# THEORETICAL ASPECTS CONCERNING GROUNDWATER RESERVES AND RESOURCES ASSESSMENT AND ADMINISTRATION

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**Abstract**. A great part of human domestic activities, agriculture and industrial water supply use groundwater. Overexploitation and other forms of quantitative and qualitative human impact have negative consequence in the protection and conservation of groundwater resources. Increasing investigation degrees in groundwater resources research, offering new detailed information allow transposition in numerical models for quantitative assessment of water reserves and resources. A correct groundwater assessment and administration is based on certain major concepts concerning resource establishment, water storage in rocks of the terrestrial crust, hydraulic properties, groundwater investigation methods and reserve and resource types.

**Key-words**: groundwater, aquifer, resources, reserves

## 1. INTRODUCTION

Groundwater accumulations in Earth's crust can be identified through a succession of works and operations, more and more complex in accordance with knowledge development. Their purpose is getting information and data related to existence, location, geometry, accessibility, natural conditions, dynamics, qualitative characteristics, exploitability and utilization of these resources. The results of these investigation works consist in information regarding different groundwater features: geometry, natural recharge, storage, flow and discharge conditions, permeability characteristics and quality conditions.

The analysis, systematization and synthesis of the aquifer by conceptual and numerical models allow the assessment of groundwater reserves and resources. By both quantitative and qualitative evaluation, the conditions for management, optimal exploitation and use can be emphasized, offering tools for groundwater protection and conservation.

## 2. RESOURCES ESTABLISHMENT

In an aquifer element, saturated with water on $H<M$, the rise of pressure $dp$ will induce, in absence of mineral matrix effects, an increase $(\partial p_a/\partial p)dp$ of the water column $Ha$. For the confined conditions $H>M$ (fig. 2), the pressure variation is accompanied by modification of compressibility $\beta$, water pore density $\varphi$, effective porosity $m_{e,}$ and aquifer thickness $M$. By introducing storage coefficient $S_S = [\partial(\gamma m_e H_a)/\partial p]$ (Jacob, 1950; de Wiest, 1966; Albu, 1981), the overloading of mineral matrix with water is emphasized. Thus, for a confined aquifer, the water volume released from a unitary base prism, due to a unitary drop of pressure is identical with the effective storage coefficient.

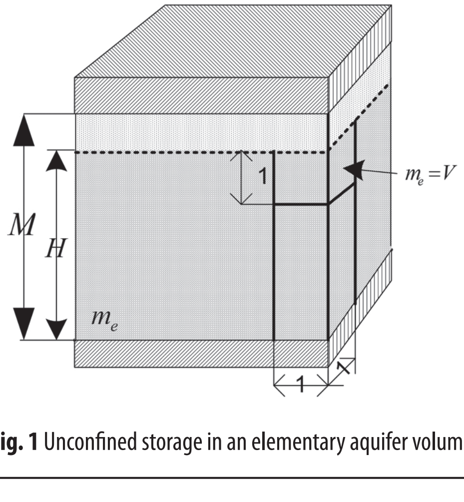


**Fig. 1** Unconfined storage in an elementary aquifer volume

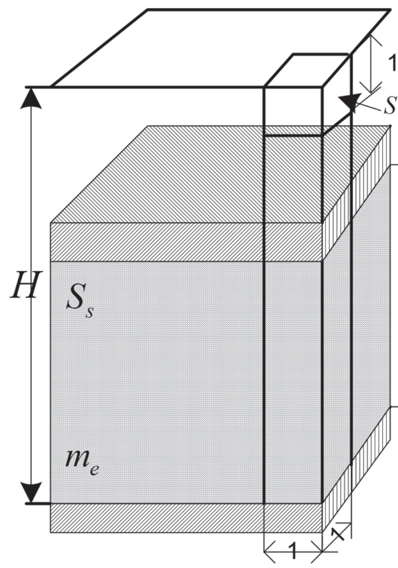


**Fig. 2** Confined storage in an elementary aquifer volume

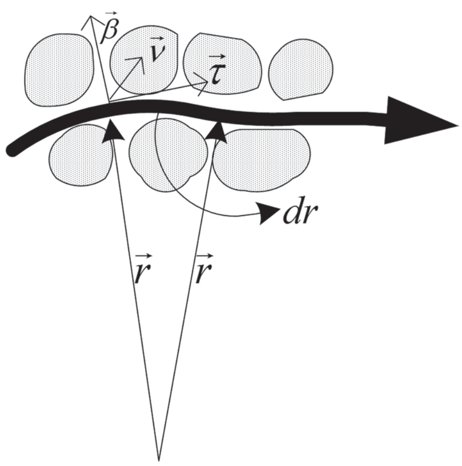


**Fig. 3** Groundwater flow trajectory

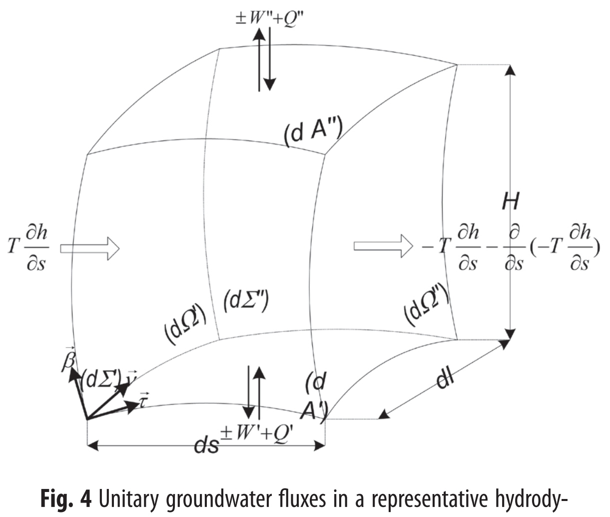


**Fig. 4** Unitary groundwater fluxes in a representative hydrodynamic element

For unconfined conditions ($H<M$, fig. 1), the effective porosity $m_e$ does not vary with the increase $[\partial(\gamma H)/\partial p]dp$, so the storage coefficient is $S_S=m_e$. In case of a unitary aquifer volume, the unit decrease of the water table corresponds to the water volume removed from the pore unit volume or to porosity value $m_e$.

For an aquifer with hydraulic conductivity $K$ and effective porosity $m_e$, the groundwater mass unit impulse is given by the linear relationship $\frac{dr}{dt}=\frac{k}{m_e}\frac{\partial h}{\partial \vec r}$, where $\frac{\partial h}{\partial \vec r}$ is the hydraulic gradient. From this equation, the effective velocity $\vec u=\frac{d\vec r}{dt}$ and the filtration velocity $\upsilon = m_e\frac{d\vec r}{dt}$, written in local forms $\vec\tau u=-\vec\tau\frac{K}{m_e}\frac{\partial h}{\partial s}$ and $\vec\tau=-\vec\tau K\frac{\partial h}{\partial s}$, have the same unit vector $\vec\tau$ as the tangent to the pathline (fig. 3). In a point of the pathline both the tangent unit vector $\vec\tau$, the main normal $\vec\upsilon$ and the double normal unit vector $\vec\beta$, constitute the vector system of the Frenet trihedral angle. This allows the best hydrodynamic representation because $\vec\tau$, $\vec\upsilon$ and $\vec\beta$ are tangent to the pathline $s$, the main potentiometric contour line | and the curved thickness of the aquifer stream $H$, defined by faces $d\Omega=Hdl,\ d\Sigma=Hds,\ dA=dlds$.

For a hydrodynamic element (fig. 4), $\vec\beta$ of storage reported to surface element $\vec\beta\, dlds$ is characterized by groundwater flux $S\frac{\partial h}{\partial t}dlds$ or $S\frac{\partial h}{\partial t}dA$. For the lateral flow faces, the groundwater flux is described by upstream unit flux $H=T\frac{\partial H}{\partial s}$ and the downstream unit flux by $H+\frac{\partial H}{\partial s}ds=-T\frac{\partial h}{\partial s}+\frac{\partial}{\partial s}(-T\frac{\partial h}{\partial s})ds.$

The resulted groundwater flux crossing the lateral faces $-\vec\tau Hdl$ (upstream) and $+\vec\tau Hdl$ (downstream) is $\frac{\partial}{\partial s}(-T\frac{\partial h}{\partial s})dA$ while the groundwater flux for lateral right $\left(-\vec\nu Hds\right)$ and left $\left(+\vec\nu Hds\right)$ faces is null. In the general case of groundwater flow, considering the flux on the upper $\left(+\vec\beta\, dlds\right)$ and lower $\left(-\vec\beta\, dlds\right)$ basal faces, present in semipermeable rocks, characterized by hydraulic conductivity $K'$ and thickness $M'$, has a $w'=\frac{K'}{M'}\left(h_{inf}-h\right)=\pm wdA$ distributed uniform flux from the adjacent aquifer, corresponding to the hydrodynamic element recharge, upward – if $h_{inf}>h$ or downward – if $h_{inf}<h$. If the basal face is impermeable ($K'=0$), the vertical distributed groundwater flux is null.

On the upper aquifer face, $+\vec\beta\, dlds$, the vertical distributed uniform fluxes can be represented by rainfall infiltration, soil water condensation, irrigation, exit groundwater fluxes, exit fluxes due to evapotranspiration. Also, the presence of a semipermeable bed, with the hydraulic parameters $K'$, $M'$, induce a leakage process, upward – if $h_{sup}<h$ or downward – if $h_{sup}>h$. The aquifer recharge occurs due to concentrated groundwater fluxes $\pm Q$ on the elementary basal surfaces $\pm\beta\,\partial A\left(\partial A \subset dA\right)$ caused by the presence of faults, wells, mining pit gallery, lithological windows, etc. On the upper basal face the aquifer recharge can be produced by: rivers, channels, boreholes, injection wells, faults, lithological windows, galleries or other aquifers.

Summarizing, at the scale of the entire aquifer unit element the hydraulic head time variation is determined not only by natural recharge/discharge factors, but also by artificial ones, following the relation:

$$S\frac{\partial h}{\partial t}dA + \frac{\partial}{\partial s}\left(-T\frac{\partial h}{\partial s}\right)dA \pm wdA \pm Q = 0 \qquad (1)$$

The expression represents the fundamental equation of hydraulic diffusivity and the ground water balance in an elementary aquifer system.

## 3. INVESTIGATION OF THE GROUNDWATER BEARING FORMATIONS

The knowledge about existence, location, geometry, natural conditions, dynamics, qualitative characteristics and exploitability of groundwater resources are obtained by methodologies, field works and operations using different methods and applications (Castany, 1972; Albu *et al.* 1989; Driscoll, 1995), such as: satellite and aero photo data interpretation, applied geophysics, geology, topography, geomorphology, climatology, hydrology, hydrogeology, hydrochemistry.

By satellite and aero photo data interpretation (Albu *et al.* 1989; Driscoll, 1995) can be identified on a regional scale not only the configuration and development of sedimentary basins susceptible to store important groundwater resources but also the aquifers thickness, rock consolidation and tectonic degree, depth of certain porous-permeable deposits etc.

Natural or induced variation of some qualitative properties, such as gravity, electric and magneto-telluric fields, radioactivity, elastic wave propagation, temperature, electromagnetic wave distribution under the influence of physical properties of rocks and geologic formations are analyzed and interpreted by applied geophysics methods, in two stages: first geologically and second hydrogeologically.

The aquifer identification and characterization of its rocks, based on their hydraulic properties (aquifer, aquitard, aquiclude formations), their structural, petrographic, physico-chemical features, together with relationships between them, can be evaluated by field inventory, geological site survey (cartography, core and detritus analysis, geophysical well logging investigations, mining works) and by lab analysis on samples. All these works correspond to the geological research concerning groundwaters. Almost all geology and hydrogeology works and methods use field measurements and a topographic base to report on a reference level. Besides topographic information, geomorphologic maps analysis, relief evolution and stream network basin investigation are also used to show the relationship between surface and underground waters. The climatologic methods offer information on the rainfall regime and all necessary parameters to estimate the real evapotranspiration. The hydrology specific methods provide the requested elements to estimate the global water balance. Other hydrologic information, concerning extension of stream network basins, surface water regime, underground flow, reserves modification, inflow/outflow from hydrographic basins complete the image of the global water balance.

Hydrogeological and hydrogeochemical methods (Albu *et al.* 1989; Driscol, 1995) can be grouped in 3 categories according to their purpose: obtaining data on aquifers, processing these data and identifying an aquifer.

The methods designed to get data are surface and groundwater point inventory, geophysical prospection, investigation by hydrogeological wells, tracer tests, hydraulic tests, laboratory analyises of rock and water samples.

Different hydrogeological maps and cross sections, geophysical profiles and well logging, hydrochemical charts, correlation graphics, breakthrough curves of tracers and environmental isotopes, experimental plots of hydrodynamic tests represent methods of processing available data. Representations of storage conditions, groundwater flow, aquifer recharge, and hydrochemical facies can also be used.

The aquifer identification consists in application of physical, impulse response (black box) and numerical modeling methods. By means of physical methods, the aquifer is divided into blocks depending on the investigation degree and subsequently assembled for a "unitary function". The black box methods consider the aquifer as a whole entity and its responses as determined by excitation history. The response analysis is given by the values of characteristic parameters. The numerical modeling involves several steps: building of the database, model development, characteristic parameter estimation, calibration, simulation of aquifer evolution for different scenarios, choosing of the optimal variant, continuous improvement of the model.

## 4. CLASSIFICATION AND ASSESSMENT OF GROUNDWATER RESERVES AND RESOURCES

The volume of water stored in a porous or fissured rock depends on the aquifer rock volume and distribution, rock porosity $m_e$, and porous water pressure. Consequently, in an aquifer with porosity $m_e$, thickness $M$ and surface distribution $\Omega$, saturated with water over a thickness $H \le M$ or $H = M$, the stored water volume is $W_{p0} = m_e\Omega H$ and respectively $W_{p0} = m_e\Omega M$. In case of confined aquifers $p > p_0$ or $H \ge M$, corresponding to a storage coefficient $S_S$, the water volume is $W_p = \Omega\left[m_e M + S_S\left(H - M\right)\right]$. Because the aquifer properties, i.e. porosity, permeability and water pressure have significant variations, the aquifer is divided into homogeneous elements having mean values for porosity $\tilde{m}_{ei}$, storage coefficients $\tilde{S}_i$, water thickness $\tilde{H}_i$, and aquifer thickness $\tilde{M}_i$. By their assemblage, (fig 5 and 6) results the global water volumes stored in:

- Unconfined aquifer :

$$W_{po} = \sum_{i=1}^{n} \tilde{m}_{ei} \Omega_i \tilde{H}_i \quad (2)$$

- Confined aquifer:

$$Wp = \sum_{i=1}^{n} \Omega_i \left[ m_{ei} M_i + S_i \left( H_i - M_i \right) \right] \quad (3)$$

These equations express the *groundwater reserves*. Depending on the geological configuration, porosity, permeability, compressibility degree, potentiometric level fluctuations, water fluxes from external sources etc., these reserves can be divided into two categories [Castany, 1972; Cineti, 1990]: *mean temporal* and *permanent*.

*Mean temporal reserves*: represent the additional groundwater volume stored from external sources inflow and depend on variations of the water table. The water table regime (fig. 5) is characterized by an inferior mean value (minimum level of water table) $\tilde{H}_{min}$ as given by:

$$W_t = \sum_{i=1}^{n} \tilde{m}_{ei} \Omega_i \left( \tilde{H}_i - \tilde{H}_{i\,min} \right) \quad (4)$$

where always $\tilde{H}_i > \tilde{H}_{i\,min}$.

In the case of confined aquifers (fig. 6) under natural conditions, the potentiometric surface variations due to inflow and outflow have small amplitudes and the mean temporal reserves specific to unconfined aquifers can be substituted by formulas applying to *elastic reserves:*

$$W_e = \sum_{i=1}^{n} \tilde{S}_i \Omega_i \left( \tilde{H}_i - \tilde{M}_i \right) \quad (5)$$

where $\tilde{H}_i > \tilde{M}_i$, and $\tilde{S}_i$, $\tilde{H}_i$, $\tilde{M}_i$ are the mean values for the storage coefficient, stored water column, and aquifer thickness on the discrete elements $\Omega_i$.

*Permanent natural reserves* [Castany, 1972; Cineti, 1990] do not vary over a long time with the aquifer inflow or outflow and correspondent to the mean value for the minimum position of the water table $\tilde{H}_{min}$. This can be calculated with the equations:

- Unconfined aquifers:

$$Wpe = \sum_{i=1}^{n} \tilde{m}_{ei} \Omega_i \tilde{H}_{i\,min} \quad (6)$$

- Confined aquifers:

$$Wpe = \sum_{i=1}^{n} \tilde{m}_{ei} \Omega_i \tilde{M}_i \quad (7)$$

The *groundwater resources* represent the water fluxes that can be exploited from an aquifer or aquifer system. They represent appropriate stored reserves, water fluxes from external sources and subordinate aquifers. Their values could depend on porosity, permeability and water flow conditions. The groundwater resources assessment needs aquifer identification and especially numerical modeling. Using field data investigation, prior to groundwater flow modeling, it is necessary to elaborate a database containing the aquifer properties, water balance, quantitative and qualitative characteristics, boundary conditions, drainage and exploitation possibilities, etc. Finally the water resources can be calculated by creating a groundwater flow model based on the numerical solution of equation (1), function of initial and boundary conditions.

*Natural resources* $Q_n$ represent the water fluxes for a flow section $\Omega_i$ (fig. 7), crossed at a normal velocity $\vec{\upsilon}$ and can be evaluated through the balance method using the equation:

$$Q_{ni} = \int_{\Omega i} \vec{\vartheta} d\vec{\Omega}_i \quad (8)$$

where $\vec{\upsilon}$ has different values and directions and $d\vec{\Omega}_i = \vec{n} d\Omega$ is the elementary section flow. If water fluxes with a flow velocity $\vartheta = K_i \left( \frac{\delta h}{\delta s} \right)_i$ cross the unit area $\Omega_i$, then for the entire aquifer flow section (fig. 7) the natural groundwater resource [Cineti, 1990] is:

$$Q_n = \sum_{i=1}^{n} K_i \left( \frac{\delta h}{\delta s} \right)_i \Omega_i \quad (9)$$

For the hydrodynamic representation of the aquifer, the water table (for unconfined aquifers) or the upper part of the aquifer in case of a confined aquifer and the aquifer thickness ($M$ or $H$) delimit the flow section. This method gives no good results in case of low gradients, karstic or piedmonts aquifers. For low gradients aquifers, the natural groundwater resource is much better expressed by using transmissivity $T_i = K_i H_i$ for potentiometric or water table line $l_i$ on the flow section. Thus, for the whole section, the formula is:

$$Q_n = \sum_{i=1}^{n} T_i l_i \quad (10)$$

In case of the drainage of an aquifer interdependent with other water sources or adjacent aquifers [Albu *et al.* 1989], the pumped water $Q_r = Q_0$ comes initially from the aquifer self storage. During time drainage, the water fluxes based on storage decrease while $Q_r = Q_0^{'} + \sum_{j=1}^{m} Q_j$ total water flux has in composition the storage water flux $Q_0^{'}$ and other flow fluxes $\sum_{J=1}^{m} Q_j$ from adjacent m water sources (surface waters, subordinated aquifers, aquitard). They represent the attracted resources into the aquifer on surface $A$. The long duration drainage effect is quantified in increasing drawdown $\tilde{h} - h$, such as to the aquifer the distributed water fluxes is $\sum_{j=1}^{m-k} (K'/H')_j (\tilde{h} - h)_j A_j$, corresponding with a leakage parameter $\left( K'/H' \right)_j$, percolation surfaces $A_j \subset A$ and concentration water fluxes $\sum_{J=1}^{k} Q_{0j}$. By consequence the origins of attracted resources are the subordinated water sources (surface waters, aquifers, aquitards, etc) and they are calculated accordingly:

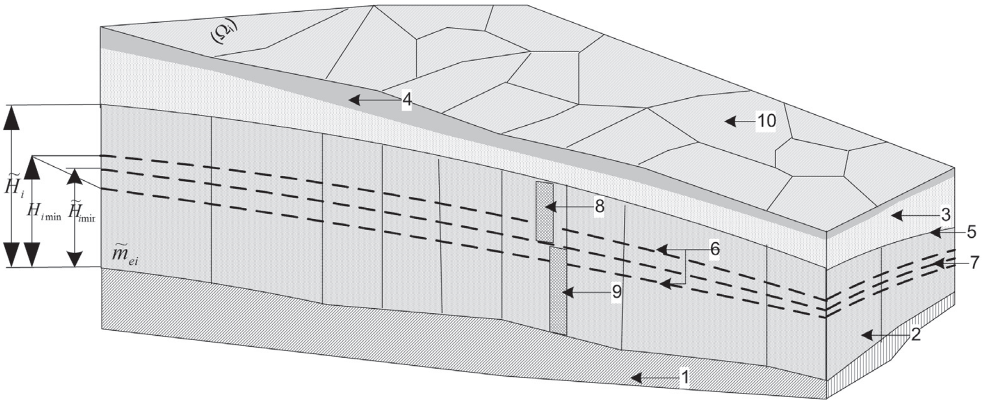


**Fig. 5** Mean temporal and permanent reserves in an unconfined aquifer. **1**. impermeable rocks **2**. saturated permeble rocks **3**. unsaturated permeable rocks **4**. soil **5**. level of water table **6**. minimum seasonal water table **7**. average minimum seasonal water level **8**. coressponding element of average temporal reserves **9**. corresponding element of permanent reserves **10**. calculus elementary surface with homogenous values

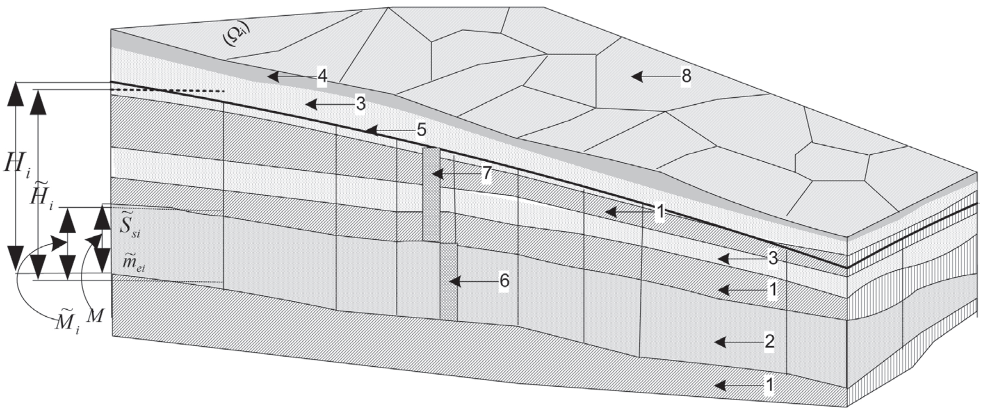


**Fig. 6** Mean temporal and permanent reserves in an unconfined aquifer. **1**. impermeable rocks **2**. saturated permeable rocks – main aquifer **3**. permeable rocks – adjacent aquifers **4**. soil **5**. main aquifer – level of potentiometric water surface **6**. corresponding element of permanent reserve **7**. corresponding element of elastic reserve **8**. calculus elementary surface with homogenous values

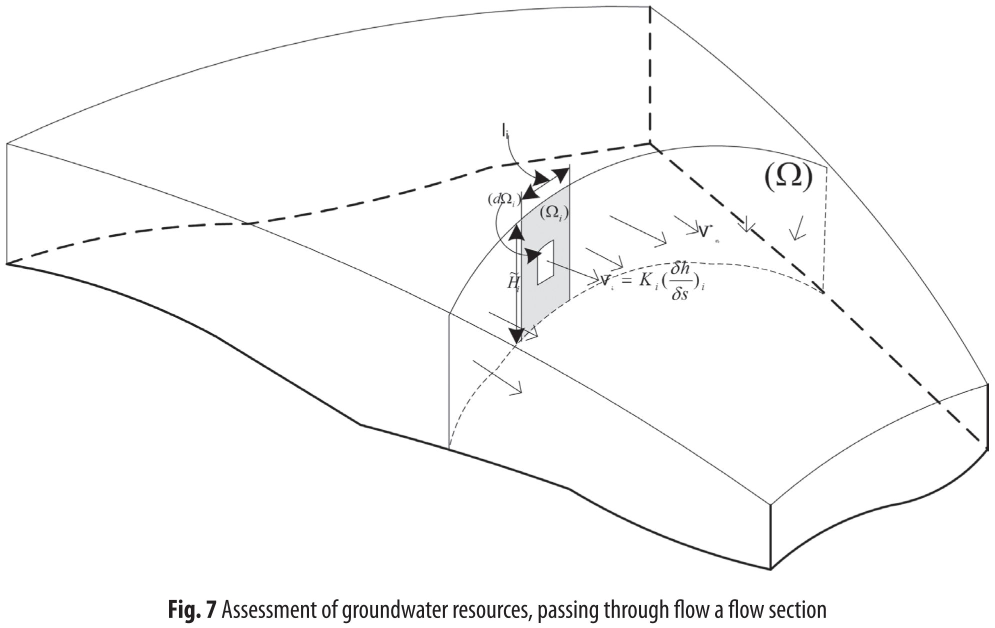


**Fig. 7** Assessment of groundwater resources, passing through flow a flow section

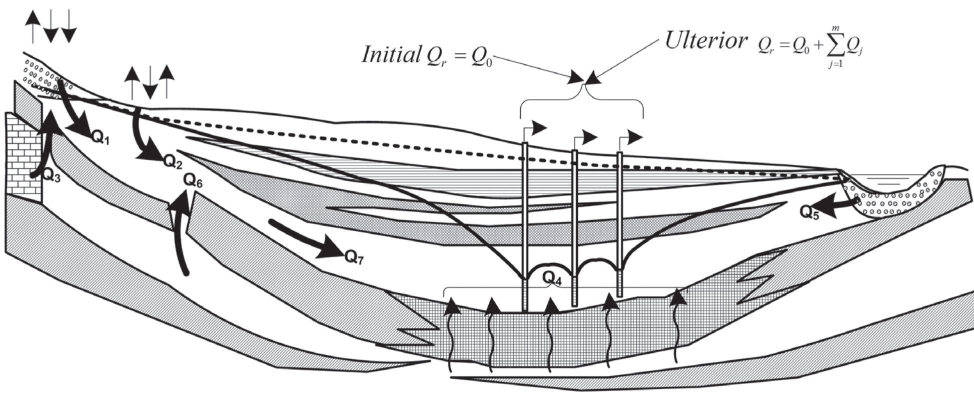


**Fig. 8** Attracted groundwater resources constituted during water wells exploitation (after Albu *et al.* 1989). Groundwater fluxes from: **1**. piedmont **2**. precipitation and soil condensation **3**. fissured – karstic aquifer by faults **4**. deep aquifer by semipermeable rocks 5. surface water and adjacent aquifers **6**. subordinated aquifers by faults and lithologic nappe **7**. self aquifer

$$Q_r = \sum_{j=1}^{m-k} (\frac{K'}{H'})_j (\tilde{h}-h)_j A_j + \sum_{J=1}^{k} Q_{0j} \qquad (11)$$

In an aquifer, besides the natural and attracted resources, the *exploitable resources* $Q_{ex}$ can be calculated by the formula:

$$Q_{ex} = Q_a + Q_r - Q_d \qquad (12)$$

by summing the recharge sources $Q_a$ and the $Q_r$ leakage sources and excluding the descharge sources $Q_d$ (caused by natural emergences, well production exploitation, drains and other surface or underground works, water transfer in other aquifers, rivers, lakes, floods, etc).

## 5. GROUNDWATER RESERVES AND RESOURCES ADMINISTRATION

The groundwater resources, like other mineral resources, are *never – failing* and their abasement carry during medium and long term negative impacts. Groundwater resources optimum exploitation, protection and preservation involve their administration instituting the stock of available reserves and resources (Heyel, 1973), in order to assure a balance between included and excluded reserves or resources (fig. 9).

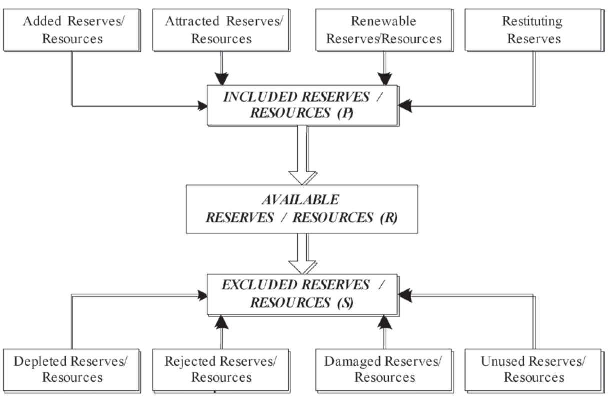


**Fig. 9** Groundwater resources administration scheme (after Albu and Popa, 1996)

The added, attracted, renewable and restituted reserves or resources constitute *included reserves or resources* $P$. The depleted, rejected, damaged and unused reserves and resources compose *excluded reserves* $S$. The *added reserves or resources* appear as a consequence of detailed quantitative and qualitative exploration phases, increase of depth investigation or by improvement of research methods. The *attracted reserves or resources* represent supplementary fluxes from adjacent aquifers or external sources, together with the quality improvement through remediation and treatment methods. *The new groundwater reserves added to the total volume of the included total reserves form by renewal and restitution process in natural water cycle.*

*Excluded reserves or resources* are those depleted or with small significance after over-exploitation, while rejected resources are those with poor characteristics, especially qualitative ones. Excessive exploitation, pollution or other human activities produce quantitative and qualitative modifications, forming rejected resources. Considering technical or economical aspects, the unused reserves cannot be use for exploitation.

The *available reserves or resources* can be expressed as a function $R = R(P,S)$ of included resources $R$ and excluded resources $S$ (Albu & Popa, 1996), and by analogy with a thermodynamic system, they present a variation

$$dR = \left(\frac{\partial R}{\partial P}\right)_S dP + \left(\frac{\partial R}{\partial S}\right)_P dS$$

and a variation rate

$$\frac{dR}{R} dR = \left[\frac{1}{R}\left(\frac{\partial R}{\partial P}\right)_S dP\right] - \left[\frac{1}{R}\left(\frac{\partial R}{\partial S}\right)_P dS\right],$$

where

$$\frac{1}{R}\left(\frac{\partial R}{\partial P}\right)_S dP = P \text{ and } -\frac{1}{R}\left(\frac{\partial R}{\partial S}\right)_P dS$$

are the inclusion and respectively exclusion coefficients. In this conditions, groundwater resources and reserves evolution from an initial stage $R_0 = R(P_0,S_0)$ to a later one, $R = R(P,S)$, follows the state equation

$$\int_{R_0}^{R} \frac{dR}{R} = \int_{P_0}^{P} pdP - \int_{S_0}^{S} sdS \tag{13}$$

with the solution:

$$R = R_0\, exp\left( \int_{P_0}^{P} pdP - \int_{S_0}^{S} sdS \right) \tag{14}$$

After series development and by approximation the equation (14) is reduced to the form

$$R = R_0\left[1 + \tilde{p}(P - P_0) - \tilde{s}(S - S_0)\right] \tag{15}$$

or the available groundwater resources and reserves variation rate is calculated with the formula

$$\frac{\Delta R}{R_0} = \tilde{p}\Delta P - \tilde{s}\Delta S \tag{16}$$

where $\tilde{p}$ and $\tilde{s}$ are the mean coefficients of inclusion respectively exclusion. According to equation (16), within a time period $\Delta t$ the variation rate can take negative, null or positive values and the corresponding administration is in deficiently, equilibrated or in excess mode. In a limit situation, the variation rates correspond (Albu&Popa, 1996) to wasteful administration, if $\tilde{p}\Delta P \to 0$ and $\frac{\Delta R}{R_0} \to -\tilde{s}\Delta S$, conservative administration, if $\tilde{p}\Delta P \to 0$ and $\frac{\Delta R}{R_0} \to 0$, avaricious administration, when $\tilde{s}\Delta S \to 0$, and $\frac{\Delta R}{R_0} \to -\tilde{p}\Delta P$.

## CONCLUSION

Groundwater reserves and resources assessment is a difficult process due to the convergence of a lot of factors. Aquifer conceptual models, groundwater flow and contaminant transport have a great importance in assessing water resources. In a first stage, formulas are not complicate, but their application is not simple, due to the modifications in time of the water table or potentiometric surface, determined by aquifer recharge, discharge, supplementary water fluxes from adjacent formations, dewatering or over exploitations, etc. The assessment solution can be applied according to different cases of unconfined or confined aquifers, for groundwater reserves or resources, using elementary aquifer blocks with homogenous properties. In the case of groundwater administration, the final simple solutions need previous calculations of water reserves and resources for every each category. The assessment methods and type of administration represent, by monitoring the evolution of aquifers, water quality determinations, groundwater remediation, etc., necessary phases in groundwater management.

## ACKNOWLEDGMENTS

We acknowledge the finacial support of the Project PN2-31083 AQUASUD (Project Director Dr. Mihaela C. Melinte).

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