 1982. Comparison of methods to estimate percolation rates, Water Res. Bull. Vol 18, No 3, pp. 465-470.

Tijani, M. 'N. 1997. Beitrag zur Genese salziger Grundwässer im Benue – Trog, Nigeria. Eine Synthese aus hydrochemischen und isotopenhydrologiscen Untersuchungen. Heft 83. Geologisch – Paläontologishes Institut und Museum. Westälische Wilhelms – Universität Münster, 172 p.

Viessman, W., Lewis, G. L., Knapp, J. W. 1989. Introduction to Hydrology. Third Edition, Harper & Row Publ., 780 p.

Watson, I., Burnett, D. B. 1995. Hydrology. An Environmental Approach. CRC Press Inc., 702 p.

Wett, B., Jarosh, H., Ingerle, K. 2002. Flood induced infiltration affecting a bank filtrate well at the River Enns, Austria. Journal Hydrology 266, pp. 222-234.

Winter, T. C. 1976. Numerical simulation analysis of the interaction of lakes and groundwater. USGS Professional paper 1001, 45 p.

Winter, T. C.1984. Modeling the interrelationship of groundwater and surface water. In: Schnoor, J. L. (ed) Modeling of total acid precipitation impacts. Buterworth Publ. Acid Precipitation series, Vol. 9, pp. 89-119.

Winter, T. C. 1995. Recent advances in understanding the interaction of groundwater and surface water, American Geophysical Union, Reviews of Geophysics, Supplement, pp. 985-994.

Winter, T. C., Harvey, J. W., Franke. O. L., Alley, W. M. 1999. Groundwater and surface water - A single resource. U.S. Geological Survey Circular 1139, 79 p.

Winter, T, C. 1999. Relation of streams, lakes and wetlands to groundwater flow systems. Hydrogeology Journal 7, pp. 28-45

Winter, T.C. 2001. Ground water and surface water: the linkage tightens, but challenges remain. Hydrological. Processes 15, pp. 3605-3606.

Woessner, W. W. 2000. Stream and fluvial plain groundwater interactions: rescaling hydrogeologic thought. Groundwater 38 (3), pp. 423-429.

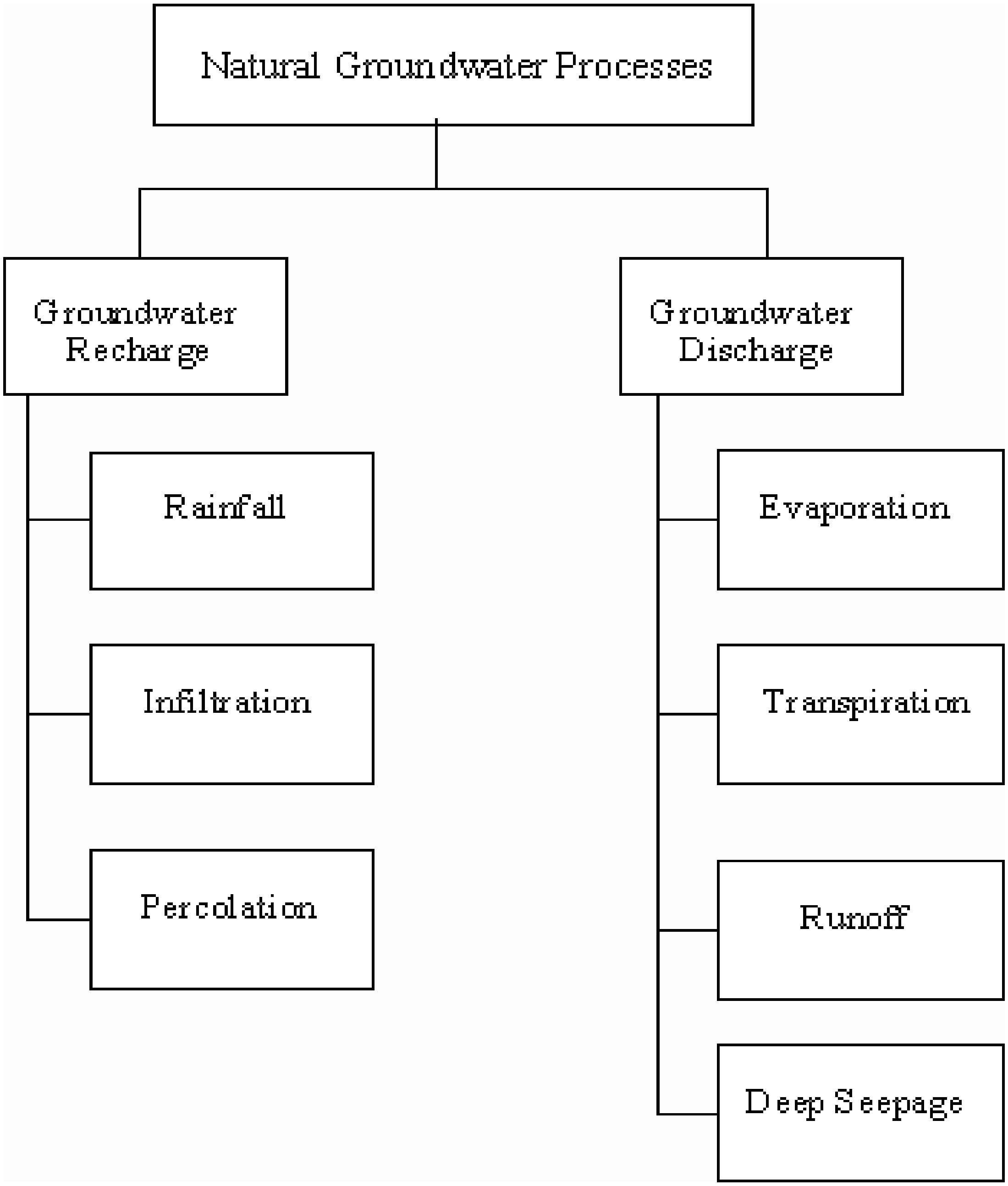

Fig. 1. The principal hydrological processes involved in surface water and groundwater interaction (Kelbe and Germishuye, 2000)

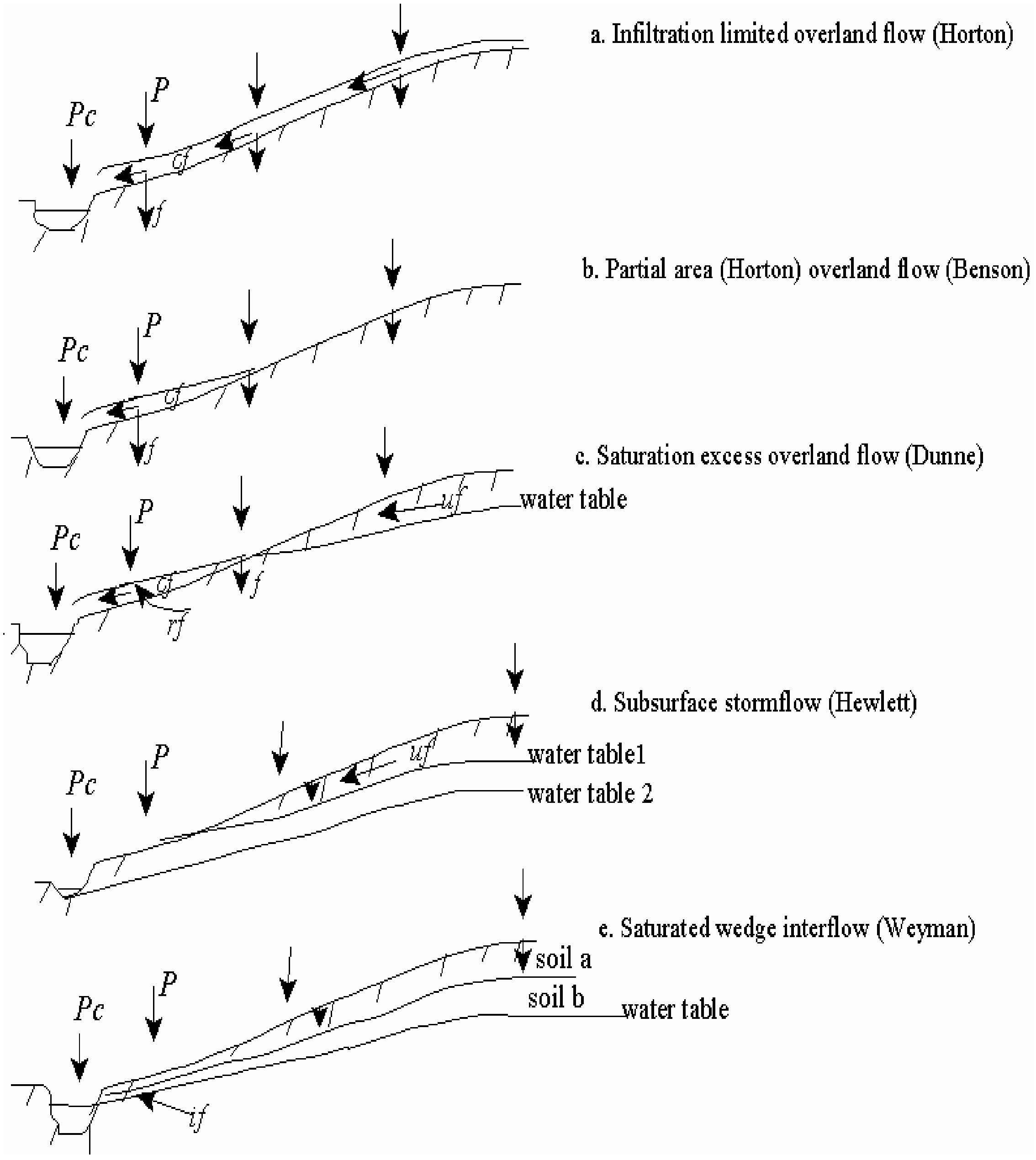

Fig. 2. Concepts of runoff production from hill slopes (Beven, 1986). *P*, precipitation; *Pc*, channel precipitation; *f*, infiltration; *of*, overland flow; *rf*, return flow; *if*, interflow; *uf*, unsaturated-zone flow

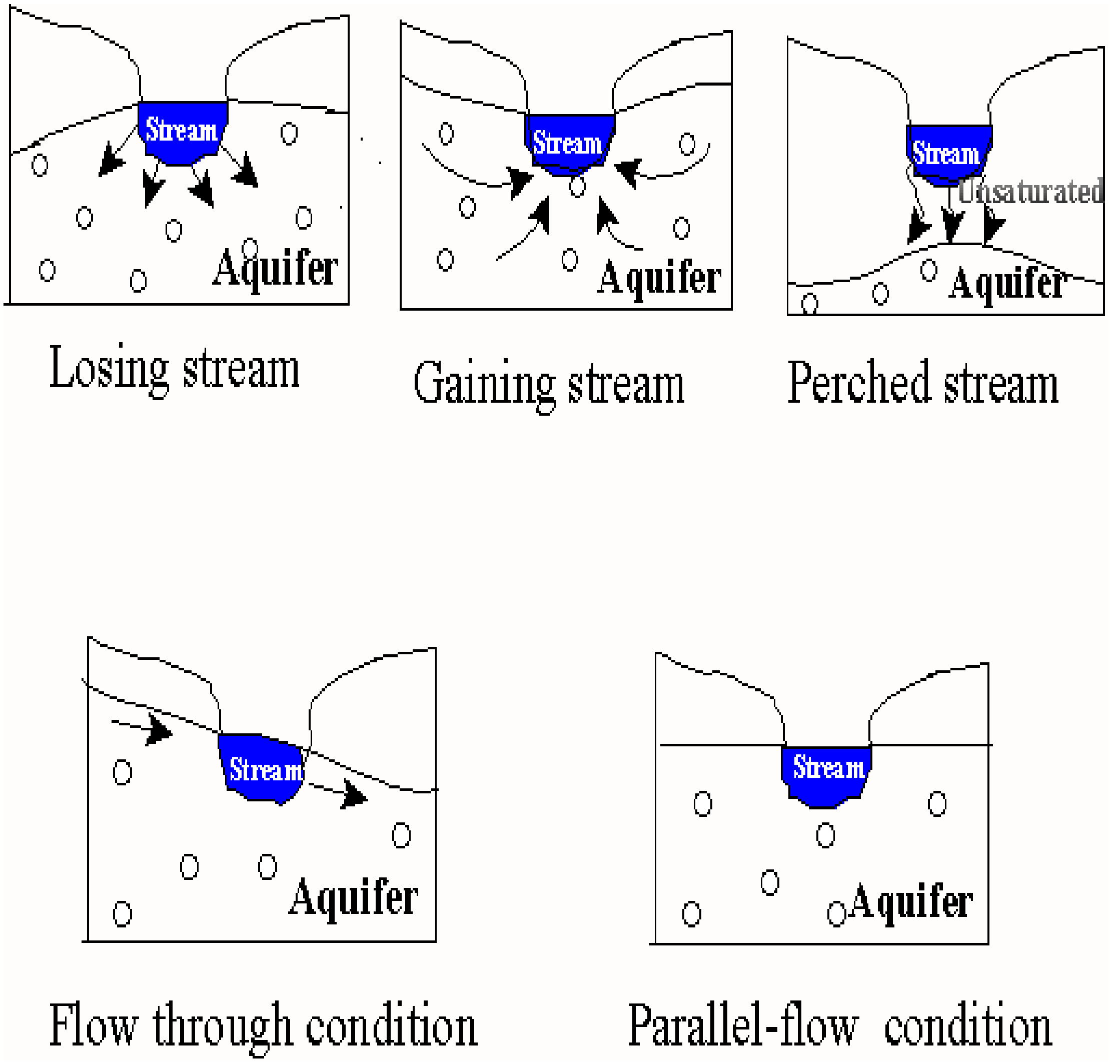

Fig. 3. Classes of stream – aquifer interaction